

ATTACHMENT D-3

Solar Energy Conversion

THE SOLAR CELL

(SECOND EDITION)

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The Solar Cell

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PREFACE

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< Previous

Next >

That the human race faced an energy crisis became painfully obvious during the 1970s. Since that time the blatant obviousness of the problem has waned, but the underlying technical and political problems have not disappeared. Humanity continues to increase in number (the world population is, at present, in excess of five billion) and, despite major efforts towards improving the efficiency of energy consumption, the overall per capita use of energy continues to increase.

Projections concerning the human population and its energy requirements during the next century estimate populations in excess of seven billion and energy consumption per person in excess of 40,000 kilowatt hours per year (approximately twice the current rate). This increasing energy use must be viewed in the light of the finite availability of conventional energy sources. When done so the energy crisis can be seen to be all too real for any long term comfort.

A frequently mentioned solution to the problem of increasing requirements for energy and dwindling energy sources is to tap the energy in sunlight. The solar energy falling on the earth's surface each year is over 20,000 times the amount presently required by the human race, making for a seemingly inexhaustible supply. For effective utilization of any energy source civilization requires an easily storable, easily transportable form of energy (after all, it is dark at night). This implies that the incoming solar energy should be transformed into electrical energy. In turn this means that we need to utilize photovoltaic (solar cell) conversion of the energy in sunlight.

Photovoltaic effects were initially observed more than a century and a half ago. In 1839 E. Becquerel observed a photovoltage (a voltage depending on the character and intensity of the illuminating light) when sunlight was allowed to shine on one of two electrodes in an electrolytic solution. The first scientific paper on photovoltage using solids was published in 1877 and concerned the semiconductor, selenium. In 1954 research groups at RCA and Bell Telephone Laboratories demonstrated the practical conversion of solar radiation into electrical energy by a silicon pn junction solar cell, and shortly thereafter Chapin, Fuller and Pearson reported on a six percent efficient solar cell (Journal of Applied Physics, Vol. 25, 1954, p. 676).

The modern solar cell is an electronic device, fabricated from semiconducting materials. It converts a fraction of the energy contained in sunlight directly to electrical energy at a voltage and current level determined by the properties of the semiconductor, the solar cell design and construction techniques, and the incident light. To gain an understanding of how solar cells work and to be in a position to design and construct energy conversion systems using solar cells requires a background covering such diverse areas as: the nature of solar radiation; semiconductor physics; quantum mechanics; the techniques of energy storage; optics; heat flow in solids; the nature of elemental, compound, single crystal, polycrystalline and amorphous semiconductors; the technology of semiconductor device fabrication; and the economics of energy flow. It is not physically possible to cover, in depth, all of these areas in a single work. In writing this volume, I have endeavored to create a survey text; a book that explores a number of critical background areas and then outlines the theory of operation of solar cells while considering their design and fabrication. Solar cell performance is treated both in the general sense and for some specific examples. These examples select semiconductor, junction type, optical orientation and fabrication technology and then highlight the problems encountered in solar cell design and illustrate, both in general and specific fashion, areas of promising future research and development. References are provided to facilitate deeper investigations of the various topics of interest—from quantum mechanics to economics.

This is the second edition of this work on solar cells. Historically, this book originated from a series of lectures on energy and solar cells given to engineering students at the University of California at Santa Barbara. These lectures culminated in the first edition of this work, in 1978. Since that time there has been much change in the fields of energy generation and consumption, solar energy and solar cells. Additional lectures at UCSB and at Northern Arizona University, coupled with considerable research into aspects of photovoltaic and solar energy have modified the original work. This, the second edition, is thus the result of more than 20 years of interest in solar energy and solar cells coupled with steady changes in these fields and our understanding of these fields. Since it is virtually impossible to separate design and operating theory, engineering, economics and politics in considering the use of solar cells in addressing the energy problem facing humanity, the systems aspect is present throughout this volume.

The first chapter is a broad (and brief) survey of the elements which make up the “energy crisis”. It is devoted to illustrating the limited nature of presently utilized energy sources and to a discussion of the various “non-conventional” energy sources proposed for the future: biological, wind, wave and solar. It has, as its major purpose, three points to make: (1) that our conventional energy sources will be exhausted at some point in the not-too-distant future, (2) that solar energy is capable of supplying the energy requirements of humanity for the foreseeable future, and (3) that photovoltaic energy conversion is a major candidate for supplying mankind with its required energy; perhaps the prime candidate.

The second chapter considers the nature of sunlight, discusses the solar spectrum, the effects of latitude, the earth's rotation and axial tilt, and atmosphere and weather. A brief discussion of optics is included as a

background for those individuals interested in this aspect of energy conversion.

The third chapter surveys the nature of semiconductors. Solar cells are theoretically constructed of various semiconductors and their performance is shown to depend upon the properties of these materials. These properties are best understood within the framework of quantum mechanics and solid state physics. [Chapter III ↗](#) discusses crystals, quantum mechanics and semiconductor physics with a view towards outlining the principal properties of semiconductors and the manner in which these properties vary with device processing technology, temperature of operation, and the characteristics of the illumination. Because the physics of single crystal semiconductors is best understood (as contrasted with polycrystalline or amorphous structured semiconductors), the emphasis in this chapter is on solar cells constructed from single crystal semiconductors. It is in this chapter that certain specific example semiconductor materials are first introduced.

[Chapter IV ↗](#) treats the interaction of light semiconductors including absorption, reflection and transmission. The generation of hole-electron pairs is treated both in the abstract and in detail using the example semiconducting materials introduced in [Chapter III ↗](#). The maximum potential output power density and the optimum output current density for photovoltaic cells are displayed for solar cells fabricated from six sample single crystal semiconductors.

The fifth chapter is devoted to a general discussion of solar cell performance as a function of the junction employed. The current versus voltage characteristics of pn, heterojunctions, mos junctions and Schottky barrier solar cells are considered and a general expression for the output power density as delivered to an optimum external load is obtained. From this expression, the maximum expectable output power density for solar cells, as a function of the energy gap of the semiconductor employed, is derived. This is displayed as a function of the saturation current of the solar cell.

In [Chapter VI ↗](#) the six example semiconductors are employed to provide specific values of estimated solar cell performance, based on various technologies of junction fabrication and upon the optical orientation of the solar cells. The solar cell performance levels computed in this chapter, and in later chapters, are not meant as absolute predictions of maximum performance. Rather, they are intended to provide indications of “typical” solar cell performance as structured by technology and materials limitations. It is intended that they will suggest areas in need of research and development.

The seventh chapter considers the effects upon solar cell operation of changes in junction temperature and the use of concentrated sunlight. The power density in natural sunlight is very low (approximately one kw/m² at sea level) and hence any sizeable energy requirement implies a large area of solar cells. By utilizing relatively inexpensive mirrors or lenses to concentrate sunlight upon expensive solar cells a significant reduction in cost can be effected. This chapter examines the limits imposed on optical concentration levels by the solar cells and shows that improved solar cell performance is possible using the six example single crystal semiconductors.

[Chapter VIII ↗](#) carries the materials of the preceding chapter a step further. In addition to considering the electrical energy output for solar cells operating under concentrated sunlight, the thermal energy available from such a situation is considered. Thus a complete systems approach to producing energy from photovoltaic cells is developed. Later in this chapter various approaches to further improving overall energy output (both electrical and thermal) from photovoltaic systems are considered. Most of these systems involve modifying the spectral characteristics of the light used to illuminate the solar cells. The altered light is a better match for the semiconductors used in fabricating the solar cells and so overall efficiency is improved.

In the ninth chapter the solar cells are constructed using polycrystalline and amorphous semiconductors. The operation of these devices depends strongly on the crystal interfaces and the properties of unsaturated chemical bonds. As a result, the theory of operation of polycrystalline and amorphous material solar cells is not well understood. Thus, this chapter is less theoretical and more empirical in nature than the previous chapters. Numerous examples of polycrystalline and amorphous solar cell operations and materials are provided.

The final chapter, [Chapter X ↗](#), is devoted to a brief survey of such topics as economics, energy storage, and overall systems effects. Potential problems and proposed solutions are noted and briefly discussed. It is intended that the reader treat this chapter as a question mark whose main purpose is to provoke inquiry.

The energy “problem” has not gone away, and will not go away. Without strenuous and continuing efforts on the part of humanity we will see a continuing series of “crises”. Fortunately, the field of photovoltaic energy conversion is growing rapidly, both in scope and complexity. Of necessity I have been forced to treat lightly many areas which deserve considerably more intense study. To those readers whose specialty in research or development lies in these areas, my apologies. I can but plead lack of space and time.

In closing I would like to thank my fellow faculty members and my students for many hours of stimulating discussion and my wife, Laura Lou for her encouragement, patience, support and proof reading. In the final analysis, any errors are, of course, my responsibility.

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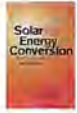


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Solar Energy Conversion

The Solar Cell

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Author:

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[Download all chapters](#)[About the book](#)

Table of contents

[Full text access](#)**Front Matter, Copyright, PREFACE**[Book chapter](#) [Full text access](#)

CHAPTER I - ENERGY NEEDS-ENERGY SOURCES

Pages 1-38

[View PDF](#)[View chapter >](#)[Book chapter](#) [Full text access](#)

CHAPTER II - THE SUN AND SUNLIGHT

Pages 39-70

[View PDF](#)[View chapter >](#)[Book chapter](#) [Full text access](#)

CHAPTER III - SEMICONDUCTORS

Pages 71-118

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

CHAPTER IV - LIGHT-SEMICONDUCTOR INTERACTION

Pages 119-153

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

CHAPTER V - BASIC THEORETICAL PERFORMANCE

Pages 155-195

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

CHAPTER VI: - SOLAR CELL CONFIGURATION AND PERFORMANCE

Pages 197-256

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

CHAPTER VII - ADVANCED APPROACHES

Pages 257-300

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

CHAPTER VIII - ADVANCED APPROACHES-II

Pages 301-337

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

CHAPTER IX - POLYCRYSTALLINE AND AMORPHOUS SOLAR CELLS

Pages 339-362

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

CHAPTER X - CONCLUDING THOUGHTS

Pages 363-396

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

APPENDIX A - CONVERSION FACTORS

Pages 397-403

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

APPENDIX B - SELECTED PROPERTIES OF SOME SEMICONDUCTORS WITH PHOTOVOLTAIC CELL POTENTIAL

Pages 403-407

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

APPENDIX C - THE SATURATION CURRENT IN PN JUNCTION SOLAR CELLS

Pages 407-411

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

APPENDIX D - SOME USEFUL PHYSICAL CONSTANTS

Page 411

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

APPENDIX E - SYMBOLS

Pages 411-419

 [View PDF](#) [View chapter >](#)

Book chapter ☐ Full text access

SUBJECT INDEX

Pages 420-426

 [View PDF](#) [View chapter >](#)

About the book

Description

CHAPTER VI: SOLAR CELL CONFIGURATION AND PERFORMANCE

Introduction

The nature of the solar spectrum was described in Chapter II. In Chapter IV we discussed the maximum energy that was potentially available for conversion to useful electrical energy within a solar cell--as a function of the energy gap of the semiconductor employed. In Chapter V we discussed the effects, on solar cell performance, of solar cell internal series resistance and internal junction biasing. This was done in a general way by assigning values of saturation current, J_s , and diode loss factor, K' , to solar cells as a function of the semiconductor energy gap. The later portions of Chapters IV and V also considered the effects of bulk and surface recombination on the potentially available photocurrent and output power from solar cells.

The characteristics of pn and heterojunction solar cells depend primarily on the properties of the semiconductor(s) employed. The most important semiconductor property in these cases is, clearly, the width of the energy gap. When Schottky junction or mos solar cells are employed, the barrier height, which is a function of the semiconductor and metal employed, is of prime importance. For all types of solar cells the charge carrier mobility and lifetime play major roles in overall performance. Both the collection/separation of electron-hole pairs (and, hence, the photocurrent) and the internal series resistance depend on the design philosophy of the solar cell and upon the techniques used in its construction.

In this chapter we will consider various solar cell optical orientations and construction techniques. With specific semiconductors as examples, we will determine solar cell series resistance, saturation current, optimum junction voltage, maximum power density delivered to the external load, and the value of the optimized external load. This will be

198 CHAPTER VI: CONFIGURATION AND PERFORMANCE

done assuming room temperature (300°C) operation. The net result will be a set of design relationships, indicating the potential output for solar cells of various types, as well as providing the reader with an appreciation of the various design trade-offs.

In keeping with the discussions of Chapters IV and V, let us select semiconductors with energy gaps lying between 1.0 and 1.8 electron volts. From these earlier discussions, we shall consider only single crystal semiconductors*. As earlier, let us select a number of semiconductors as specific examples, indicated in Table VI.1.

Table VI.1

Example semiconductors

Semiconductor	Symbol	Energy Gap at 300°C (eV)
Silicon	Si	1.106
Indium Phosphide	InP	1.35
Gallium Arsenide	GaAs	1.42
Cadmium Telluride	CdTe	1.50
Aluminum Antimonide	AlSb	1.58
Cadmium Selenide	CdSe	1.70

The preceding table of semiconductors does not exhaust the list of possibilities. It does, however, span the range of energy band gap widths which is considered to be most promising and provides a distribution of single element and compound semiconductors with a broad distribution of available technology and potential performance and problems. Clearly any one of these materials is also a potential semiconductor in a heterojunction or Schottky barrier solar cell. For example, GaAs has been

* Besides the additional complexity involved in the analysis of polycrystalline based solar cells, single crystal based solar cells exhibit a higher operating efficiency. We will, in a later chapter, consider amorphous and polycrystalline semiconductor based solar cells.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 199

used for some time as the substrate semiconductor in a GaAs-AlGaAs heterojunction solar cell [1-3] and the other materials have been used as well [4-8].

Let us now proceed to a discussion of design philosophy and construction technology as applied to solar cells made from these example materials.

Optical Orientation

Light can enter a solar cell from a number of directions. Consider a pn junction or heterojunction solar cell. In Figure VI.1 we display three general configurations of solar cell-light interaction. In the top illustration of Figure VI.1 the solar cell is securely mounted on a heat sink. This heat sink also acts as an electrical contact to the larger of the two regions of the solar cell, the substrate. The light enters the solar cell via the other region, the "front layer". Metallic contacts to the upper region mask portions of the solar cell and thereby reduce the effective optically absorbing area. The middle illustration of Figure VI.1 presents a second configuration, known as the vertical configuration. Here, the light enters the solar cell unhampered by the presence of metallic contacts. The electrical contacts are at the non-illuminated ends of the solar cell and the junction is both parallel to the incoming light and vertical, in orientation, to the heat sink. Note that care must be taken to insure that the heat sink does not short out the pn junction. This limits the effectiveness of this configuration of solar cell.

There are two types of inverted configuration solar cell, displayed in the bottom illustration of Figure VI.1. In one case, there are electrical contacts on the illuminated surface, a situation which restricts the photon input. In the other inverted configuration the electrical contacts are on the down side and do not interfere with the passage of photons. In both instances the inverted configuration solar cell has a heat sink which is on the non-illuminated side and is positioned very close to the junction of the solar cell. This positioning assists in maintaining junctions at a low temperature and, as we will see, enhances the operating efficiency. Note that, if the electrical contacts to both solar cell regions (substrate and "front layer") are on the lower or heat sink side, it is necessary to configure the electrical contacts and heat sink in order to avoid shorting the junction.

200 CHAPTER VI: CONFIGURATION AND PERFORMANCE

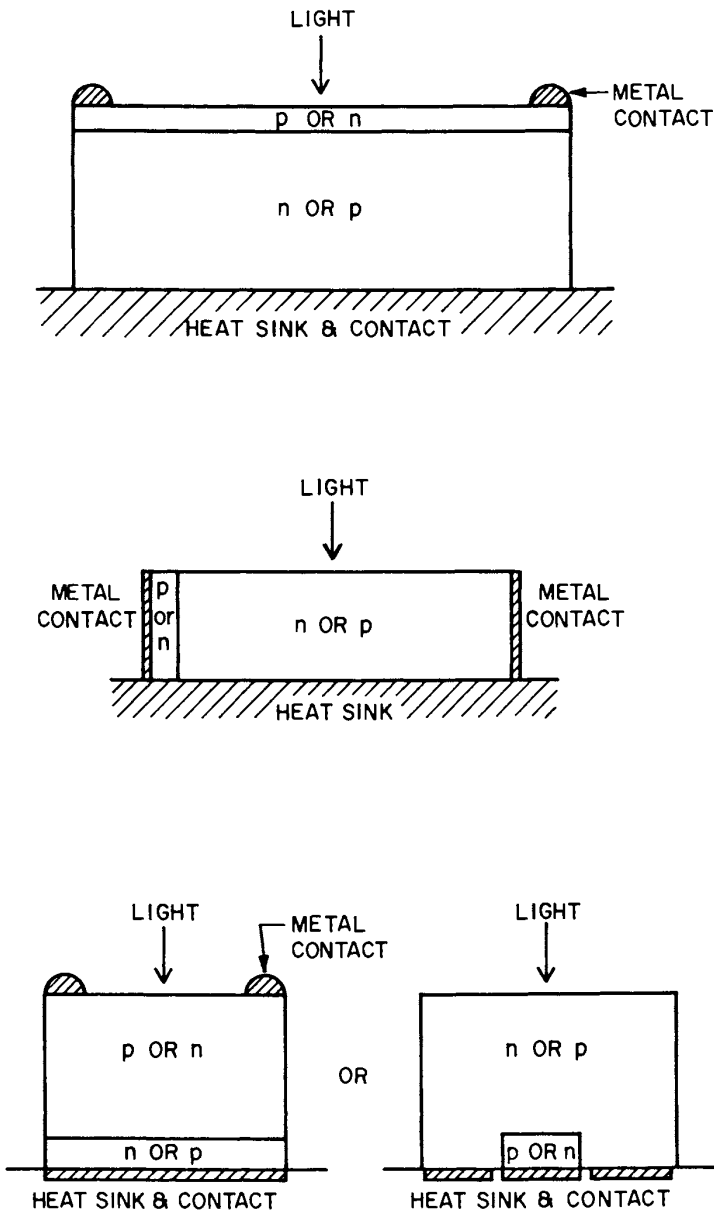


Figure VI.1. PN and heterojunction solar cell-light configurations.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 201

Figure VI.1 is drawn for a pn or heterojunction cell with two semiconductor regions per solar cell. If we replace the thinner of the two regions by either a thin metal or thin metal-oxide layer, the same optical configuration classifications can be seen to apply to Schottky and mos cells. For standard configurations, it is clear that care is required to form metal layers thin enough to pass light and thick enough to carry current.

Before any numerical computations are made, consider some of the advantages and disadvantages of each configuration of solar cell. The standard configuration (top illustration of Figure VI.1) solar cell is simple to construct and has good contact from solar cell to heat sink. This last item is important for all semiconductor solar cells and, most particularly so, in terms of those systems where optical concentration is employed to increase the intensity of the photon flux. Recall, from Chapter V, that the saturation current density for the four types of junctions (pn junction, heterojunction, Schottky junction and mos junction--Equations V.2, V.17, V.19 and V.21). In every case, for every junction type, the saturation current density rises sharply with increasing temperature. From Equations V.31 through V.33 an increase in saturation current density results in a decrease in the solar cell delivered power density. Since practical solar cell efficiencies are rarely in excess of 25% this means that some 75%, or more, of the solar energy ($\sim 80 \text{ mW/cm}^2$ under AM1 conditions) is converted into heat within the semiconductor. This heat must be removed from the solar cell to avoid further increase in the operating temperature.

The standard configuration solar cell has a number of drawbacks as well. Once the electron-hole pairs are generated, they must be split into their component electrons and holes and the individual charge carriers must be collected by the junction. In the upper, or "front layer", the charge carriers must flow laterally to the electrical contacts. This upper region is a very thin (optically transparent) conductor (or semiconductor). Because this upper region is of low lifetime*, it acts, in part, as a "dead layer" (see Chapter IV). To minimize the loss of photon generated charge carriers in this "dead layer" we must make it thin. This thinness creates high internal resistance with attendant decreased power performance. This drawback is particularly severe in Schottky barrier and mos solar cells.

* This low lifetime is the result of the construction techniques employed. We will consider these techniques later in this work.

202 CHAPTER VI: CONFIGURATION AND PERFORMANCE

PN junction solar cells also show ill effects from this phenomenon, but heterojunction solar cells avoid the problem by constructing the "front layer" of the solar cell of a semiconductor which is optically transparent. This advantage is, in turn, counterbalanced by excess recombination at the heterojunction proper and by a more complicated fabrication technology. Another major drawback in standard configuration solar cells is the presence, on the illuminated surface, of the thick metal electrical contacts (the thickness is required to minimize the series resistance). This results in a reduction of the produced photocurrent.

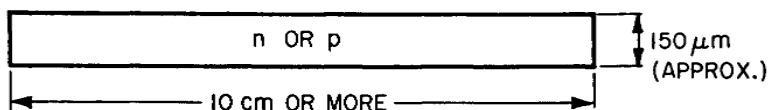
The vertical configuration solar cell can be very well heat sunk, has no metal on the optical surface to reflect light and reduce optical input and photocurrent, and possesses a major circuit advantage. In Chapter V the low voltage output of solar cells was discussed in connection with the need for "stacking" or series connecting solar cells in order to obtain practical operating voltages (12 to 24 volts). The vertical configuration solar cell is particularly suited to stacking. The principal disadvantages of vertical solar cells are: (1) the need to passivate (protect) the large illuminated surface (which, in this configuration contains one "end" of the junction) from ambient conditions* and (2) the large number of electron-hole pairs generated at some considerable distance from the junction. When remote carrier generation occurs, the likelihood of charge carrier separation by the junction is reduced, decreasing the photocurrent. Both of these problems arise from the methods required for construction of a vertical solar cell.

Referring to Figure VI.2, note that a vertical solar cell is often fabricated as one would construct a standard configuration solar cell--by taking a large slice of semiconductor[#] and placing a junction parallel to one side. A standard configuration solar cell would next be mounted on a heat sink and the "front layer" electrical contacts applied. In a vertical solar cell, the large slice is now diced into a large number of small cells (see Figure VI.2c). The small solar cells are rotated through 90° and

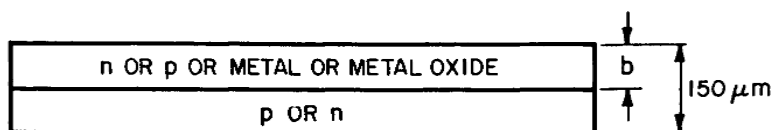
* The incoming photons are absorbed close to the illuminated surface and the passivation is required to minimize surface recombination and saturation current, and so to maximize the photocurrent.

[#] Presently, the slices of semiconductor are circular with diameters of some 15 to 20 centimeters. Other shapes and sizes will be discussed in a later chapter.

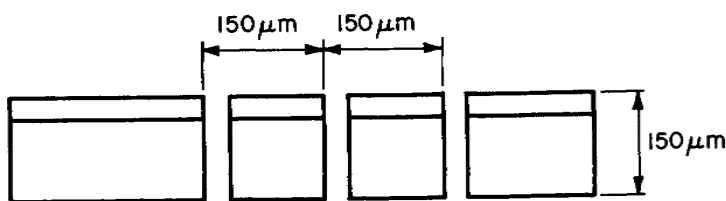
CHAPTER VI: CONFIGURATION AND PERFORMANCE 203



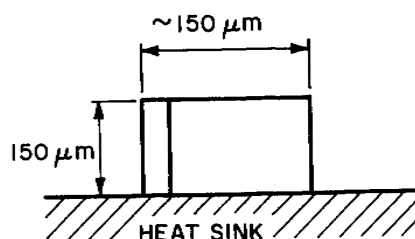
(a) A large slice, rectangular or round, of semiconductor



(b) Slice of semiconductor after junction fabrication



(c) Separation of slice into individual cells, two of which are detailed



(d) Attachment of vertical solar cell to heat sink

Figure VI.2. A brief outline of the fabrication process for a vertical configuration solar cell. In Figure VI.2b dimension b is between one and $10\ \mu\text{m}$ for a heterojunction solar cell, less than one for a pn junction and on the order of $500\ \text{\AA}$ for Schottky or mos solar cells.

204 CHAPTER VI: CONFIGURATION AND PERFORMANCE

mounted upon a heat sink--very carefully, to avoid shorting the junction. The passivation and antireflection coating must now be applied to the illuminated surface. The size of a completed vertical configuration solar cell is dictated, in part, by the discussion in Chapter IV. There it was noted that a solar cell need only be some 150 μm thick, in the direction parallel to the incoming photons, to absorb in excess of 95% of the incoming optical energy. Any increase in thickness beyond this value increases construction cost with little or no corresponding increase in electrical power produced. Any decrease in thickness makes for substantially increased handling difficulty during fabrication, as a result of the fragile nature of semiconductors. This increases the cost of fabrication while diminishing the output power. The length of a vertical solar cell, in a direction at right angles to the photon flux, is limited by the mobility and lifetime of the minority charge carriers. Direct energy gap semiconductors have low minority carrier lifetimes and, as a result, hole-electron pairs generated far from the junction have a low probability of separation and collection.

The inverted solar cell configurations in the lower illustrations of Figure VI.1 have the advantage that no "dead layer" exists near the illuminated surface. The two types of inverted configurations presented represent two approaches to solving circuit, optical and thermal difficulties. In one, the contacts to the bulk (or substrate) region are on the illuminated surfaces. This reduces the optically absorbing area and increases the difficulty encountered in electrically "stacking" the solar cells to achieve higher system voltage, but does improve the heat sinking of the solar cell. The other approach places both sets of contacts on the down side, reducing "stacking" and photon collection problems, but making assembly more expensive and increasing the difficulty of adequately heat-sinking the solar cell.

In this chapter we will examine both standard and inverted configurations in detail, making use of our six example semiconductors. The results may be extended quite simply to vertical solar cells, provided that the semiconductor has sufficient lifetime and the charge carriers possess adequate mobility to enable them to reach the electrical contacts. Study of the lifetime and mobility data in Appendix B indicates that silicon is, by far, the most promising material for inverted and vertical solar cells. For an second examination of inverted solar cells, the reader is referred to Lammert and Schwartz [9].

CHAPTER VI: CONFIGURATION AND PERFORMANCE 205

Device Design - Minority Carrier Collection

When fabricating pn junction or heterojunction solar cells of any configuration, the bulk or substrate region of the semiconductor device is lightly or moderately doped with impurities while the second region (the top or "front layer" or illuminated region in a standard configuration cell, the bottom or non-illuminated region in an inverted solar cell and a thin, side-illuminated region in a vertical solar cell) is heavily doped. This heavy concentration of impurities is required to reduce the series resistance of the solar cell and to permit ohmic contact to be made to this region. Note that the large impurity concentration reduces the carrier lifetime and creates a "dead layer". This "dead layer" is not a problem in inverted or vertical configuration solar cells, but is of major concern for standard configuration solar cells. Therefore, for reasons of cost (the thicker a region of a solar cell, the greater the expense of fabrication) and, in standard solar cells, to minimize the "dead layer" width, it is desirable to keep this second region to minimum thickness.

From Chapter III we have the following expressions for the extent of the junction electric field into the p- and n-regions of a pn step junction solar cell.

$$x_n = \sqrt{\{2\epsilon V_D / q N_D\}} \sqrt{\{1 / (1 + N_D / N_A)\}} ,$$

$$\text{and} \quad (VI.1)$$

$$x_p = (N_D / N_A) x_n ,$$

where x_n is the space charge region expansion distance into the n-region from the junction (taken as $x = 0$), x_p is the expansion into the p-region, ϵ is the permittivity of the semiconductor, N_D is the impurity concentration in the n-region, and N_A is the impurity concentration in the p-region. The quantity, V_D , is the net voltage across the junction and is given by:

$$V_D = V_B - V_p , \quad (VI.2)$$

where V_p is the photovoltage and V_B is the built-in voltage across the step junction and is determined from:

206 CHAPTER VI: CONFIGURATION AND PERFORMANCE

$$V_B = (kT/q) \ln \{N_A N_D / n_i^2\} , \quad (VI.3)$$

where k is Boltzmann's constant, T is the absolute temperature of the junction and n_i is the intrinsic carrier concentration*.

Consider a pn step junction with $N_L \gg N_s^\#$. In this situation, the value of X_L' , the space charge (or electric field) width in the "front layer" will be zero (see Equation VI.1). In a heterojunction solar cell this is also effectively the case since the difference in energy gap widths for the two materials forces the electric field to expand only into the semiconductor with the lower energy gap. In metal/semiconductor or metal-oxide/semiconductor junctions the electric field also expands principally into the semiconductor substrate layer. The value of X_s , the space charge width in the substrate, is, at most, X_s' , where:

$$X_s' = \sqrt{\{2\epsilon E_g / q n_i\}} . \quad (VI.4)$$

Here, X_s' has been calculated assuming a built-in voltage equal to the band gap width of the semiconductor and a carrier concentration equal to the intrinsic value, n_i .

Table VI.2 presents a value of X_s' for the six sample semiconductors.

Table VI.2

Maximum extent of the junction electric field (the depletion or space charge layer), X_s'

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
X_s' (cm)	0.031	0.891	2.08	3.45	19.66	53.1

* From Chapter V we expect a positive value for the photovoltage when a solar cell is converting solar to electrical energy.

Here N_L refers to the "front layer" (which is the illuminated layer in standard configuration solar cells) and N_s refers to the substrate region (the illuminated region in an inverted solar cell). One of these two regions will be n-type and the other will be p-type.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 207

Note that, under the assumptions made, this electric field (the depletion region) extends into the semiconductor in mos and Schottky junctions, into the smaller energy gap semiconductor in heterojunctions, and into the lightly doped substrate region in pn step junctions. Recall, also, that we are considering solar cells having a practical total thickness of $150\text{ }\mu\text{m}^*$. The electric field width as given in Table VI.2 is sufficient to completely fill the substrate region for all standard, vertical and inverted configuration solar cells. However, Table VI.2 is based on three assumptions; none of which can be fully realized in a realistic solar cell. The first assumption is that the substrate is intrinsic. In practice, the technology of the early 1990s cannot meet this requirement. A reasonable technology limited minimum value for N_s is on the order of $10^{14}/\text{cm}^3$. Moreover, in order to lower the saturation leakage current of the solar cell diode, N_s generally needs to be on the order of $10^{15}/\text{cm}^3$. The second assumption is that the junction voltage is only the built-in voltage of the step junction and is equal to the energy gap of the pn junction (or the energy gap of the substrate semiconductor in a heterojunction, mos or Schottky barrier solar cell. In practice, the junction voltage is always less than the energy gap width (see Equation VI.3). A third factor that must be included in any discussion of the substrate depletion layer width is that the solar cell becomes forward biased, owing to the separation/collection of the hole-electron pairs. As a result, the voltage, V_D , in Equation VI.2 is reduced, rapidly, towards some fraction of a volt[#].

To estimate the junction voltage that actually exists in a Schottky barrier solar cell, consider the maximum built-in potential, ϕ_{Bo} , for a Schottky barrier solar cell. Given this value, we can substitute for V_B in Equation VI.2, and so determine the depletion layer thickness, for built-in voltage alone (i.e., for short circuit conditions), X_{ss} :

$$X_{ss} = \sqrt{\{2\epsilon\phi_{Bo}/qN_s\}} \quad (\text{VI.5})$$

* This thickness is almost entirely due to the semiconductor in mos and Schottky junctions, the smaller energy gap semiconductor in heterojunctions and the lightly doped semiconductor substrate in pn step junctions.

Examples, using the six sample semiconductors, to be worked later in this chapter and in subsequent chapters, will demonstrate the exact values to be expected.

208 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.3 presents values of Schottky barrier voltages for the six example semiconductors under consideration and selected metals.

Table VI.3

Metal-semiconductor barrier energies, ϕ_{Bo} , in eV for the six example semiconductors (10-15)

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
Metal	n-type semiconductor					
Pt	0.90	0.60	0.84	0.76	0.60	0.37
Au	0.80	0.52	0.90	0.71	0.51	0.49
Ag	0.78	0.54	0.88	0.81	0.52	0.43
Al	0.72	0.51	0.80	0.76	-----	0.36
Pd	0.81	0.55	0.85	0.74	0.55	0.42
	p-type semiconductor					
Pt	-----	0.74	0.48	0.75	0.58	-----
Au	0.34	0.76	0.42	0.73	0.55	-----
Al	0.58	-----	0.67	0.54	-----	-----
Ti	0.61	0.74	0.53	-----	0.53	-----
Cu	0.46	-----	-----	-----	0.44	-----

Observe that the barrier values listed in Table VI.3 depend upon the metal, the semiconductor, and upon the semiconductor type. The values provided are all less than one volt and are less than the energy gap.

The mos junction is less well understood than the Schottky junction. As of 1993, this solar cell type has been constructed primarily on silicon because of the ease in fabricating the required thin oxide layer (see Chapter V) with this semiconductor. For this type of barrier, values of barrier energy of 0.85 (aluminum-silicon dioxide-on p-type silicon) and 0.67 (chromium-silica-on p-type silicon) have been reported [16]. Data from other sources [17-20] for mos barriers on both silicon and gallium arsenide substrates indicate similar values. Note that reduced leakage currents, resulting from the oxide layer, make these devices promising; even if, as yet, insufficiently understood.

The purpose of this chapter is to estimate the efficiencies of solar cells of "practical" construction. To this end, let us consider Schottky

CHAPTER VI: CONFIGURATION AND PERFORMANCE 209

and mos junctions under a single heading (Schottky) and select the "best" barrier energies from Table VI.3 and the literature. Then, the maximum barrier energies to be encountered, in practice, for Schottky junctions may be taken as those in Table VI.4.

Table VI.4

Practical maximum Schottky junction barrier energies (eV) and the specific metal employed for the six example semiconductors

Semiconductors	Si	InP	GaAs	CdTe	AlSb	CdSe
n-type semiconductor						
Energy	0.90	0.60	0.90	0.81	0.60	0.49
Metal	Pt	Pt	Au	Ag	Pt	Au
p-type semiconductor						
Energy	0.95	0.76	0.67	0.75	0.58	*
Metal	Hf	Au	Al	Pt	Pt	*

To compute pn junction built-in potentials we utilize Equation VI.3. As stated earlier, the minimum potential value for substrate impurity concentration, N_s , is an impurity concentration of $10^{14}/\text{cm}^3$. The value for the "front layer" concentration, N_L , depends, in part, on whether this region is introduced by diffusion or ion implantation. An effective value for N_L of $5 \times 10^{19}/\text{cm}^3$ is commonly encountered. Combining these values, with those for n_i^2 at 300°K from Chapter III, we have for the built-in voltage, the values of Table VI.5.

It is difficult to predict the effective barrier potential of a heterojunction. A rough estimate may be effected by observing the open circuit voltage of a heterojunction solar cell. From Sreedhar [21] and Sahi

* In Chapter III we discussed the fact that p-type CdSe has not been practically fabricated to date. Thus, neither metal-semiconductor (Schottky) junctions on p-type CdSe nor CdSe pn junctions are feasible. It is possible to construct heterojunction devices using n-type CdSe as one side of the junction. The values given in Table VI.6 are estimates for this case.

210 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.5

Estimated practical maximum built-in voltages for pn junctions constructed from the example semiconductors (in volts)

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
V_B	0.76	1.08	1.18	1.23	1.41	*

and Milnes [22] some values of open circuit heterojunction solar cell voltages are: (1) n-type GaP on p-type Si, 0.67 V; (2) n-type GaP on p-type GaAs, 0.82 V; (3) p-type GaP on n-type GaAs, 1.05 V; and (4) n-type ZnSe on p-type GaAs, 0.925 V. Note that these values are on the order of those of Table VI.5 for pn junctions. Calculations of substrate depletion layer width using these barrier voltages lead to results similar in magnitude to those using of the results of Table VI.4 in Equation VI.5 for Schottky and Table VI.5 in Equation VI.3 for pn junctions.

For a substrate impurity concentration of $10^{14}/\text{cm}^3$ we can obtain an estimate of the substrate depletion layer width in a solar cell under short circuit conditions (the photovoltage equal to zero). These depletion widths, for the example semiconductors are given in Table VI.6.

Table VI.6

The "practical" maximum depletion layer width (in μm) in the semiconductor substrates for the six example semiconductors, as a function of the various junction types and at a temperature of 300°K

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
Metal-semiconductor barrier on n-type semiconductor substrate	3.457	3.049	3.547	3.126	2.703	2.398
Metal-semiconductor barrier on p-type semiconductor substrate	3.552	3.432	2.983	2.999	2.657	*
Step pn junction or heterojunction	3.192	4.093	4.036	3.860	4.129	4.21

* P-type CdSe is not available so there is no Schottky barrier on p-type CdSe, but there can be a heterojunction in an n-type semiconductor.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 211

Observe that the depletion layer widths of Table VI.6 are not only very much smaller than the electric field widths of Table VI.2, but they are also much less than the optical absorbing thickness of the semiconductor ($\sim 150\mu\text{m}$). If electron-hole pair separation/collection depended solely on the depletion layer width, the performance of standard and inverted configuration solar cells would be largely negated. Fortunately, there are other phenomena which can assist in the production of photocurrent. These phenomena are used to bring the optically generated carriers within range of the electric field in the depletion layer of a solar cell junction. First, consider the diffusion length in a semiconductor and to what extent it effectively extends the collecting range of the depletion layer.

Once generated by photon absorption in the bulk regions (areas of no electric field) of the solar cell, hole-electron pairs move randomly through the semiconductor. Should there be a junction in the semiconductor crystal, there will be, of course, an electric field in the vicinity of the junction. This field serves to collect electron-hole pairs and to separate them, thus producing a concentration gradient in electron-hole pairs. Now consider the p-type region of a solar cell. Electrons in this region, close to the depletion region often, randomly, move into the electric field. When this occurs, the electrons are accelerated across the junction to the n-type side. A similar process occurs, of course, to the holes randomly moving on the n-type side as they are accelerated towards the p-type side. The effect of this minority carrier removal is to create an electron concentration gradient between the bulk region on the p-type side and the edge of the depletion region. Thus, an electron within a diffusion length of the junction on the p-type side will be collected (the same goes for holes within a diffusion length of the junction on the n-type side). The diffusion length, L , is given by:

$$L = \sqrt{D\tau} \quad , \quad (\text{VI.6})$$

where, from Chapter III:

$$D = \{kT/q\}\mu \quad . \quad (\text{VI.7})$$

The lifetimes, τ , and mobilities, μ , for the semiconductors being used as examples in this work were discussed in Chapter III. Recall that these material properties are functions of temperature and impurity

212 CHAPTER VI: CONFIGURATION AND PERFORMANCE

concentration. In this chapter we are considering solar cell operation at room temperature (27°C). The preceding discussion of depletion layer width used a substrate impurity concentration of $10^{14}/\text{cm}^3$ and a high impurity concentration "front layer" of $5 \times 10^{19}/\text{cm}^3$. A few additional words concerning the "practicality" of these concentrations are in order. The "front layer" concentration varies with distance into the semiconductor. If the "front layer" is the result of a diffusion process, the impurity concentration at the surface is much higher than that at the junction. Typically, $N_L(x)$ will follow an error function curve [23, 24] with a surface concentration well in excess of either the conduction band or the valence band density of states (see Appendix B and [25]). If the "front layer" is the result of ion implantation, the impurity density reaches a peak at some distance into the semiconductor; the distance determined by the semiconductor, its crystal orientation, the impurity species and the energy of the implant [26]. Utilizing modern technologies, such as molecular beam epitaxy [27, 28], it is possible to keep the "front layer" concentration at approximately the density of states level, which is roughly $5 \times 10^{19}/\text{cm}^3$. This impurity concentration is high enough to adversely affect the lifetime of the "front layer", but it also is high enough to support a thin "front layer" without excessive resistance.

The substrate impurity concentration must be small in order to enhance the diffusion length and the depletion layer width, but needs to be sufficiently high to reduce the bulk series resistance of the solar cell. This bulk series resistance, r_D , is given by:

$$r_D = \{l/A_D\} \{1/q\mu_{sm}N_s\} , \quad (\text{VI.8})$$

where l is the length of the substrate (generally taken to be $150 \mu\text{m}$ in this work); A_D is the junction area of the solar cell, which we assume is equal to the cross-sectional area of the substrate; μ_{sm} is the substrate majority carrier mobility; and N_s is the impurity concentration in the substrate. In Chapter V, in connection with saturation current, we used a substrate impurity concentration of $10^{16}/\text{cm}^3$. This produced a low value of saturation current density. Earlier in this chapter we utilized a substrate impurity concentration of $10^{14}/\text{cm}^3$ because this value yields a wider depletion layer width, at the cost of increased saturation current density. In practice, a carrier concentration of approximately $10^{15}/\text{cm}^3$ provides a satisfactory balance between series resistance, diffusion length, saturation current and processing technology.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 213

Using a value of N_s equal to $10^{15}/\text{cm}^3$ and a value of N_L equal to $5 \times 10^{19}/\text{cm}^3$, in conjunction with the mobilities and lifetime values of Appendix B, the literature and Chapter III, we have the data provided in Table VI.7. This will be used as input for the computation of the minority carrier diffusion lengths in the substrates of solar cells made from our example semiconductors.

Table VI.7

Estimated values of impurity concentration, minority carrier mobility and lifetime, as functions of semiconductor for a temperature of 300°K and the six example semiconductors [22, 29, 30]

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
"Front Layer"						
Concentration (cm^{-3})	----- 5×10^{19} -----					
	"front layer" mobility ($\text{cm}^2/\text{volt-second}$)					
p-type layer	135	450	1000	700	140	-----
n-type layer	80	150	100	50	180	450
	"front" layer lifetime (seconds)					
p-type layer	10^{-7}	10^{-10}	10^{-10}	10^{-9}	10^{-10}	-----
n-type layer	10^{-7}	10^{-10}	10^{-10}	10^{-9}	10^{-10}	10^{-10}
Substrate						
Concentration (cm^{-3})	----- 1×10^{15} -----					
	substrate mobility ($\text{cm}^2/\text{volt-second}$)					
p-type layer	1500	3500	6500	950	200	-----
n-type layer	500	600	350	90	400	600
	substrate lifetime (seconds)					
p-type layer	8×10^{-5}	6×10^{-8}	6×10^{-8}	2×10^{-6}	1×10^{-7}	-----
n-type layer	8×10^{-5}	3×10^{-8}	3×10^{-8}	1×10^{-7}	9×10^{-8}	1.5×10^{-9}

In a "realistic" solar cell, both the minority carrier mobilities and lifetimes may well be less than the values provided in Table VI.7, particularly if the processing involved in fabrication of the solar cell is substandard. However, the mobilities and lifetimes furnished in Table VI.7 are achievable and lead to the diffusion lengths of Table VI.8.

214 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.8

Estimated minority carrier diffusion lengths for n- and p-type regions of solar cells employing the example semiconductors, at 300°K

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
"front layer" diffusion length (μm)						
p-type layer	5.91	0.341	0.509	1.35	0.191	-----
n-type layer	4.55	0.197	0.161	0.36	0.216	0.341
substrate diffusion length (μm)						
p-type layer	577	145	198	436	44.7	-----
n-type layer	322	42.4	32.4	30	60	9.49

From the discussion relating to "dead layer" thickness in Chapter V, the heavily doped "front layer" region in standard or vertical configuration step junction and heterojunction solar cells should be small, with a maximum thickness under a micron. Since this region has a low lifetime (see Table VI.7), and the surface recombination velocity of such heavily doped regions is high, it is unlikely that a large percentage of carriers will be collected and separated in this region. The diffusion lengths for the "front layer" provided in Table VI.8 are, therefore, adequate. The substrate, however, is another matter. For any configuration of solar cell, the electron-hole pairs will be generated by photon absorption within some distance of the illuminated surface. From Figures IV.7 and IV.8, this distance is given in Table VI.9.

Table VI.9

The approximate depth beneath the illuminated surface at which electron-hole pair optical generation ceases (μm)

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
Depth	1000	0.3	2	20	8	1

From practical considerations we have set the maximum solar cell thickness to a value of 150 μm . This results in a loss in the potentially

CHAPTER VI: CONFIGURATION AND PERFORMANCE 215

convertible solar energy of approximately 5% for silicon based solar cells. Note that, for the other example semiconductors, the absorption occurs so rapidly that this limited thickness of solar cell has no effect. Comparing the values of optical absorption depth in Table VI.9 with the diffusion lengths presented in Table VI.8, we see that, for 150 μm thick solar cells the diffusion lengths for all six example semiconducting materials are adequate to collect all of the optically generated charge carriers for standard configuration solar cells*.

Consider inverted and vertical configuration solar cells. From our discussions in connection with Figures VI.1 and VI.2 and Tables VI.9 it is possible, in these configurations, for optical hole-electron pair generation to take place at a distance approximating 150 μm from the junction. Considering the minority carrier diffusion lengths of Table VI.8 we note that, if the substrate is p-type, then silicon, indium phosphide, gallium arsenide and cadmium telluride have the potential of collecting almost all of the hole-electron pairs. Not all, because, even in the case of silicon with its 557 μm minority carrier diffusion length, the diffusion length in any of these example semiconductors is never more than four times the 150 μm limit. For indium phosphide and gallium arsenide, the diffusion length is approximately equal to the maximum generation distance of 150 μm . In the case of n-type substrates only silicon has a sufficiently large minority carrier diffusion length, long enough to assure the collection of most of the hole-electron pairs.

There is an additional source of charge carrier loss. The illuminated surface of vertical junction configuration solar cells is formed by sectioning the original wafer (see the discussion in association with Figure VI.2). This procedure enhances the surface recombination velocity and reduces the photocurrent for these devices. Note that this problem is not so severe with inverted configuration solar cells. For this configuration of device, the fabrication process is tailored to minimize surface recombination velocity. In standard configuration solar cells the surface recombination contributes to the "dead layer" and, hence, has already been taken into consideration. Finally, note that, at the substrate contact, the surface recombination is assumed to be essentially infinity (see the discus-

* This, clearly, does not include those carriers generated by optical absorption within the "dead layer".

216 CHAPTER VI: CONFIGURATION AND PERFORMANCE

sion in Chapter III). This produces a minority concentration gradient in the vicinity of the substrate contact which funnels charge carriers in the wrong direction. Study of Figure VI.1 will demonstrate to the reader that this problem is unimportant for standard configuration solar cells and those inverted configuration solar cells with their substrate contacts on the non-illuminated surface. It is, however, of importance to vertical junction solar cells, resulting in a "dead layer" near the substrate contact and reducing overall performance for the solar cell.

There is a solution to all of these problems; a solution which has the additional advantage of reducing the substrate series resistance. Consider the energy-versus-distance diagram for the solar cell displayed in Figure VI.3.

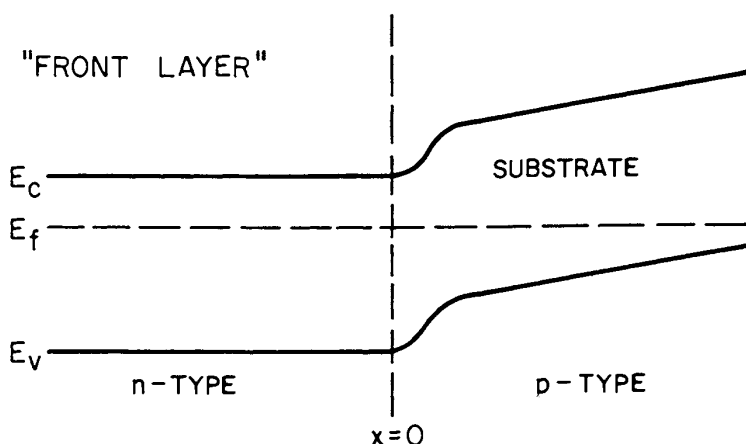


Figure VI.3. A solar cell with a variable impurity concentration in the substrate. E_c is the lower edge of the conduction band, E_f is the Fermi level and E_v is the upper edge of the valence band.

In Figure VI.3 the heavily doped "front layer" is assumed to have a constant impurity concentration of approximately $5 \times 10^{19}/\text{cm}^3$. At $x = 0$ (the junction) the substrate is relatively lightly doped (an impurity concentration of approximately $10^{19}/\text{cm}^3$), but the impurity concentration (acceptor in the example of Figure VI.3) of the substrate is increased as the distance from the junction is increased. The result is a built-in electric field which impels minority carriers towards the junction. This electric

CHAPTER VI: CONFIGURATION AND PERFORMANCE 217

field is given by:

$$\mathcal{E}(x) = \frac{kT}{qN_s(x)} \frac{\partial N_s(x)}{\partial x}, \quad (\text{VI.9})$$

where $N_s(x)$ is the substrate impurity concentration. This varies from approximately $10^{14}/\text{cm}^3$ to a value on the order of 10^{17} to $10^{18}/\text{cm}^3$ (a value less than one-tenth of the effective density of states value for the substrate*). Note that if we desire a constant value of electric field, $\mathcal{E}$, then the substrate impurity concentration will be:

$$N_s(x) = N_s(0) \exp\{q \mathcal{E}x/kT\}, \quad (\text{VI.10})$$

where $N_s(0)$ is the substrate impurity concentration at the junction and x is positive into the substrate#.

Assume a substrate of 150 μm width. Then, for an electric field in the substrate of 16 volts/cm, the ratio $N_s(150)/N_s(0)$ is ten thousand. Given such a field, extending the width of the substrate, we can collect essentially all of the hole-electron pairs generated in the substrate and transport them to the edge of the depletion layer. In turn, the depletion layer separates the hole-electron pairs. As an added advantage, the graded substrate discussed here also serves to decouple the surface recombination velocity at the substrate contact [31-33].

Consider the photocurrent that may be expected in a solar cell of standard, inverted or vertical configuration. Suppose we have an inverted configuration solar cell, with a graded substrate, 95% efficient antireflection coating and 100% collection efficiency for all generated hole-electron pairs. The expected photocurrent density is that of Table VI.10.

In the case of a vertical configuration solar cell we must include additional losses from surface recombination owing to the fact that the

* Increasing the substrate impurity concentration above this value will decrease the minority carrier lifetime and mobility to such an extent as to decrease the collected photocurrent.

Clearly, the same procedure can be followed when the substrate is n-type.

218 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.10

Estimated photocurrent density (mA/cm^2) in an inverted configuration solar cell at 300°K

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
AM0-conditions	44.65	41.7	37.2	35.8	28.6	26.0
AM1-conditions	36.1	31.8	28.7	27.2	21.9	20.5

surface which is illuminated has been cut from a wafer (see the discussion accompanying Figure VI.2). Assuming a reasonable surface recombination velocity of $10,000\text{ cm}/\text{second}$, and using the data of Table VI.7 and Figure III.8, we can estimate that the maximum realizable photocurrent density will be some 5% or so below the photocurrents of the inverted solar cell, yielding the numbers of Table VI.11.

Table VI.11

The estimated photocurrent density (mA/cm^2) in a vertical configuration solar cell at 300°K

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
AM0-conditions	42.7	39.5	35.3	33.9	27.1	24.7
AM1-conditions	34.2	30.1	27.2	25.7	20.8	19.5

The expected photocurrent from a standard configuration solar cell is still less. There are additional recombination losses due to the "dead layer" (which is a result of the heavily doped "front layer") in pn step junctions, from the interface effects in a heterojunction solar cell and from reflection effects in the case of mos and Schottky junction solar cells. In the following table the estimated photocurrent density for a standard configuration solar cell is provided. In the case of a pn step junction, the "front layer" is thin to minimize the "dead layer" thickness (keeping this layer from 0.3 to $0.6\text{ }\mu\text{m}$ thick). The "dead" layer does not completely fill the "front layer", but comprises the top third or so. Assuming that this

CHAPTER VI: CONFIGURATION AND PERFORMANCE 219

"dead layer" is, indeed, totally dead, and utilizing Figures IV.10 and IV.11 the estimated maximum photocurrent density for standard configuration pn step junction solar cells is provided in Table VI.12. The estimated possible photocurrents for standard configuration heterojunctions are higher because the "dead layer" is not present--the semiconductor forming the "front layer" being transparent to the photons of interest. The photocurrent is also estimated for Schottky barrier standard configuration solar cells. The existence of a metal layer on the illuminated side of the solar cell drastically reduces the potential photocurrent and values indicated in Table VI.12 are, at best, estimates.

Table VI.12

The estimated photocurrent density (mA/cm²) in a standard configuration solar cell, for pn step junction, heterojunction and Schottky junction devices at 300°K

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
heterojunction solar cells						
AM0-conditions	37.95	35.44	31.62	30.43	24.31	22.10
AM1-conditions	30.68	27.03	24.40	23.12	18.62	17.42
pn step junction solar cells						
AM0-conditions	31.77	07.02	20.88	22.54	18.45	11.25
AM1-conditions	25.02	05.67	15.75	17.10	14.04	09.18
Schottky junction solar cells						
AM1-conditions	10.59	02.34	06.96	07.53	06.15	03.75
AM1-conditions	8.34	01.89	05.25	05.70	04.68	03.06

In studying Table VI.12 it is clear that the high absorption coefficient of InP results in unusually high recombination losses in step pn junction standard configuration solar cells. Also note that, for every one of the example semiconductors, there is a decline in the expected photocurrent density from inverted configuration through vertical configuration and to standard configuration. This decline is minor when vertical and inverted configuration solar cells are compared, but of major proportions when standard configuration solar cells are considered. It cannot be overemphasized that the values of expected photocurrent

220 CHAPTER VI: CONFIGURATION AND PERFORMANCE

density in Tables VI.10 through VI.12 are estimates and strongly dependent on the fabrication techniques employed in constructing the solar cells, upon surface crystal orientation, and on the semiconductor itself. The values listed above should be realizable, if sufficient care is exercised, but "mistakes" in fabrication technology and surface preparation can result in substantial reductions.

The overall purpose of this chapter is to provide an estimate of performance for several "realistic" situations. The heterojunction and pn step junction photocurrent density estimates of Table VI.12 are reasonable. The Schottky photocurrent density estimates are more problematic. To allow for photon penetration of the metal layer on top of a Schottky diode the layer must be very thin ($<500 \text{ \AA}$) [34]. Even so there is considerable loss due to photon reflection and the photocurrent density in such devices is small.

Device Design - Saturation Current

The saturation current densities for solar cells depend on the type of junction. From Chapter V and the discussions in Appendices B and C we have for the saturation current, J_s , in pn step junction solar cells:

$$J_s = \frac{qD_{pn}n_i^2}{L_{pn}N_D} + \frac{qD_{np}n_i^2}{L_{np}N_A}, \quad (\text{VI.11})$$

where D_{pn} and D_{np} are the diffusion constants for holes on the n-side of the junction and electrons on the p-side of the junction, L_{pn} and L_{np} are the diffusion lengths for holes on the n-side of the junction and electrons on the p-side of the junction. N_D and N_A are the net donor impurity concentration on the n-side and acceptor concentration on the p-side of the junction.

The saturation current for a heterojunction is given by:

$$J_s = J_{SH} = \frac{qD_s n_i^2}{L_s N_s} X_T, \quad (\text{VI.12})$$

where D_s , L_s and N_s are the minority carrier diffusion constants and

CHAPTER VI: CONFIGURATION AND PERFORMANCE 221

diffusion length in the substrate semiconductor (the semiconductor with the smaller energy gap) and the impurity concentration in the substrate. The quantity, X_T , is used to account for internal effects at the interface between the two semiconductors (see Chapter V).

The saturation current density for a Schottky junction is:

$$J_s = J_{ss} = A^* T^2 \exp\{-\lambda \phi_{Bn}\}, \quad (\text{VI.13})$$

where λ is q/kT and the Richardson constant, A^* , is given by:

$$A^* = 120m^*, \quad (\text{VI.14})$$

where m^* is the effective mass of the majority charge carrier in the semiconductor (see Appendix B). The quantity, ϕ_{Bn} , is the barrier voltage adjusted for image force lowering (see Table VI.4).

As discussed earlier, mos junctions are imperfectly understood at present. This being the case, further discussions of mos cells will not be conducted in this work. The reader who wishes to estimate the performance of the mos solar cell is referred to, as an introduction, [16-20, 35 and 36].

Using Equations VI.11 through VI.14 in conjunction with a substrate impurity concentration level of $3 \times 10^{15}/\text{cm}^3$, the barrier energies for Schottky barriers of Table VI.4, the carrier mobility and lifetime values of Table VI.7, the diffusion lengths of Table VI.8, the intrinsic carrier concentrations from Table III.2 and the effective mass values from Appendix B, it is possible to estimate the saturation currents for pn step junctions, Schottky junctions and heterojunctions. In the case of heterojunctions, we will assume that X_T , the interface factor, is unity. In practice, it is probable that X_T is less than unity [37] so that the estimate used here is conservative. Because the impurity concentration of the illuminated or "front" layer in a pn step junction is much larger than the impurity concentration of the substrate (by approximately four orders of magnitude), Equation VI.11 is reduced to a single term, dependent on the substrate. The estimated values of saturation current are presented in Table VI.13.

Examination of Table VI.13 in conjunction with the minimum values of saturation current density used in the preceding chapter indicates that the values of saturation current density that we may reasonably expect to encounter in practice are one to two orders of magnitude

222 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.13

Typical values of saturation current density for heterojunctions, pn step junctions and Schottky junctions on the example semiconductors (A/cm^2). The junction temperature is 300°K. (Note that the junction value for CdSe is valid for heterojunctions only, as p-type CdSe is not available)

Semi- cond- uctor	For pn step junctions and heterojunctions		For Schottky Barriers	
	p+n	n+p	on n	on p
Si	4.50×10^{-12}	7.80×10^{-12}	9.15×10^{-9}	6.89×10^{-9}
InP	1.27×10^{-16}	2.16×10^{-16}	6.43×10^{-5}	7.58×10^{-7}
GaAs	7.20×10^{-19}	2.19×10^{-18}	6.10×10^{-5}	3.13×10^{-5}
CdTe	1.31×10^{-20}	9.53×10^{-21}	3.02×10^{-8}	9.76×10^{-7}
AlSb	1.22×10^{-21}	8.20×10^{-22}	1.01×10^{-4}	7.56×10^{-4}
CdSe	1.89×10^{-22}	-----	8.38×10^{-3}	-----

higher than the ideal minimum values for pn and heterojunctions. The saturation current densities for Schottky barrier junctions are much higher. It is possible that breakthroughs in Schottky (or mos) technology will permit lower saturation current densities and that improvements in material preparation and junction fabrication technology will, by increasing minority carrier lifetime, lower the saturation current densities for both types of pn junctions. For the present, however, Table VI.13 is a reasonable approximation.

Device Design - Series Resistance

We have arrived at estimates for photocurrent density (Tables VI.10 through VI.12) and junction saturation current density (Table VI.13). These values can now be used in Equations VI.16 - VI.19 to determine the operating junction voltage for maximum power output density, V_p' , the maximum power density which is transferable to the load, P_{max}/A , the efficiency for maximum power transference, η_s , and the internal loss factor, K' :

CHAPTER VI: CONFIGURATION AND PERFORMANCE 223

$$(\lambda V_D' + 1 + K') \exp\{\lambda V_D'\} = (J_{ph} + J_s)(1 + K')/J_s, \quad (VI16)$$

$$K' = 2(r_D A_D) J_s \lambda \exp\{\lambda V_D'\}, \quad (VI17)$$

$$P_{\max}/A_D = \frac{(J_{ph} + J_s)(\lambda V_D') V_D'}{(\lambda V_D' + 1 + K')} (1 - (K'/2)/(1 + K')) , \quad (VI18)$$

and

$$\eta_s = (P_{\max}/A_D)(I_{ns}), \quad (VI19)$$

where $\lambda = q/kT$, A_D is the junction area of the solar cell (assumed to be equal to the light collecting area of the cell), J_{ph} is the photocurrent, J_s is the saturation current density, r_D is the solar cell series resistance, and I_{ns} is 135.3 mW/cm² under AMO conditions and 107 mW/cm² under AM1 conditions.

In Chapter V we assumed values of the loss factor, K' and then computed efficiencies and power output densities for solar cells. We are now in a position to make estimates of the series resistance of a solar cell, and to calculate K' directly. To do this, let us assume the geometries for solar cells of the three configurations. Probable geometries for standard and vertical configuration cells are shown in Figure VI.4.

The standard cell is assumed to be round with a light sensitive area of πa^2 ; a "front layer" thickness, d , of 0.4 μm for pn step junctions, 0.5 μm for heterojunctions and 0.05 μm for Schottky junctions; and a substrate thickness, T_s , of 150 μm . Vertical configuration solar cells are rectangular parallelepipeds with light collecting areas of $T_s W$, where T_s is 150 μm and W is arbitrary*; a substrate width (distance in the direction of photon travel, Y , of 150 μm ; and a total thickness of barrier plus substrate contact ($d + T_s + \Delta$) of 150.4 μm . The inverted solar cell we will take to be equivalent to the standard cell turned upside down (see Figure VI.1). Following Figure VI.1, the light sensitive area for inverted

* If the procedure for making vertical cells discussed in Figure VI.2 is followed, reasonable values of W might be as large as 10 cm. Since this dimension drops out of our calculations, the precise value is unimportant.

224 CHAPTER VI: CONFIGURATION AND PERFORMANCE

solar cells is taken to be twice the area of the junction (assuming that both contacts for the inverted solar cell are on the down or non-illuminated side). The actual junction, then, occupies only about half of the down side).

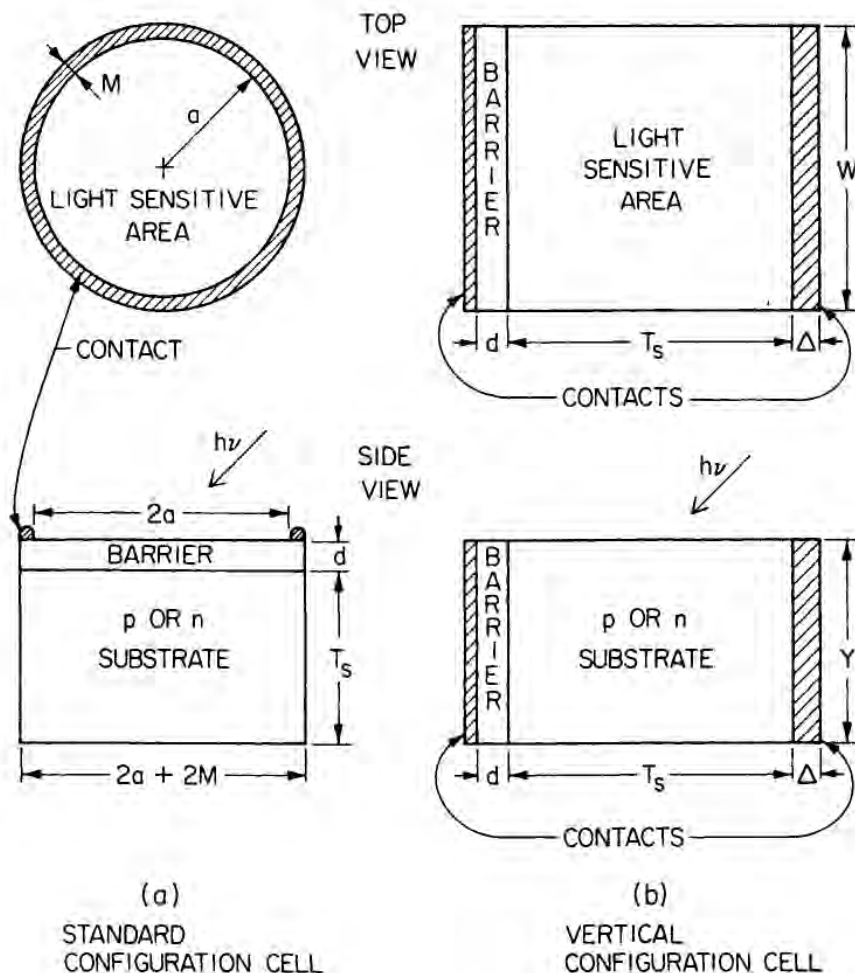


Figure VI.4. Probable standard and vertical solar cell configurations.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 225

Note that in both the standard and vertical configurations some of the illuminated surface is obscured by the contacts on the illuminated surface. For the standard configuration solar cells the ratio of optically absorbing surface to total surface area, Φ , is given by:

$$\Phi_{\text{standard}} = a^2/(a + M)^2, \quad (\text{VI2a})$$

where M is the width of the metal contact ring (see Figure VI.4). Even with a heavily doped barrier region, the metal contact ring is much better at carrying current. A practical ratio of contact area to light absorbing area is 1:10.

For vertical configuration solar cells, Φ is:

$$\Phi_{\text{vertical}} = T_s/(T_s + d + \Delta), \quad (\text{VI2b})$$

where, from the preceding discussion, $\Phi_{\text{vertical}} = .997$.

For inverted configuration solar cells, the entire illuminated surface can be light absorbing; there being no contacts on the illuminated surface.

Note that, for standard configuration Schottky junction solar cells, the illuminated surface must be coated with a thin metal contact layer. This layer must be thick enough to conduct current to the metal contacts without excessive electrical resistance and thin enough to permit light to pass through it and reach the semiconductor substrate. The estimated photocurrent for this case is provided in Table VI.12.

The junction area, the area through which the current flows, is YW for vertical configuration solar cells, πa^2 for standard configuration solar cells and $\pi a^2/2$ for inverted configuration devices*. Now the series resistance of a solar cell consists of contact and lead resistance (small

* Note that the majority of the absorbed photons in a vertical configuration solar cell are absorbed close to the illuminated surface. Thus the photocurrent is generated close to the upper surface. The fact that the hole-electron pairs do spread via diffusion and the effect of electric fields does spread the hole-electron population, but the fact remains that the photocurrent does flow through a somewhat smaller area than that indicated. Lacking sufficient experimental data to predict this value exactly, we make the conservative assumption provided here.

226 CHAPTER VI: CONFIGURATION AND PERFORMANCE

since these are metal parts); resistance due to the substrate and resistance due to the "front layer". We will ignore the contact and lead resistance.

The substrate impurity concentration is often graded in order to improve the collection efficiency of the generated electron-hole pairs. From the discussion on this topic earlier in this chapter and using Equation VI.10, we can write for the series resistance times area product of the substrate:

$$(r_D A_D)_S = z \int_0^{T_s} [\exp\{-\lambda \mathcal{E}_s x\} / q \mu_{SM} N_{Sj}] dx \quad (VI.21)$$

In Equation VI.21, A_D is the area of the junction*, z is unity for vertical and standard configuration devices and is 0.96 for inverted configuration solar cells#. $\mathcal{E}_s$ is the electric field in the substrate region of the solar cell, μ_{SM} is the majority carrier mobility in the substrate and N_{Sj} is the impurity concentration in the substrate at the junction. Equation VI.21 is further complicated by the fact that the mobility of the carrier is a function of the impurity concentration (see data in Appendix B). Assume that the substrate thickness is 150 μm , N_{Sj} is $10^{15}/\text{cm}^3$ and $\mathcal{E}_s$ is 16 volts/cm**. From the data of Chapter III, Appendix B and using Equation VI.21, we can obtain for the approximate substrate series resistance times area product the results in Table VI.14.

The series resistance times junction area product of the heavily doped "front layer" for a vertical configuration solar cell is determined by using Equation VI.22:

* Recall that the junction and optically absorbing surfaces are approximately the same in vertical and standard configuration devices, while the optically absorbing surface is some twice the area of the junction for inverted configuration devices.

This factor reflects the efficiency of collection of hole electron pairs as a result of recombination on the lateral surfaces.

** For this value of substrate electric field we have seen that the substrate impurity concentration varies from $10^{15}/\text{cm}^3$ at the junction to $10^{19}/\text{cm}^3$ at the far side of the substrate. Recall that this range results from balancing the need for low saturation current (and hence high impurity concentration in the substrate) and a large extent for the electric fields produced by the junction in the substrate (and hence a low impurity concentration in the substrate).

CHAPTER VI: CONFIGURATION AND PERFORMANCE 227

Table VI.14

The approximate substrate series resistance times junction area $(r_D A_D)_S$ product for solar cells with a 150 μm thick substrate with an exponentially graded substrate impurity concentration ranging from $10^{15}/\text{cm}^3$ at the junction to $10^{19}/\text{cm}^3$ at the far substrate surface, at a temperature of 300°K (in ohm-cm^2)

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
vertical and standard configurations						
n-type substrate	.0069	.0032	.0016	.0110	.0746	.0176
p-type substrate	.0192	.1033	.0294	.1127	.0258	*
inverted configuration						
n-type substrate	.0066	.0030	.0015	.0106	.0695	.0169
p-type substrate	.0183	.0953	.0282	.1078	.0250	*

* p-type single crystal CdSe is not available.

$$(r_D A_D)_L = (\Delta + d)/(q\mu_{LM}N_L) \quad (\text{VI.22})$$

The resistance area product of the "front layer" can be easily computed using the approximation of a constant impurity concentration and the mobility values from Table VI.7. For Schottky barriers we can use the resistivity of a typical metal (approximately 5 $\mu\text{ohm-cm}$) and find that $(r_D A_D)_L \approx 2 \times 10^{-10} \text{ ohm-cm}^2$. For devices utilizing heterojunctions the resistance time junction area product for the "front" layer is on the order of 10^{-7} ohm-cm^2 . The product for devices with pn junctions can similarly be determined, again using Table VI.7 and Equation VI.22, along with a "front layer" thickness of 0.4×10^{-4} centimeters.

Upon investigation of the "front layer" series resistance times junction area product for inverted configuration solar cells, we discover that the values are essentially of the same order of magnitude as those for the vertical configuration. These values are present in Table VI.15. Note that they are far smaller than the resistance times junction area product of the substrate region--so small as to enable us to ignore them in future calculations of solar cell performance.

In a standard configuration solar cell the "front layer" resistance times junction area product is not necessarily less than the substrate

228 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.15

The series resistance times junction area product for the heavily doped "front layer" of vertical and inverted configuration solar cells as a function of the type of junction and at 300°K (ohm-cm²)

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
pn junctions						
n-type "front layer"	3.12 x 10 ⁻⁷	1.67 x 10 ⁻⁷	2.50 x 10 ⁻⁸	3.57 x 10 ⁻⁸	1.79 x 10 ⁻⁷	8.33 x 10 ⁻⁷
p-type "front layer"	1.85 x 10 ⁻⁷	5.56 x 10 ⁻⁸	2.48 x 10 ⁻⁷	4.99 x 10 ⁻⁷	1.37 x 10 ⁻⁷	*
heterojunctions*						
	10 ⁻⁷	-----				10 ⁻⁷
Schottky junctions*						
	2 x 10 ⁻¹⁰	-----				2 x 10 ⁻¹⁰
* p-type single crystal CdSe is not available						

* p-type single crystal CdSe is not available

area times junction product. Here, the current flows through the substrate and "front layer" to the metal contacts (See Figure VI.4). If we assume that the current flowing at the junction proper is uniformly distributed, then, from Ohm's law:

$$(R_D A_D)_L = (\rho_L a^2)/4d \quad (VI.23)$$

Equation VI.23 has been used to compute the "front layer" series resistance times junction area product for standard configuration solar cells. The data of Table VI.7 and Appendix B have been used, together with a value of d of 0.4 μm for pn junctions, ρ_L equal to 5 x 10⁻⁶ ohm-cm for Schottky metals and d equal to 0.05 μm for Schottky barriers. For a heterojunction we assume ρ_L equal to 5 μm and a resistivity of 0.01 ohm-cm [38]. Under these conditions, we have the results outlined in Table VI.16 for the "front layer" series resistance of standard configuration solar cells.

We are now in a position to determine the potential performance of the three configurations. Note that the results which we are about to determine are not intended to be the maximum potential. Rather, these

CHAPTER VI: CONFIGURATION AND PERFORMANCE 229

Table VI.16

The series resistance times junction area product for the "front layer" of a standard configuration solar cell as a function of the junction type and at 300°K (ohm-cm²)

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
Schottky junctions*						
	0.25a ²					0.25a ²
heterojunctions*						
	5a ²					5a ²
substrate	pn junctions					
n-type	28.94a ²	08.68a ²	03.91a ²	05.58a ²	27.9a ²	*
p-type	48.82a ²	26.04a ²	39.06a ²	78.12a ²	21.7a ²	*
* p-type CdSe is not available						

results are meant to indicate the "practical" output values achievable with more or less "normal" fabrication technologies. We will discuss potential, all-out, maximum output potentials later. The expected solar cell delivered power density is given by Equation V.33 where the junction voltage (the photovoltage) and loss factor for maximum power delivered (under the assumed conditions) must mutually satisfy Equations V.31 and V.32. The series resistance times junction area products for the "front layer" and substrate are provided in Tables VI.14 and VI.16. Note that for inverted and vertical configuration solar cells only the substrate series resistance is of importance. For the standard configuration solar cell, the "front layer" resistance times area product is of importance. The larger the area of the solar cell the larger the "front layer" resistance and the less expensive (within reason) it is to construct the device. For our purposes we will assume that the standard configuration solar cells are sufficiently large to exhibit a "front layer" series resistance times area product equal to one-tenth of the substrate resistance times area product. Thus, the effective resistance times junction area product for our example standard configuration solar cells is given by the substrate value from Table VI.14 times one point one. The saturation current densities for the various junction types are provided in Table VI.13. The photocurrent density for inverted configuration solar cells is taken to be 1.95 times the values in

230 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.10 (the physical structure assumed in the discussion of this chapter leads to a degree of optical concentration equal to this value). The photocurrent density for vertical configuration solar cells is provided in Table VI.11 and the photocurrent for standard configuration solar cells lies between 0.3 and 0.9 times that of the values furnished in Table VI.12*. The solar spectra employed are AMO and AM1.

The loss factor, which depends directly on the series resistance times junction area product, for these devices is considerably less than unity. Selected values for K' are presented in Table VI.17 for standard configuration solar cells. Table VI.18 provides the loss factors for vertical configuration solar cells as a function of junction and substrate type. Table VI.19 presents the same data for inverted configuration solar cells. Note that p-type CdSe is not available. Comparison of these values of loss factor with those used in computing Tables V.2 and V.3 indicates that the assumptions used in those tables were conservative. Also note that the loss factor is higher for inverted configuration solar cells than for vertical configuration devices, which are, in turn, higher than K' values for standard configuration solar cells.

Figures VI.5 through VI.10 present values of the photovoltage, V_D , under conditions of maximum delivered power density, the maximum solar cell delivered power density, $P_{\max}/A_D$, and η_s , the solar cell efficiency under these conditions, for standard configuration solar cells under AMO and AM1 illumination. Note that the relatively low barrier energies of the Schottky barrier solar cells, lead to high saturation current density and poor overall performance of Schottky barrier solar cells.

* The physical configuration of an inverted solar cell, as described here, leads to a light collected area which is twice that of the junction. The collection of holes and electrons from the furthest distances within the solar cell is not perfect—hence the photocurrent density is 1.95 times Table VI.13. In the case of standard configuration solar cells, the necessity to make electrical contact to the illuminated surface results in a loss of at least 10% of the incoming light, owing to reflection from the metal contacts. In the case of a Schottky barrier standard configuration solar cell, the requirement for a metal surface (to complete the Schottky junction) results in further decreases in the photocurrent density. Thus to determine the photocurrent density for pn and heterojunction standard configuration solar cells we multiply the values of Table VI.12 by 0.9, while for Schottky barrier diodes, we multiply by 0.3.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 231

Table VI.17

The loss factor, K' , as a function of the illumination conditions, barrier type, and substrate for six semiconductors used in standard configuration solar cells (at 300°K)

AMO light input						
Junction	n-type substrate			p-type substrate		
	pn	hetero	Schottky	pn	hetero	Schottky
Si	.000904	.001072	.000500	.002581	.003058	.001361
InP	.000065	.000311	.000191	.002148	.010363	.002910
GaAs	.000082	.000123	.000228	.001524	.002281	.003620
CdTe	.000536	.000719	.000639	.005480	.007357	.009218
AlSb	.002833	.003712	.010524	.000969	.001269	.006453
CdSe	*	.000763	.015264	*	*	*
AM1 light input						
Si	.000720	.000875	.000401	.002055	.002496	.001091
InP	.000053	.000239	.000163	.001747	.007955	.002413
GaAs	.000062	.000096	.000182	.001158	.001773	.002871
CdTe	.000410	.000550	.000495	.004181	.005618	.007190
AlSb	.002168	.002859	.008512	.000742	.000978	.005461
CdSe	*	.000605	.014785	* p-type CdSe is not available		

Table VI.18

The loss factor, K' , as a function of the illumination conditions, barrier type, and substrate for six semiconductors used in vertical configuration solar cells (at 300°K)

AMO light input						
Junction	n-type substrate			p-type substrate		
	pn	hetero	Schottky	pn	hetero	Schottky
Si	.001089	.001089	.001660	.003114	.003114	.004544
InP	.000316	.000316	.001724	.010468	.010468	.033751
GaAs	.000122	.000122	.000777	.002312	.002312	.013064
CdTe	.000726	.000726	.002327	.007430	.007430	.032825
AlSb	.003750	.003750	.032108	.001282	.001282	.016549
CdSe	*	.000772	.025312	*	*	*

232 CHAPTER VI: CONFIGURATION AND PERFORMANCE

Table VI.18, continued

Junction	AM1 light input					
	n-type substrate			p-type substrate		
	pn	hetero	Schottky	pn	hetero	Schottky
Si	.000881	.000881	.001350	.002519	.002519	.003691
InP	.000243	.000243	.001369	.008025	.008025	.026237
GaAs	.000095	.000095	.000623	.001794	.001794	.010425
CdTe	.000554	.000554	.001800	.005662	.005662	.025427
AlSb	.002894	.002894	.025687	.000990	.000990	.013570
CdSe	*	.000613	.022677	* p-type CdSe is not available		

Table VI.19

The loss factor, K' , as a function of the illumination conditions, barrier type, and substrate for six semiconductors used in inverted configuration solar cells (at 300°K)

Junction	AMO light input					
	n-type substrate			p-type substrate		
	pn	hetero	Schottky	pn	hetero	Schottky
Si	.002059	.002059	.003092	.005871	.005871	.008459
InP	.000596	.000596	.003001	.019598	.019598	.061330
GaAs	.000230	.000230	.001348	.004477	.004477	.023573
CdTe	.001417	.001417	.004389	.014478	.014478	.061249
AlSb	.006915	.006915	.054453	.002454	.002454	.002759
CdSe	*	.001499	.035937	*	*	*
Junction	AM1 light input					
	n-type substrate			p-type substrate		
	pn	hetero	Schottky	pn	hetero	Schottky
Si	.001680	.001680	.002534	.004789	.004789	.006924
InP	.000458	.000458	.002376	.015009	.015009	.047348
GaAs	.000179	.000179	.001079	.003475	.003475	.018742
CdTe	.001083	.001083	.003398	.011037	.011037	.047620
AlSb	.005457	.005457	.044116	.001939	.001939	.002226
CdSe	*	.001188	.031298	* p-type CdSe is not available		

CHAPTER VI: CONFIGURATION AND PERFORMANCE 233

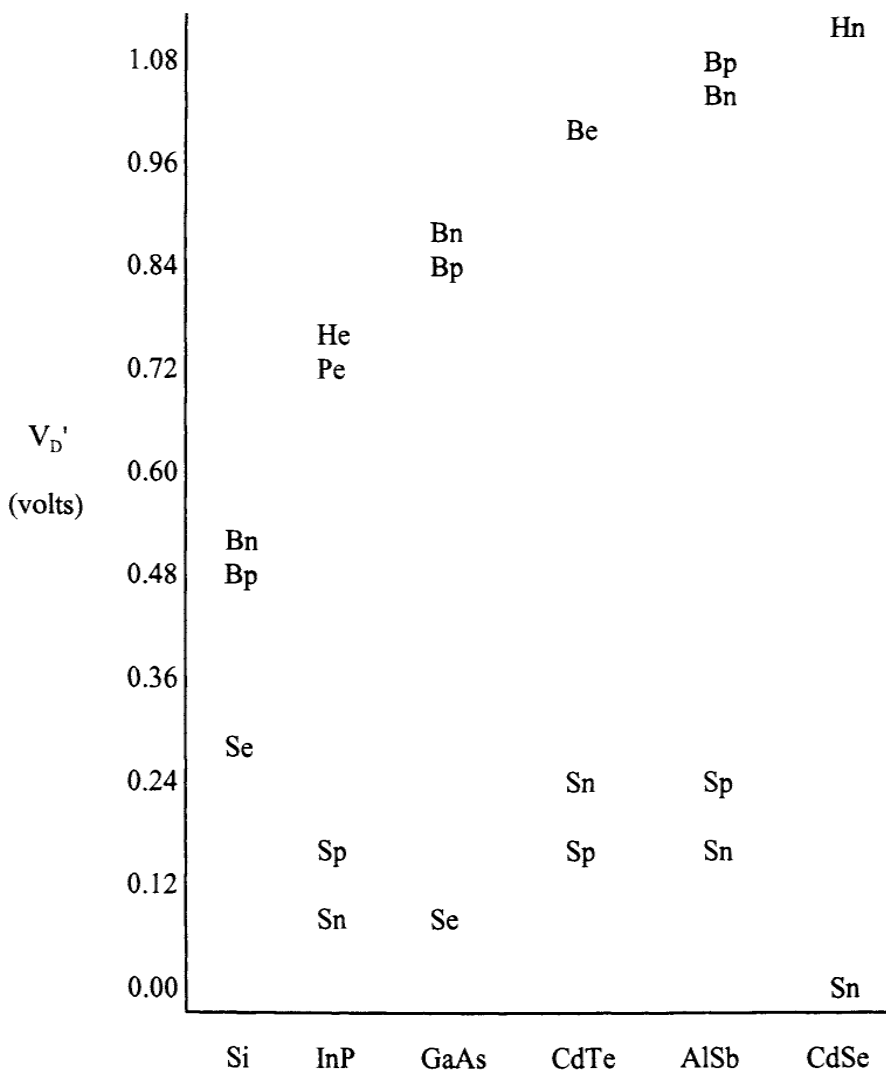


Figure VI.5. Photovoltage when the delivered solar cell power is a maximum, V_D' , for standard configuration solar cells, as a function of barrier and substrate, under AMO light, at 300°K and for six example semiconductors.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

234 CHAPTER VI: CONFIGURATION AND PERFORMANCE

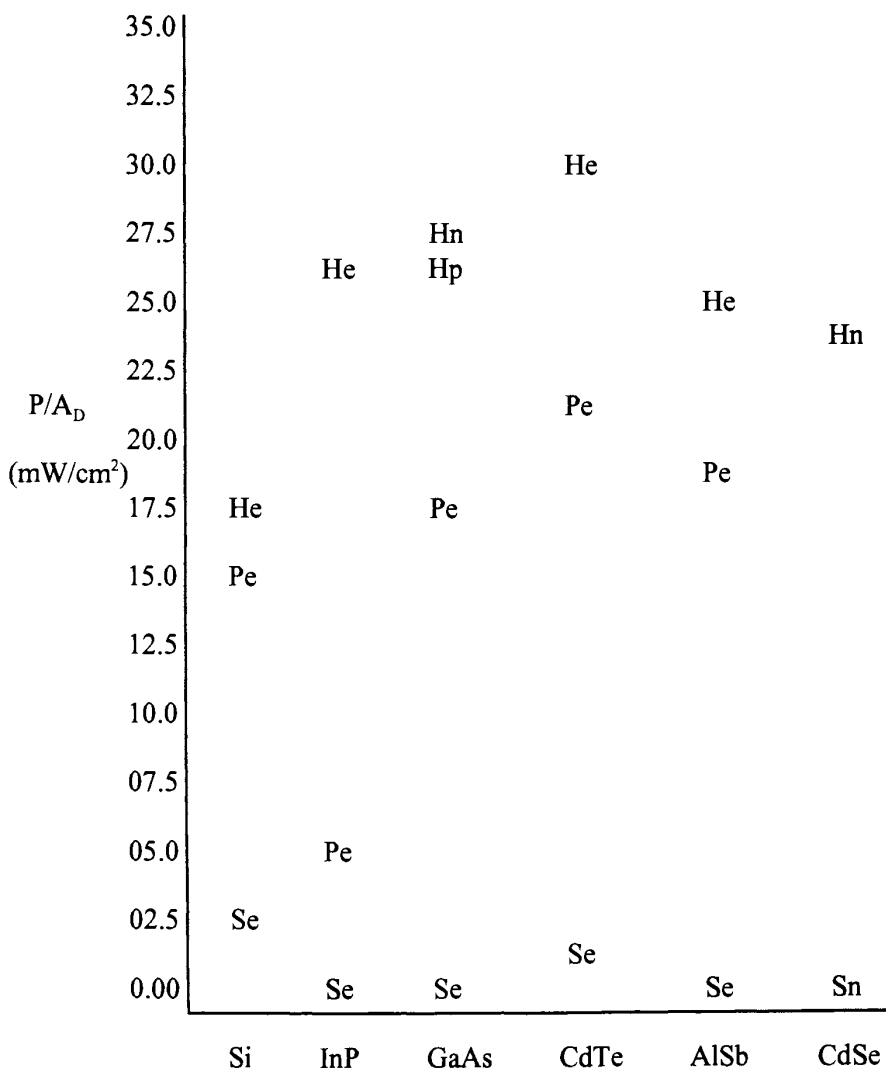


Figure VI.6. The maximum delivered power density, P/A_D , for standard configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AMO illumination and at 300°K .

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 235

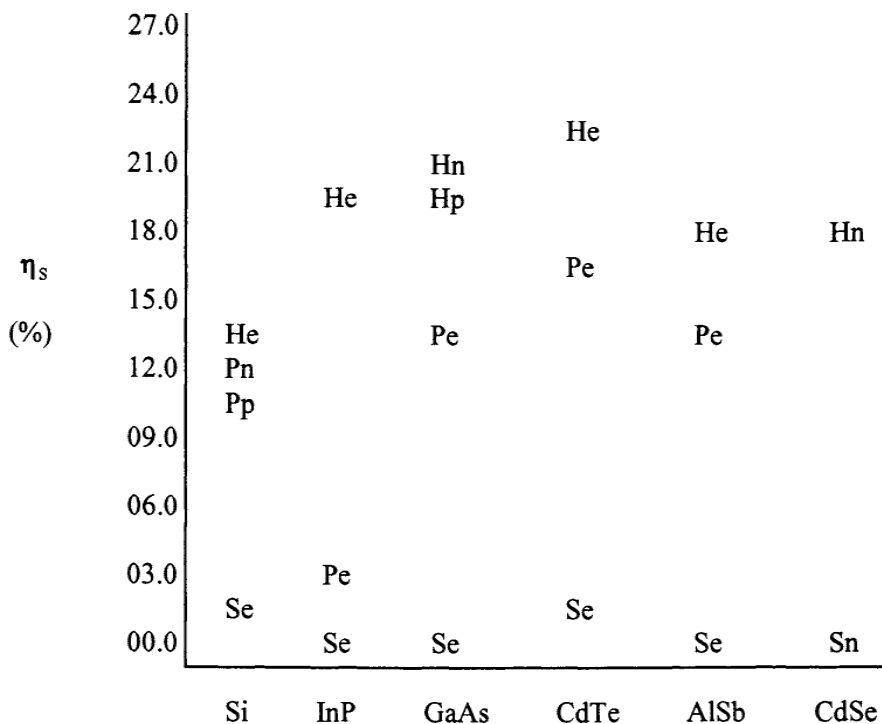


Figure VI.7. Solar cell efficiency, η_s , under the conditions of maximum delivered power density, for standard configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AMO illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

Figures VI.11 through VI.16 present values of photovoltage, maximum delivered power density and solar cell efficiency at 300°K for vertical configuration solar cells of various junction and substrate types. Note that the performance of these vertical configuration solar cells is higher than for standard configuration solar cells, partly as a result of higher effective (potentially higher!) photocurrents and partly as a result of the lower series resistance times junction area product of these solar cells. Further note that the low Schottky barrier heights result in higher saturation current density and poorer solar cell performance.

236 CHAPTER VI: CONFIGURATION AND PERFORMANCE

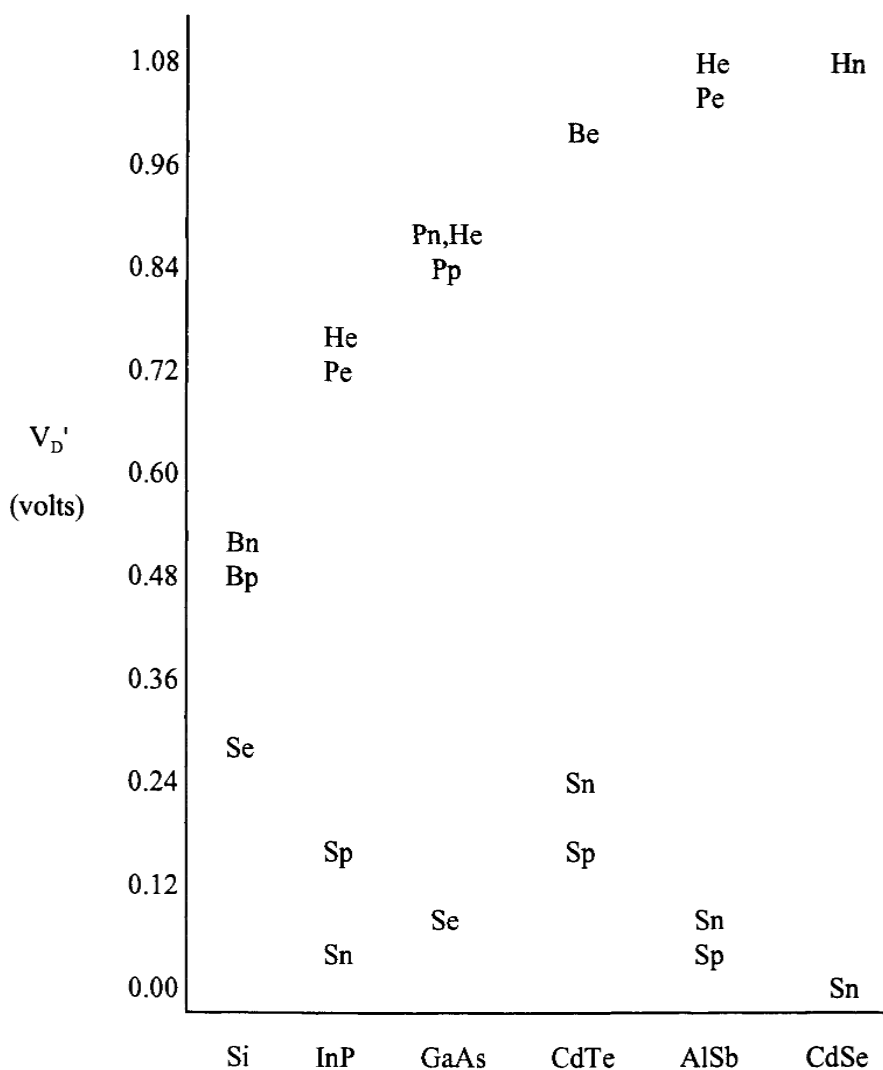


Figure VI.8. Photovoltage when the delivered solar cell power is a maximum, V_D' , for standard configuration solar cells, as a function of barrier and substrate, under AM1 light, at 300°K and for six example semiconductors.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 237

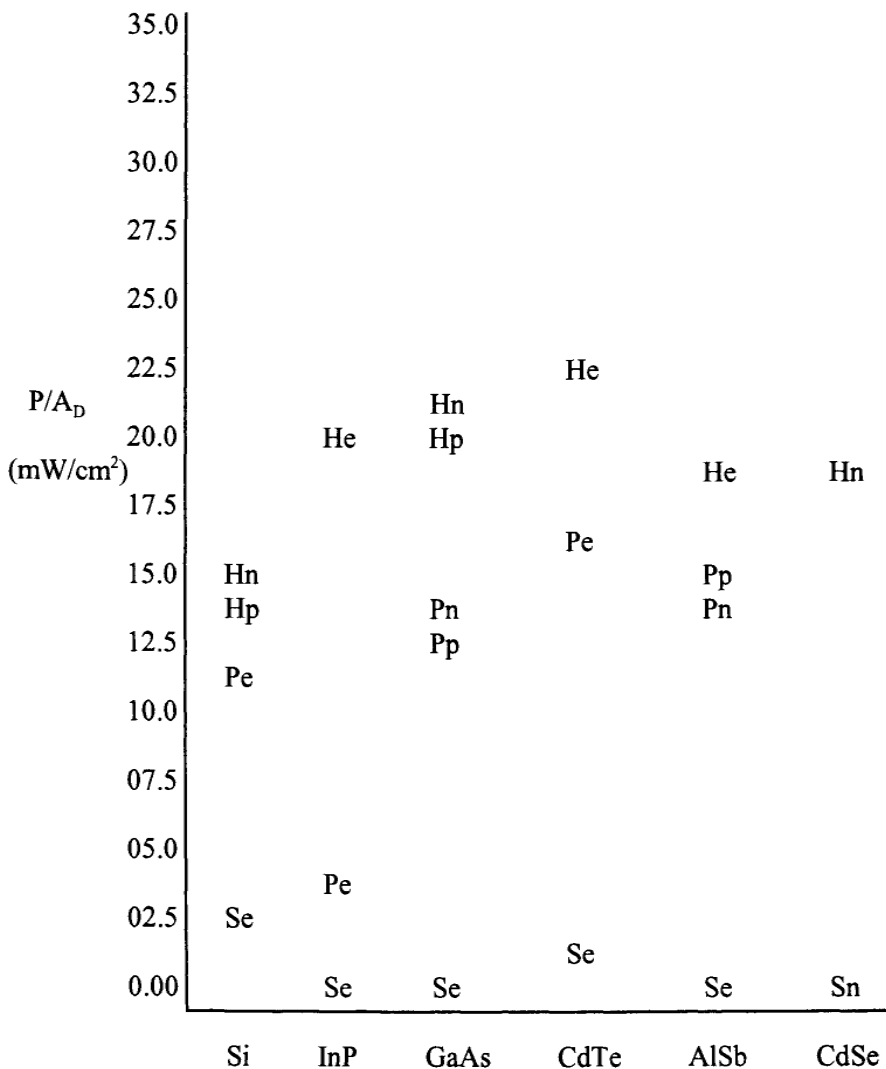


Figure VI.9. The maximum delivered power density, P/A_D , for standard configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AM1 illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

238 CHAPTER VI: CONFIGURATION AND PERFORMANCE

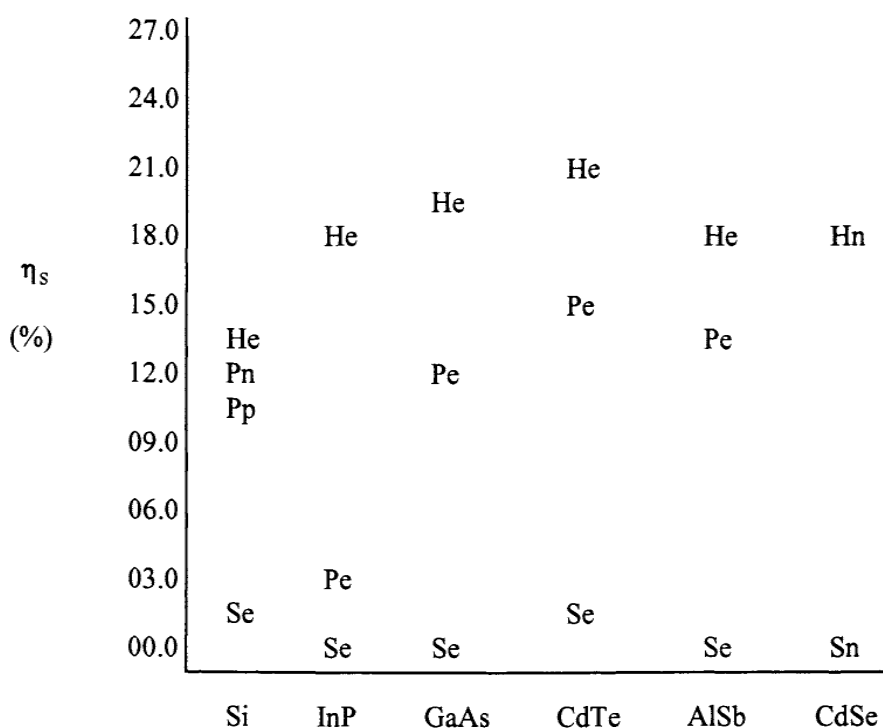


Figure VI.10. Solar cell efficiency, η_s , under the conditions of maximum delivered power density, for standard configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AM1 illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

Figures VI.17 through VI.22 present values of photovoltage, maximum delivered power density and solar cell efficiency at 300°K for inverted configuration solar cells of various junction and substrate types. Note that the performance of these inverted configuration solar cells is higher than for standard configuration solar cells, partly as a result of higher effective (potentially higher!) photocurrents and partly as a result of the lower series resistance times junction area product of these solar cells. Further note that the low Schottky barrier heights result in higher saturation current density and poorer solar cell performance.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 239

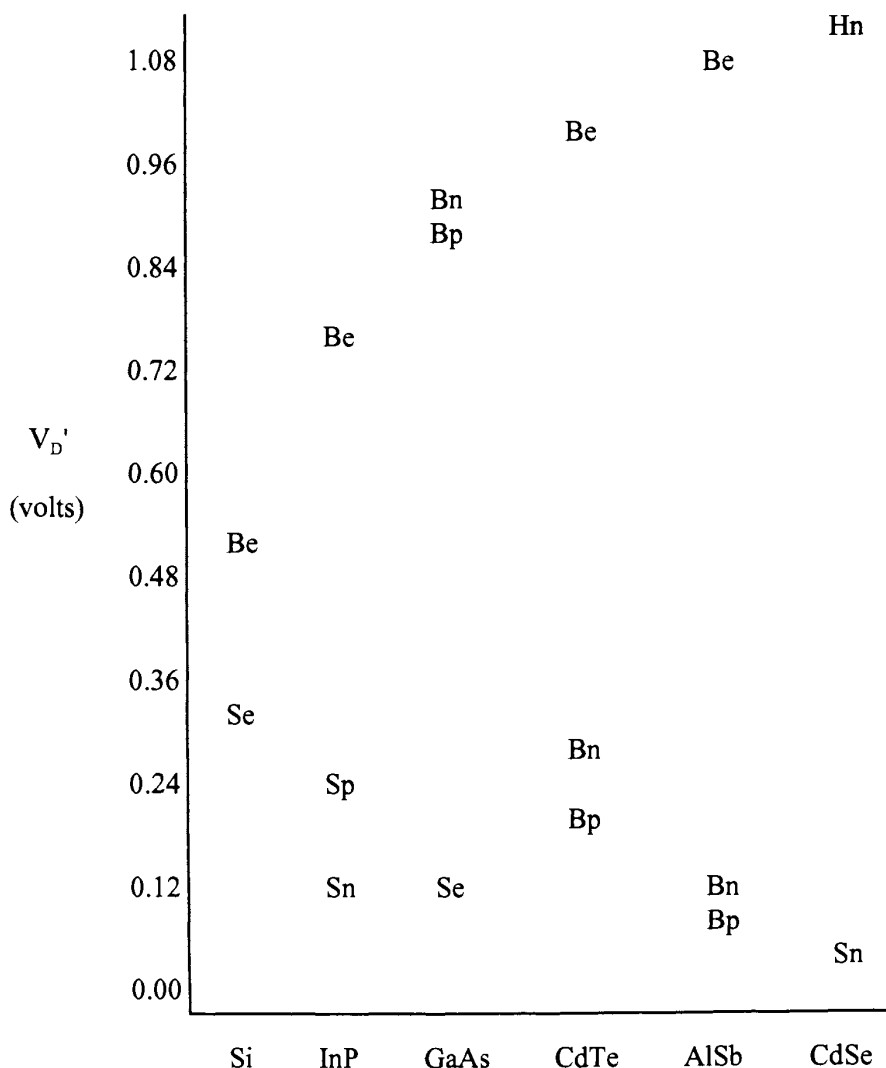


Figure VI.11. Photovoltage when the delivered solar cell power is a maximum, V_D' , for vertical configuration solar cells, as a function of barrier and substrate, under AMO light, at 300°K and for six example semiconductors.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

240 CHAPTER VI: CONFIGURATION AND PERFORMANCE

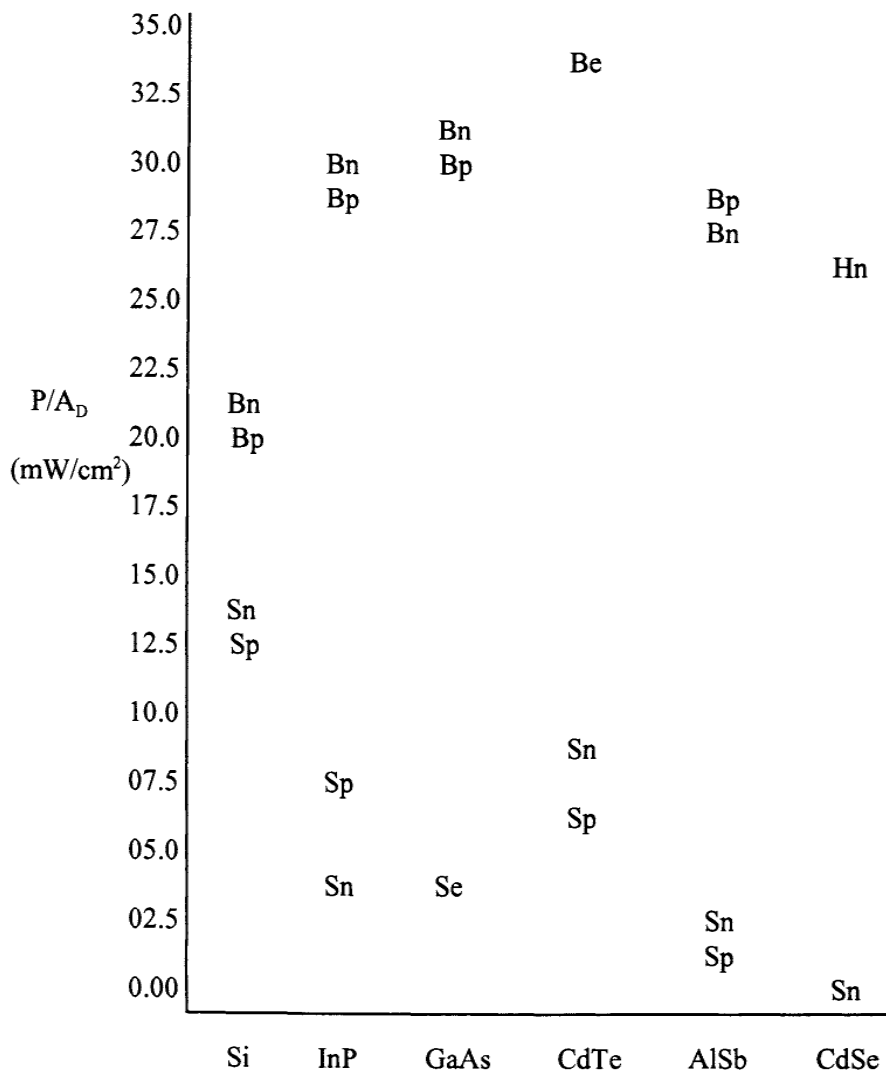


Figure VI.12. The maximum delivered power density, P/A_D , for vertical configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AMO illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 241

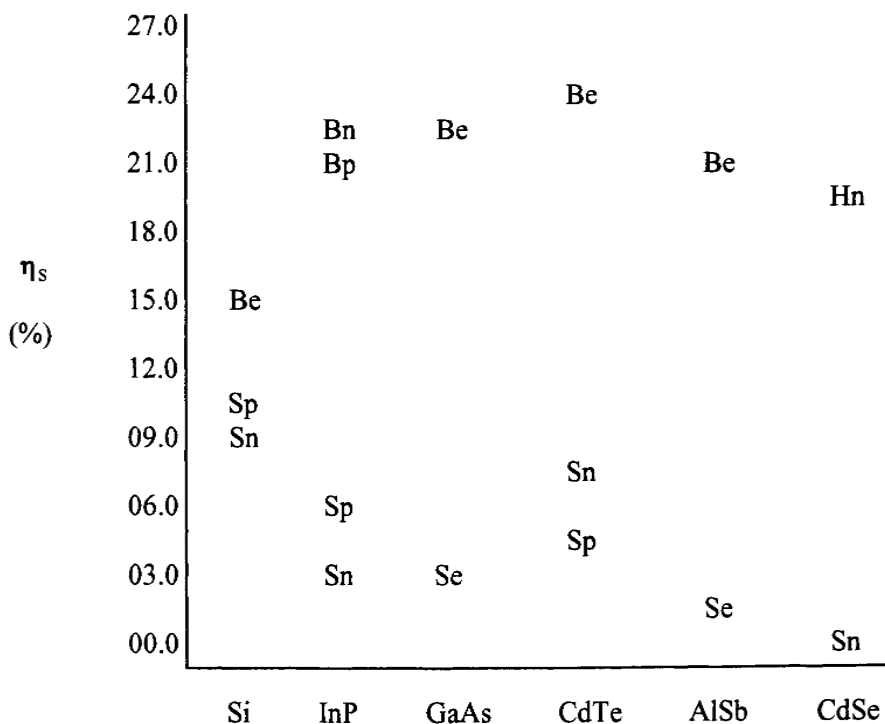


Figure VI.13. Solar cell efficiency, η_s , under the conditions of maximum delivered power density, for vertical configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AMO illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

Comparing the inverted solar cell types of Figures VI.17 through VI.22 with the vertical solar cell performance estimated in Figures VI. 11 through VI.16 note that the performance of the inverted solar cells is estimated to be significantly higher than that of the vertical solar cells. The principal reason for this is the higher photocurrent of the inverted type of solar cell. For inverted cells the effective junction area is approximately one half of the illuminated area. Thus there is significantly higher photocurrent in the inverted solar cells as these devices exhibit a moderate amount of built-in optical concentration.

242 CHAPTER VI: CONFIGURATION AND PERFORMANCE

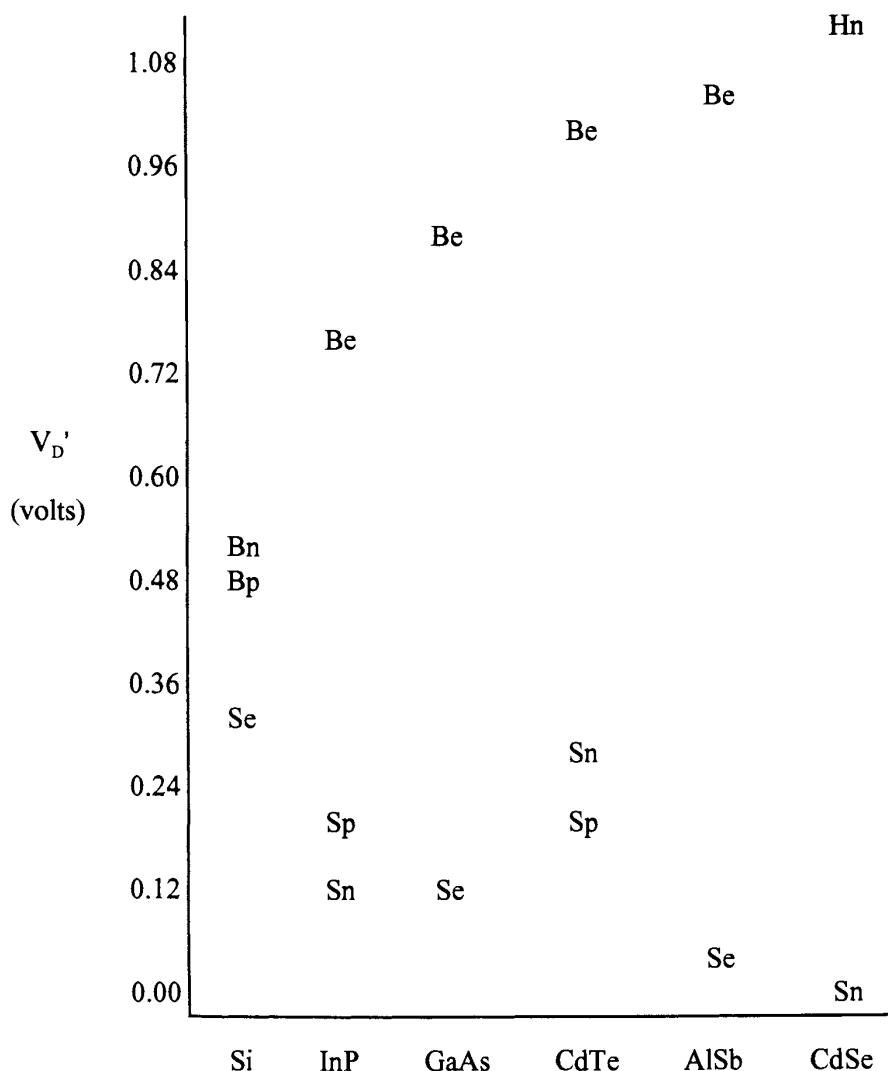


Figure VI.14. Photovoltage when the delivered solar cell power is a maximum, V_D' , for vertical configuration solar cells, as a function of barrier and substrate, under AM1 light, at 300°K and for six example semiconductors.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 243

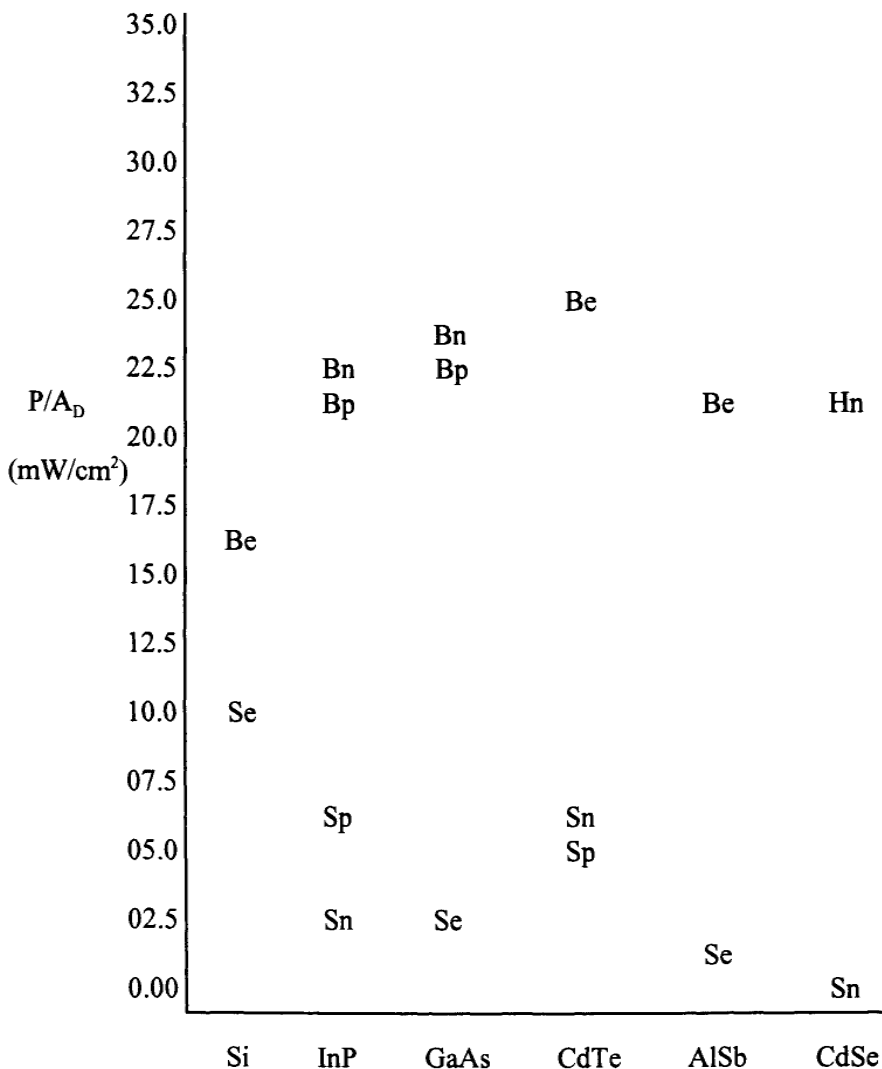


Figure VI.15. The maximum delivered power density, P/A_D , for vertical configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AM1 illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

244 CHAPTER VI: CONFIGURATION AND PERFORMANCE

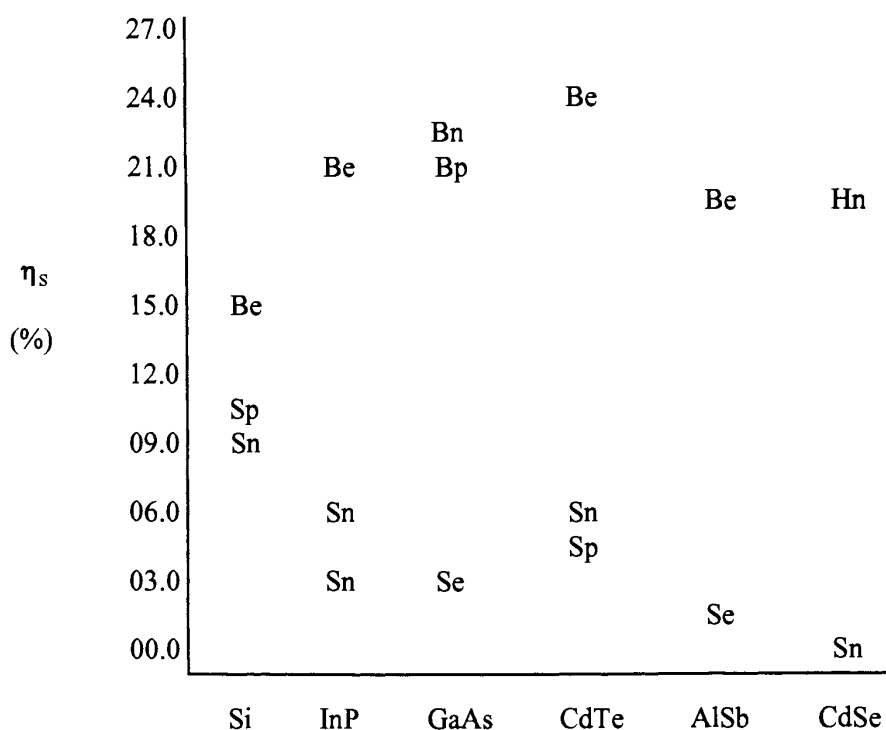


Figure VI.16. Solar cell efficiency, η_s , under the conditions of maximum delivered power density, for vertical configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AM1 illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

Solar Cell Performance - Discussion

Let us conclude this chapter with some discussion regarding Figures VI.5 through VI.22. Let it be emphasized that the devices whose photovoltage, maximum delivered power density and efficiency are shown in these figures are not considered to be the "best there can be" at performing as solar cells. Instead, these solar cells are constructed to represent practical devices. In other words, they are taken to be

CHAPTER VI: CONFIGURATION AND PERFORMANCE 245

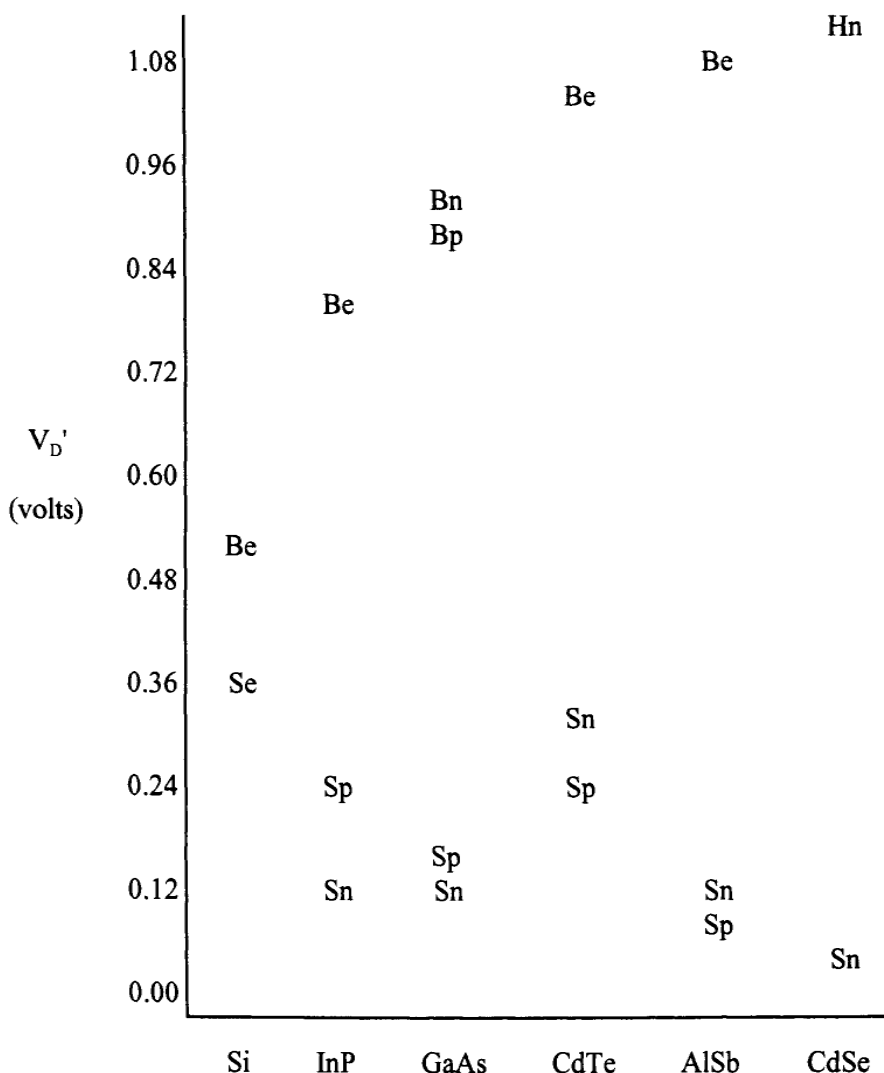


Figure VI.17. Photovoltage when the delivered solar cell power is a maximum, V_D' , for inverted configuration solar cells, as a function of barrier and substrate, under AMO light, at 300°K and for six example semiconductors.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

246 CHAPTER VI: CONFIGURATION AND PERFORMANCE

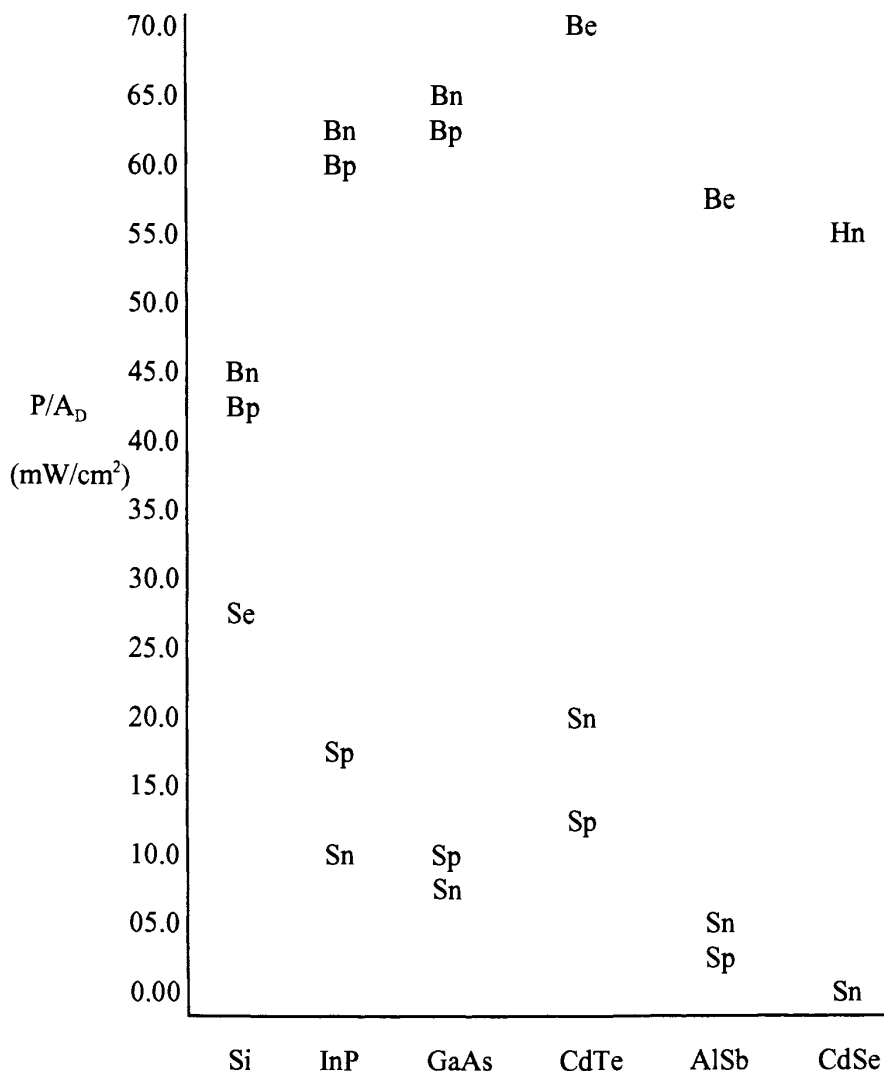


Figure VI.18. The maximum delivered power density, P/A_D , for inverted configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AMO illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 247

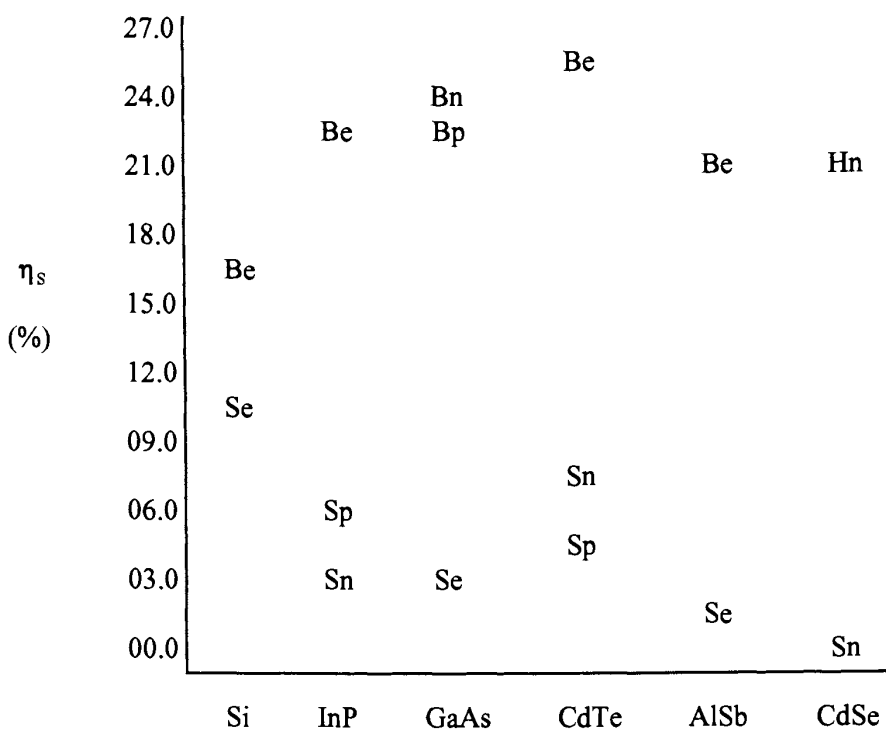


Figure VI.19. Solar cell efficiency, η_s , under the conditions of maximum delivered power density, for inverted configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AMO illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

representative of devices which can be reliably and repeatedly constructed to operate at the performance level indicated. It is possible to better the performance levels indicated in Figures VI.5 through VI.22 by spending a considerable amount of effort at maximizing the photocurrent, while minimizing the saturation current density and series resistance. For example, silicon devices with efficiencies in excess of 20% have been reported [39]. It is also, unfortunately, possible to "snatch defeat from the jaws of victory" and do much worse. The solar cells considered in this chapter are achievable, and allow us to draw some design conclusions.

248 CHAPTER VI: CONFIGURATION AND PERFORMANCE

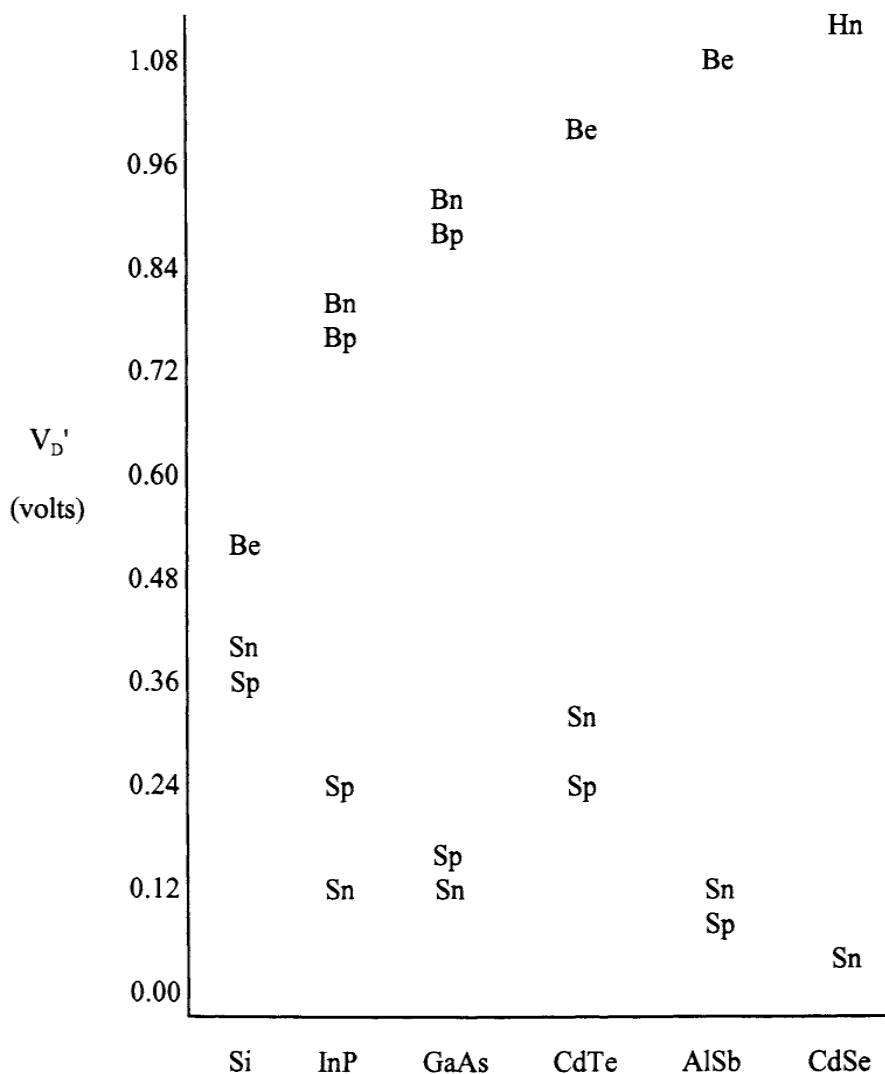


Figure VI.20. Photovoltage when the delivered solar cell power is a maximum, V_D' , for inverted configuration solar cells, as a function of barrier and substrate, under AM1 light, at 300°K and for six example semiconductors.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 249

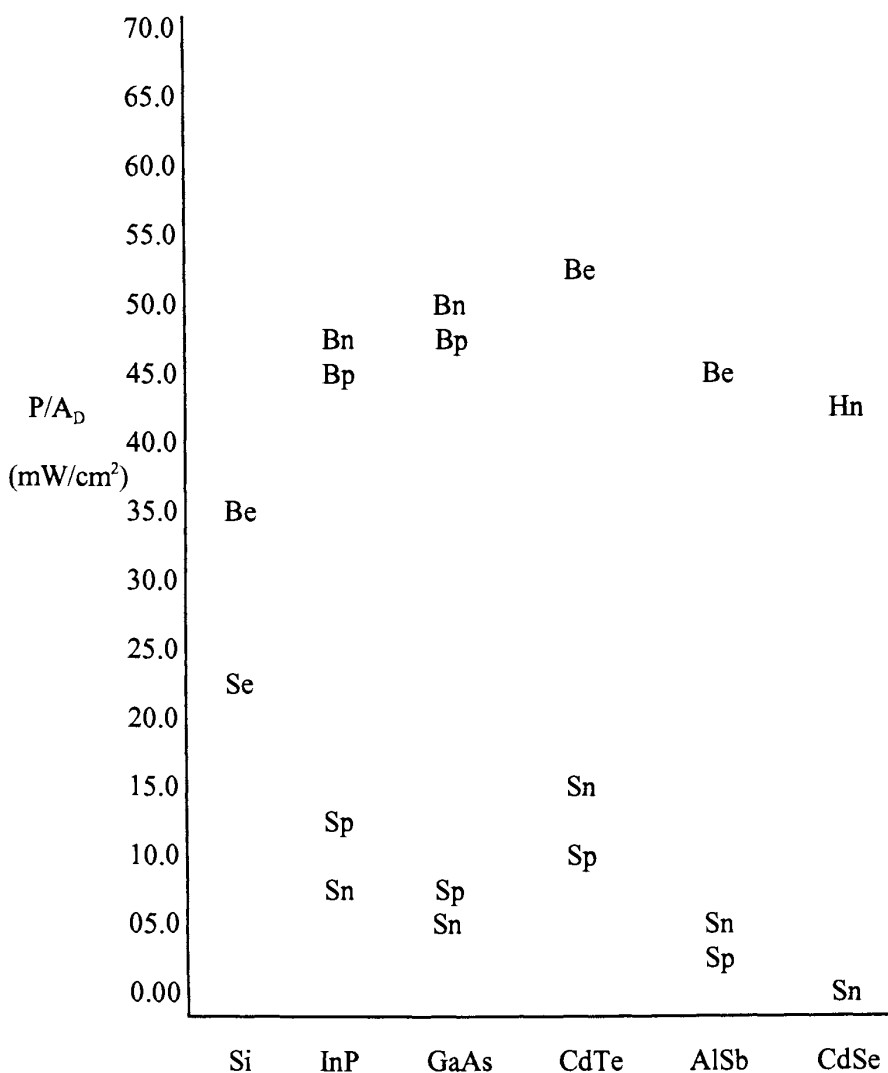


Figure VI.21. The maximum delivered power density, P/A_D , for inverted configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AM1 illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

250 CHAPTER VI: CONFIGURATION AND PERFORMANCE

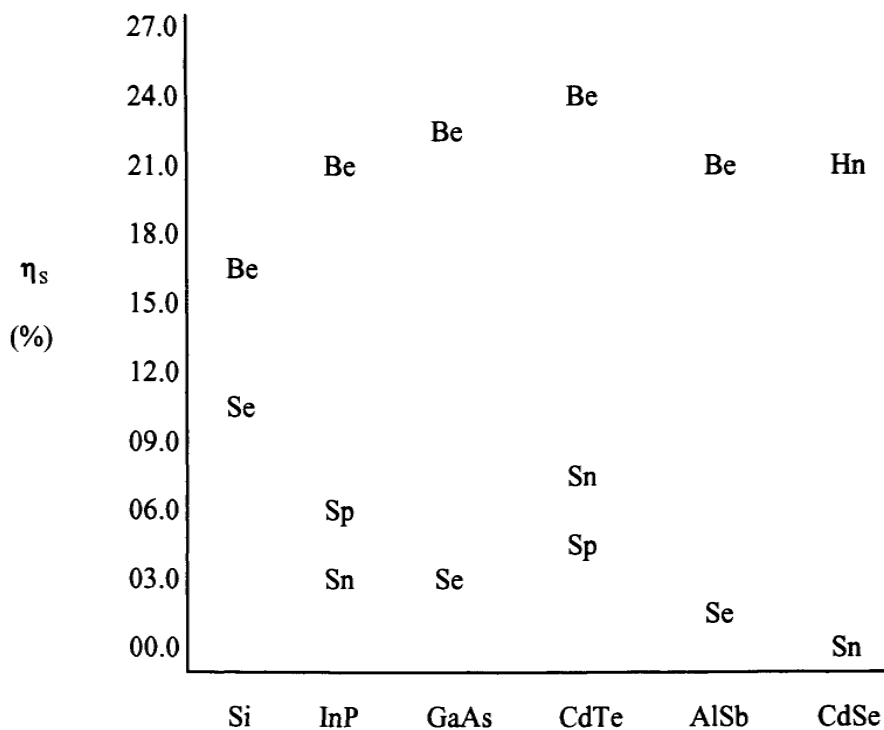


Figure VI.22. Solar cell efficiency, η_s , under the conditions of maximum delivered power density, for inverted configuration solar cells, as a function of barrier and substrate, for six example semiconductors under AM1 illumination and at 300°K.

Junction symbols: H for heterojunction, P for pn junction, S for Schottky barrier and B for both pn and heterojunctions.

Substrate symbols: n for n-type, p for p-type and e for either type.

Overall, pn junction and heterojunction solar cells are potentially capable of generating larger amounts of photopower than are Schottky barrier solar cells. This is the result of lower saturation current densities, particularly for non-silicon semiconductors. In all three optical configurations; standard, vertical and inverted; the predicted performance for solar cells appears to be at a maximum for CdTe. Also note that, in general, the substrate type is relatively unimportant.

From our discussion in Chapter V, the values for photovoltage, given in Figures VI.5, VI.8, VI.11, VI.14, VI.17 and VI.20, should be

CHAPTER VI: CONFIGURATION AND PERFORMANCE 251

in excess of V' , the voltage at which the diode current is contributed equally by diffusion and by generation-recombination components. We can solve Equation V.11 to determine V' for the devices considered in this chapter. The results of this operation, along with the effective built-in voltage for pn junctions are provided in Table VI.20.

Table VI.20

Values of V_B and V' (in volts) for pn junctions made from the example semiconductors with the material parameters indicated in this chapter

Semiconductor	Si	InP	GaAs	CdTe	AlSb
for p-type substrates					
V_B	0.815	1.14	1.23	1.29	1.46
V'	0.063	0.56	0.66	0.71	0.86
for n-type substrates					
V_B	0.815	1.14	1.23	1.29	1.46
V'	0.036	0.52	0.59	0.65	0.87

Examination of Figures VI.5, VI.8, VI.11, VI.14, VI.17 and VI.20 shows that the experienced photovoltages for heterojunction and pn junction solar cells, for standard, inverted and vertical configurations, are in excess of V' . The photovoltages for Schottky diode solar cells are less than V' in Table VI.20 but the above mentioned limitation does not apply, because the overall performance is so low as to make Schottky barrier devices of little, or no, interest. Note that the optimum output solar cell voltage is less than V_B for all pn and heterojunction devices and is less than ϕ_{Bo} (see Table VI.4) for Schottky junction solar cells.

The performance of standard configuration solar cells as displayed in Figures VI.5 through VI.10 involves an approximation. The power density obtainable depends on the actual physical dimensions of the solar cell. The series resistance times area product contains a term due to the substrate which is independent of the illuminated area radius, a , and which is provided in Table VI.14. However, it also includes a term due to the series resistance of the "front layer". This term was presented in Table VI.16, assuming a circular area for the solar cells, and it was indicated in Table VI.16 that the series resistance times area product for standard

252 CHAPTER VI: CONFIGURATION AND PERFORMANCE

configuration solar cells varies as a^2 . The performance displayed in Figures VI.5 through VI.10 is based on the assumption that the series resistance times area product for standard configuration solar cells is that of the substrate plus a contribution from the "front layer"--a contribution that amounts to 10% of the substrate value. Note that the greater the radius of the standard configuration solar cell the greater the light collecting area and the greater the experienced photocurrent. However, the resistance times area product will also increase, leading to a larger loss factor and a lower output power density and operating efficiency. The exact size which is most efficient is a function of the type of junction, the intensity of the light illuminating the solar cell and the economics of the fabrication process employed in constructing the solar cells. Clearly, if output power density is the sole important item, then the ideal solar cell has no internal resistance what-so-ever--a topic which will be addressed in the following chapter.

We will not pursue this topic further at present. For now, the reader will be interested in Table VI.21 which presents the effective radius of standard configuration solar cells for the case in which the "front layer" contributes an amount equal to 10% of the substrate series

Table VI.21

The illuminated region radius, a , (in μm) for standard configuration solar cells for a "front layer" series resistance times area product which is 10% of that of the substrate product

Semiconductor	Si	InP	GaAs	CdTe	AlSb	CdSe
Junction Type						
			n-type substrates			
Schottky	525	358	253	663	1727	839
heterojunction	152	103	073	191	0499	242
pn	038	035	020	038	0185	*
			p-type substrates			
Schottky	876	2032	1084	2123	1015	*
heterojunction	253	0567	0313	0613	0294	*
pn	081	0345	0027	1412	0096	*
* p-type CdSe is not available						

CHAPTER VI: CONFIGURATION AND PERFORMANCE 253

resistance times area product--the situation leading to Figures VI.5 through VI.10. Note that the dimensions, a , are small, leading the reader to conclude that a larger device would exhibit a significantly higher series resistance area product, and hence would have a substantially lower performance.

Careful study of the theoretical predictions contained in Figures VI.5 through VI.22 and of the rest of this chapter indicates that inverted configuration solar cells are potentially capable of the highest level of performance, followed by vertical configuration solar cells and, followed, at the lowest level, by standard configuration solar cells. Considering the type of junction, pn or heterojunction (given the availability of suitable matching semiconductors) solar cells appear to be preferable, as compared to the poorly performing Schottky barriers. Substrate type, while it does exhibit some effect on solar cell performance, does not play a major role in device output. Finally, it would seem that the performance of solar cells (in terms of output power density and efficiency) is highest for those situations in which the semiconductor employed has an energy gap in the vicinity of 1.5 eV.

What we have not done, as yet, is consider the economics of the fabrication processes employed and the effects of increased illumination levels and solar cell junction temperatures. These topics will be covered in the succeeding chapters. In addition, we will consider additional techniques for improving solar cell performance. Even without these improvements, the potential performance for solar cells, as indicated in this chapter, is encouraging when we consider solar cells as a major energy source for our civilization.

References

- 1 Electronics, 29 May, 1975, p. 41.
- 2 J. A. Hitchby and R. L. Fudurich, in *Journal of Applied Physics*, Vol. 47, 1976, p. 3152.
- 3 A. M. Sekela, D. L. Feucht and A. G. Milnes, in *IEEE Transactions on Electron Devices*, Vol. 24, 1977, p. 373.
- 4 J. L. Shay, et. al., in *Journal of Applied Physics*, Vol. 47, 1976, p. 614.
- 5 R. L. Soukap, in *Journal of Applied Physics*, Vol. 47, 1976, p. 555.

254 CHAPTER VI: CONFIGURATION AND PERFORMANCE

- 6 A. K. Sreedhar, B. L. Sharma and R. K. Purchet, in *IEEE Transactions on Electron Devices*, Vol. 16, 1969, p. 309.
- 7 W. G. Thompson, et. al., in *IEEE Transactions on Electron Devices*, Vol. 24, 1977, p. 463.
- 8 R. H. Bube, et. al., in *IEEE Transactions on Electron Devices*, Vol. 24, 1977, p. 487.
- 9 M. D. Lammert and R. J. Schwartz, "A Silicon Solar Cell for Use at High Illumination Intensities, Technical Report TR-EE-75-37, 1975. See also *IEEE Transactions on Electron Devices*, 1977, p. 337.
- 10 H. J. Hovel, *Semiconductors and Semimetals, Vol.11*, Academic Press, New York, 1975, p. 14.
- 11 S. M. Sze, *Physics of Semiconductors, 2nd Edition*, John Wiley and Sons, New York, p. 291.
- 12 R. C. Neville, unpublished data on CdTe, AlSb and InP.
- 13 A. N. Saxena, et. al., personal communication on hafnium-silicon surface barriers.
- 14 C. A. Mead, in *Solid-State Electronics*, Vol. 9, 1966, p. 1023.
- 15 M. F. Millea, in *Physics Review*, Vol. 177, 1969, p. 1164.
- 16 W. A. Anderson, et. al., in *Journal of Vacuum Science and Technology*, Vol. 13, 1976, p. 1158.
- 17 J. P. Ponpon and P. Siffer, in *Journal of Applied Physics*, Vol. 47, 1976, p. 89.
- 18 R. J. Stirn, Y. C. M. Yeh and S. J. Fonash, in *Journal of Vacuum Science and Technology*, Vol. 13, 1976, p. 894.
- 19 R. Singh and J. Sewchun, in *Journal Vacuum Science and Technology*, Vol. 14, 1977, p. 89.
- 20 W. A. Anderson, J. K Kim and A. E. DeLahoy, in *IEEE Transactions on Electron Devices*, Vol. 24, 1977, p. 453.
- 21 A. K. Sreedhar, B. L. Shavna and R. K. Purchit, in *IEEE Transactions on Electron Devices*, Vol. 16, 1969, p. 309.
- 22 R. Rahi and A. G. Milnes, in *Solid State Electronics*, Vol. 13, 1970, p. 1289.
- 23 A. S. Grove, *Physics and Technology of Semiconductor Devices*, John Wiley and Sons, New York, 1967, Chap. 3.
- 24 S. M. Sze, *Semiconductor Devices, Physics and Technology*, John Wiley and Sons, New York, 1985, Chap. 9.

CHAPTER VI: CONFIGURATION AND PERFORMANCE 255

- 25 The upper limit on impurity densities in a semiconductor is the solid solubility of the impurity species in the semiconductor. For typical examples see, F. A. Trumbore, in *The Bell System Technical Journal*, Vol. 39, 1960, p. 205.
- 26 A full discussion of ion implantation and diffusion as techniques for introduction of impurities into solar cells is too lengthy for inclusion in this work. The scientific literature is replete with references to the technique. For those who wish to further pursue these subjects, suggested titles are: D. C. Gupta, editor, Silicon Processing, ASTM Technical Publications, Philadelphia, 1983 and Reference [23], pages 40 and 210.
- 27 J. Singh, Physics of Semiconductors and Their Heterostructures, McGraw-Hill, New York, 1993, p. 47-49.
- 28 The topic of molecular beam epitaxy (MBE) requires considerably more space to adequately cover than is available here. It is suggested that the interested reader begin study of MBE by reading S. M. Sze, Semiconductor Device Physics and Technology, John Wiley and Sons, New York, 1985, p. 333-338. There is voluminous literature on this topic, reaching back to 1974, particularly A. Y. Cho, et. al., in *Applied Physics Letters*, Vol. 25, 1974, p. 224.
- 29 K. B. Wolfstirn, in *Physics Chemistry Solids*, Vol. 16, 1960, p. 279.
- 30 Unpublished data obtained by the author.
- 31 M. A. Green, in *IEEE Transactions on Electron Devices*, Vol. 23, 1976, p.11.
- 32 J. Mandelkorn, J. H. Lamneck and L. R. Scudder, in the Conference Proceedings of the 10th IEEE Photovoltaic Specialists Conference, Nov. 1973, p. 20.
- 33 M. Wolf, in *Proceedings of IEEE*, Vol. 51, 1963, p. 674.
- 34 A. Adibi, "Schottky Barrier Solar Cells", Thesis, University of California, Santa Barbara, 1977.
- 35 E. J. Charlson and J. C. Lein, in *Journal of Applied Physics*, Vol. 47, 1975, p. 3982.
- 36 J. Schewchun, R. Singh and M. A. Green, in *Journal of Applied Physics*, Vol. 48, 1977, p. 765.
- 37 H. J. Hovel, Semiconductors and Semimetals, Volume III, Solar Cells, Academic Press, New York, 1975, p. 765.
- 38 N.C. Wyeth, in *Solid State Electronics*, Vol. 20, 1977, p. 629. This article treats the "front layer" resistance in greater detail than space permits here--for both circular and rectangular solar cell geometries.

256 CHAPTER VI: CONFIGURATION AND PERFORMANCE

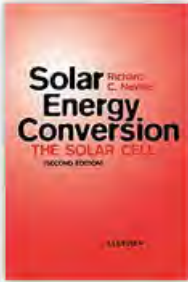
- 39 M. Green, University of New South Wales, reported in the *Photovoltaic Insider's Report*, 30 April, 1993.

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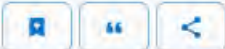
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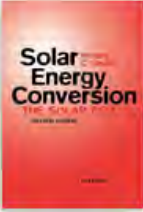
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ATTACHMENT E-1

Light Trapping for Thin-Film Silicon Solar Cells Fabricated on Insulator

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We have developed a new solar cell using thin-film silicon supported by a silicon substrate etched in a grid form. The light-trapping structures of this cell have been studied by considering rear surface light reflections, electrical power loss and mechanical strength. High rear reflectance can be obtained by employing a multi-layer rear electrode. The pattern of the rear substrate is designed to provide sufficient mechanical strength and to minimize the electrical power loss, taking account of the current flow path. A conversion efficiency of 14.2% for a practical size of $10 \times 10 \text{ cm}^2$ is obtained by applying these calculated parameters using a single-crystal silicon substrate.

KEYWORDS: thin-film silicon solar cell, light trapping, light reflection, silicon on insulator, zone melting recrystallization

1. Introduction

Many types of thin-film silicon solar cells have been developed over the last 15 years, because of their potential to lower cost and provide higher efficiency. Chu *et al.*¹⁾ fabricated thin-film silicon solar cells on a carbon substrate with 9.75% efficiency for a small size of 9 cm^2 . Kendall *et al.*²⁾ reported cells with 10.9% efficiency for a practical cell size of 100 cm^2 on a conductive ceramic substrate.

For the realization of high conversion efficiency, highly efficient optical confinement and high crystal quality of silicon films are essential for thin-film solar cells. However, since the rear surface of conventional structures is entirely covered with the substrate, highly reflective structures at the rear surface might not be easily formed. There was an attempt to form a textured structure on the surface of the supporting substrate to increase total reflection,³⁾ but the process to form this structure resulted in high cost, and the rough substrate surface was disadvantageous for active layer formation.

The cells recently developed in our laboratory⁴⁾ have overcome these problems. The crystallographic quality of the thin-film active layer supported by an insulator-coated substrate is improved by the zone melting recrystallization (ZMR) method. The contact of the rear electrode is obtained by partial substrate etching, and this opening of the substrate makes it possible to form a highly reflective structure. This cell fabrication method and the structure will be described in detail elsewhere.⁵⁾

On the other hand, many studies have been made on optical confinement of conventional photovoltaic devices,^{6,7)} assuming a flat-plate wafer whose entire rear surface can be designed for optical trapping; however, since the rear structure of our cell is composed of both openings and frames, it requires a new analysis technique to determine its light-trapping ability. This paper is concerned with the design of a new type of thin-film silicon solar cells considering not only light trapping but also mechanical strength and electrical power loss. Finally, the performance of the thin-film silicon solar cell will be described.

2. Results and Discussion

Figure 1 shows the structure of the thin-film solar cell. The thin-film silicon active layer is formed by ZMR and epitaxial growth on an insulator-coated $\sim 600\text{-}\mu\text{m}$ -thick heat-resistive substrate. In this study, single-crystal silicon is used as a substrate. In order to obtain the rear contact and light reflection, partial openings are fabricated on the rear surface by selective etching of the substrate. The cell size is $10 \times 10 \text{ cm}^2$. Rear surface texturing is not performed in this study. The main points of the light-trapping design for this cell structure are as follows.

- Light reflection at the rear opening.
- Light reflection at the rear frame.
- Mechanical strength in handling.
- Electrical power loss at the upper part of the frame.

In order to fully utilize the rear light reflection, a larger area of the opening is desired. However, a larger area leads to decrease in mechanical strength. Consequently, items a)–d) require comprehensive optimiza-

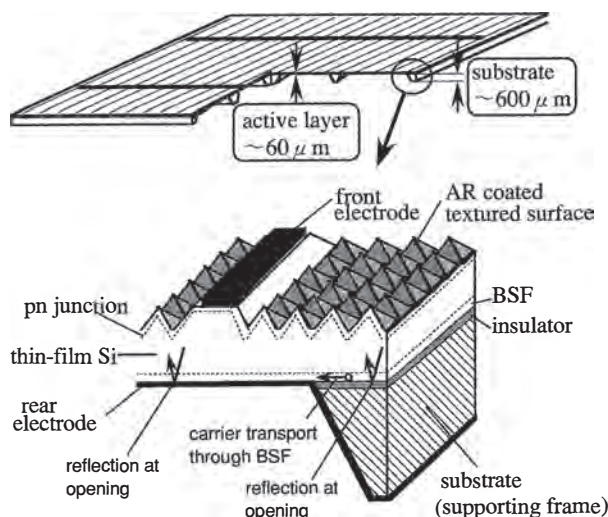


Fig. 1. Cell structure of thin-film silicon solar cell fabricated on insulator-coated substrate by zone melting recrystallization.

tion. From this point of view, each item above is discussed in the following sections.

2.1 Light reflection at rear opening

As shown in Fig. 1, this cell structure can be used to achieve high light reflectivity using rear surface treatments such as a textured structure or deposition of highly reflective metals. The requirements on the rear structure of the cell include high reflectivity as well as electrical conductivity. In order to realize reflectivity higher than that of conventional aluminum (Al) metal, we have adopted silver (Ag) metal and a transparent conductive indium tin oxide (ITO) film inserted between the thin Si film and Ag layer. This ITO film also plays the important role of an ohmic contact to the p^+ (BSF: back surface field) of the silicon film.

In Fig. 2, the results of the reflectance calculated at $\lambda=1000$ nm are shown, which includes the expected rear surface configuration for four different conditions. The matrix method^{8,9)} was used for the calculation, and calculated thickness of the ITO film was 900 Å. Comparing the result obtained using only Al film ($R=83.3\%$), the Ag film can increase the reflectance to $R=94.9\%$. Furthermore, insertion of the ITO film between Si and Ag makes it possible to obtain a sufficiently high reflectance of $R=98.5\%$. It is roughly estimated that the internal quantum efficiency, which is the light absorption, at $\lambda=1000$ nm is 0.319 ($R=0\%$), 0.525 ($R=94.9\%$) and 0.533 ($R=98.5\%$), and also that the enhancement of the short-circuit current density (J_{sc}) by the reflection of the rear electrode is 1.55 mA/cm² with Ag in comparison with the case of $R=0\%$, and is 1.6 mA/cm² with the ITO/Ag electrode. On the other hand, for low-cost fabrication (using the less-expensive Al electrode), insertion of the ITO film can improve the reflectance from $R=83.3\%$ to $R=95.2\%$. Since we have applied the ITO film, which has high electrical conductivity and high transparency as the inserted film, electrical and optical losses in the ITO layer are negligible.

2.2 Light reflection at rear frame

As shown in Fig. 1, incident light on the frame is partially reflected at the Si-insulator interface. Figure 3 shows the calculated reflectances ($\lambda=1000$ nm) at the Si-insulator interface for two types of conventional insulators (SiO_2 and Si_3N_4). Reflectances change periodically as functions of the film thicknesses. The maximum reflectance for the SiO_2 layer ($n=1.45$) is 51% and that

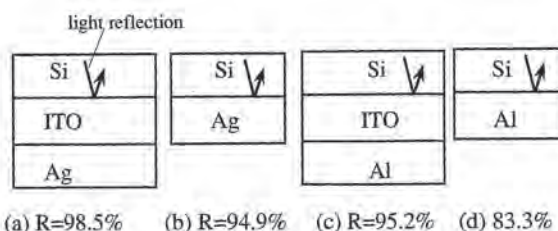


Fig. 2. Calculated reflectances for four different conditions of rear reflectors at opening.

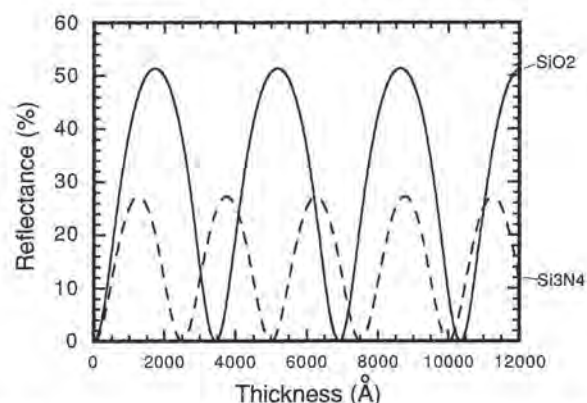


Fig. 3. Calculated reflectances at the upper part of the frame. Solid and dashed lines show reflectances of SiO_2 and Si_3N_4 , respectively.

for Si_3N_4 ($n=2.0$) is 28%. This is because the reflectance tends to be higher for a larger difference of refractive indices between the silicon and insulator than for a lower one. Therefore, SiO_2 is a better material for use as the insulator of the thin-film cell. If the material of the insulator can withstand the high-temperature ZMR process, air or highly reflective metals are more suitable than insulators to obtain higher reflection, because such materials have large refractive index differences with silicon. The calculated result shows the maximum reflectance of 51% for SiO_2 at thicknesses of about 1700 Å, 5200 Å, 8600 Å, and 12000 Å. In the case of thin films (less than 2000 Å), high-quality silicon film is difficult to obtain due to its tendency to aggregate or form holes in the insulator. On the other hand, thick films (more than 10000 Å) lead to more cracks or surface roughening, aside from their higher costs. Therefore, 5200 Å or 8600 Å is a suitable thickness for the insulator of this cell.

2.3 Mechanical strength

In industry, conventional solar cells use about 200- μm -thick silicon wafers with the size of 10 cm square because of the ease of wafer handling without wafer fracture. In this regard, we have evaluated the strength of thin-film solar cells using a three-point bending rupture test analysis.

The fracture limit (P_C) of a plate is expressed as

$$P_C = \frac{2W\zeta t^2}{3L}, \quad (1)$$

where W is the cell width, L is the cell length, ζ is the stress limit of silicon, and t is the substrate thickness. Although the fracture limit of the supporting frame shown in Fig. 1 has a complicated form, the strength of the plate must be proportional to the area of the frame as a first approximation. Moreover, in the case of a synthesized structure (a thin film is mounted on a thick substrate), if the film is sufficiently thin compared to the substrate, the stress caused by the thin film is negligible in this calculation. Considering these assumptions, Fig. 4 shows the results of the allowable area of the opening for handling during fabrication as a function of

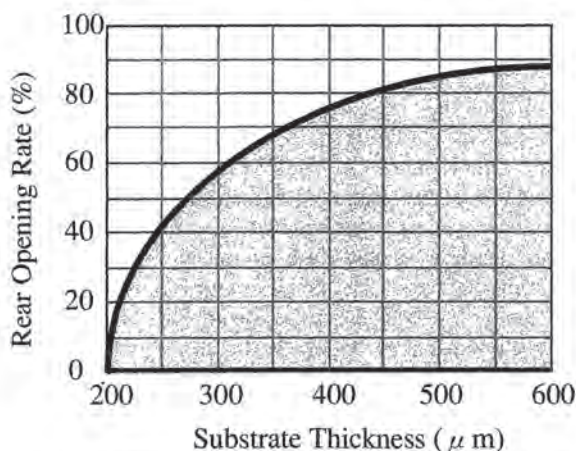


Fig. 4. Calculated possible rear opening area as a function of substrate thickness. Shaded part indicates possible range for handling.

the substrate thickness. The curve indicates that the strength of the cell is equal to that of the 200- μm -thick wafer. For example, the result shows that 84% of the area can be opened for a 600- μm -thick substrate. The shaded part shows the possible range for handling. Equation (1) suggests that the strength of the cell is proportional to the square of the substrate thickness; thus it is advantageous to employ a thicker substrate.

Now we consider the pattern of the frame. Possible basic patterns are honeycomb, circle and grid. In the case of a honeycomb pattern, it is flexible in the transverse direction, resulting in higher stress on the thin film. A circular pattern cannot achieve high packing density, resulting in a small area of the opening. Therefore we concluded that the simple grid pattern is suitable for thin-film solar cells.

2.4 Electrical power losses

As shown in Fig. 5, carriers generated at the upper part of the frame travel laterally to the rear electrode at the opening through a BSF layer, causing electric power loss. We calculate this power loss approximately using

$$P_{\text{loss}} = 8 \left(\frac{W}{L_f} \right)^2 \int_0^{W/2} \left(J_{\text{ph}} \cdot x \cdot \frac{L_f}{2} \right) \cdot \frac{\rho_{\text{BSF}}}{d_{\text{BSF}} \cdot \frac{L_f}{2}} dx$$

$$= \frac{J_{\text{ph}}^2 \cdot W^2 \cdot W_f^2 \cdot \rho_{\text{BSF}}}{6 \cdot L_f \cdot d_{\text{BSF}}}, \quad (2)$$

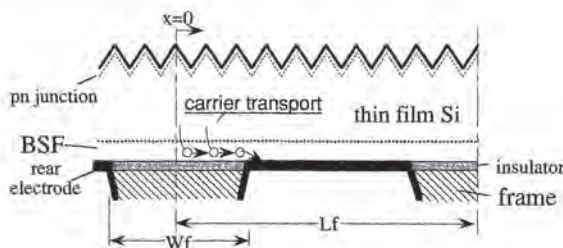


Fig. 5. Schematic of the generated carrier transport through the BSF layer on the upper part of the frame.

where W_f is the width of the frame, L_f is the center-to-center spacing of frames, W is the cell size, ρ_{BSF} is the resistivity of BSF, d_{BSF} is thickness of BSF and J_{ph} is short-circuit electric current density.

Figure 6 shows calculated results of electrical power loss as a function of the rate of the opening area for two

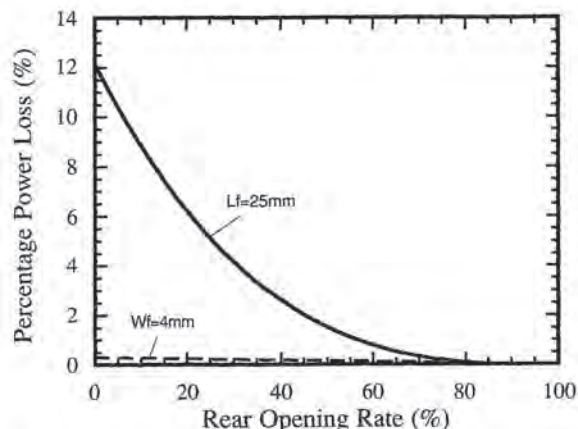


Fig. 6. Calculated power loss as a function of the rate of the rear opening area.

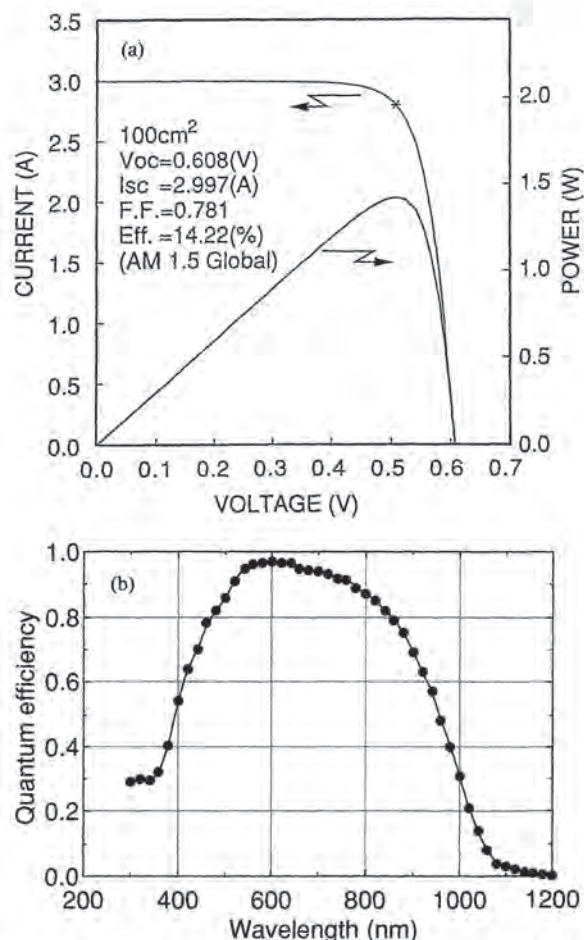


Fig. 7. I - V characteristics (a) and spectral response (b) of a thin-film silicon solar cell with a cell size of $10 \times 10 \text{ cm}^2$ under simulated AM1.5, 100 mW/cm^2 .

cases: one with the width of the frame (W_f) fixed at 4 mm and the other with the center-to-center spacing (L_f) fixed at 25 mm. In this calculation, $\rho_{BSF}=10^{-3} \Omega \cdot \text{cm}$, $d_{BSF}=3 \mu\text{m}$, $W=10 \text{ cm}$ and $J_{ph}=35 \text{ mA/cm}^2$ are assumed. The decrease of the opening area leads to the increase of power loss. The large power loss at the region of the small opening area for $L_f=25 \text{ mm}$ indicates that a wide W_f of more than 4 mm generates large power loss. Equation (2) indicates that the power loss is proportional to the third power of W_f . Then, the power loss increases drastically with wider W_f , which is equal to longer carrier transport distance. Therefore, in order to decrease the power loss, a slender frame with many lines is advantageous over a wide frame with few lines for the same area of the opening.

2.5 Fabrication of solar cells

Applying the results from the above sections, we have fabricated a thin-film silicon solar cell. Since it was the first fabrication of this type of cell, not all parameters could not be optimized in this study. Fabricated cell parameters were as follows: 600- μm -thick silicon substrate, ITO (900 Å)/Ag rear electrode at the openings, SiO_2 layer as an insulator (1 μm thick), $W_f=4 \text{ mm}$, $L_f=25 \text{ mm}$, and rate of the opening area was 60%. As shown in Fig. 7(a), a high efficiency of 14.2% can be obtained with the new thin-film solar cell having an area of $10 \times 10 \text{ cm}^2$ and high quantum efficiency at a longer wavelength of the 60 μm thin-film silicon solar cell (Fig. 7(b)).

3. Conclusions

The light-trapping structure of the thin-film silicon solar cell has been studied by considering the mechanical strength, the electrical power loss and the rear surface light reflections at both the opening and the frame. At the rear opening, very high reflectance (98.5%) can be obtained by inserting a transparent conductive ITO film between the Si and rear Ag metal without an increase of electrical power loss. At the upper part of the

supporting frame, a high reflectance (51%) can be obtained using a SiO_2 layer with low refractive index as an insulator by optimizing its thickness. The limit of the area of the rear opening is determined by the limit of the mechanical strength. A thicker substrate leads to fewer occurrences of cell fracture, because cell strength is proportional to the square of the substrate thickness. A simple grid pattern is suitable for the rear frame, leading to low damage of the thin film and a wide opening area. Electrical power loss due to current flow through a BSF layer can be suppressed by using a slender frame rather than a wide one, because the power loss is proportional to the third power of the carrier transport distance. A high efficiency of 14.2% for a practical size of $10 \times 10 \text{ cm}^2$ is obtained in a cell fabrication applying these calculated parameters.

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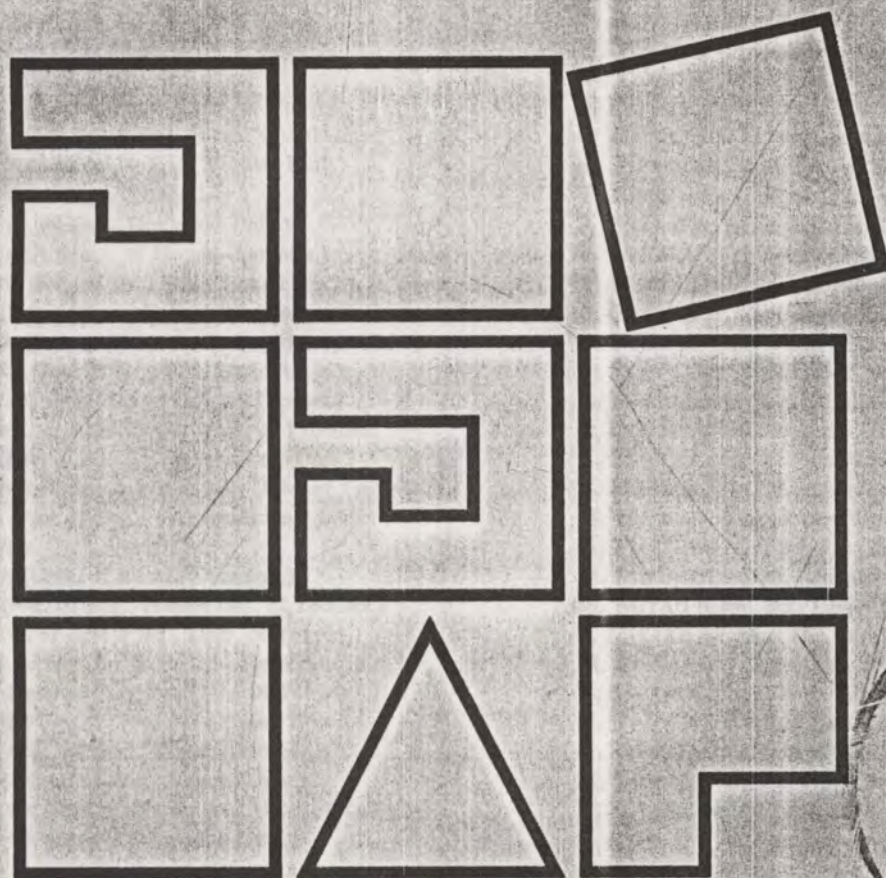
- 1) T. L. Chu, S. S. Chu and E. D. Stokes: *Sol. Energy Mater.* **2** (1979/1980) 265.
- 2) C. L. Kendall, J. C. Checchi, M. L. Lock, R. B. Hall and A. M. Barnett: *Proc. 21st IEEE Photovoltaic Specialists Conf., Florida, 1990* (IEEE, New York, 1990) p. 604.
- 3) J. A. Rand, R. B. Hall and A. M. Barnett: *Proc. 9th E.C. Photovoltaic Solar Energy Conf., Freiburg, 1989* (Kluwer Academic Publishers, Dordrecht, 1989) p. 309.
- 4) T. Ishihara, S. Arimoto, H. Morikawa, H. Kumabe, T. Murotani and S. Mitsui: *Appl. Phys. Lett.* **63** (1993) 3604.
- 5) T. Ishihara: in preparation for publication.
- 6) P. Campbell and M. A. Green: *J. Appl. Phys.* **62** (1987) 243.
- 7) A. Goetzberger: *Proc. 15th IEEE Photovoltaic Specialists Conf., Florida, 1981* (IEEE, New York, 1981) p. 867.
- 8) M. Born and E. Wolf: *Principles of Optics* (Pergamon, New York, 1964) Chap. 4.8, p. 69.
- 9) J. Zhao and M. A. Green: *IEEE Trans. Electron Devices* **ED-38** (1991) 1925.

ATTACHMENT E-2

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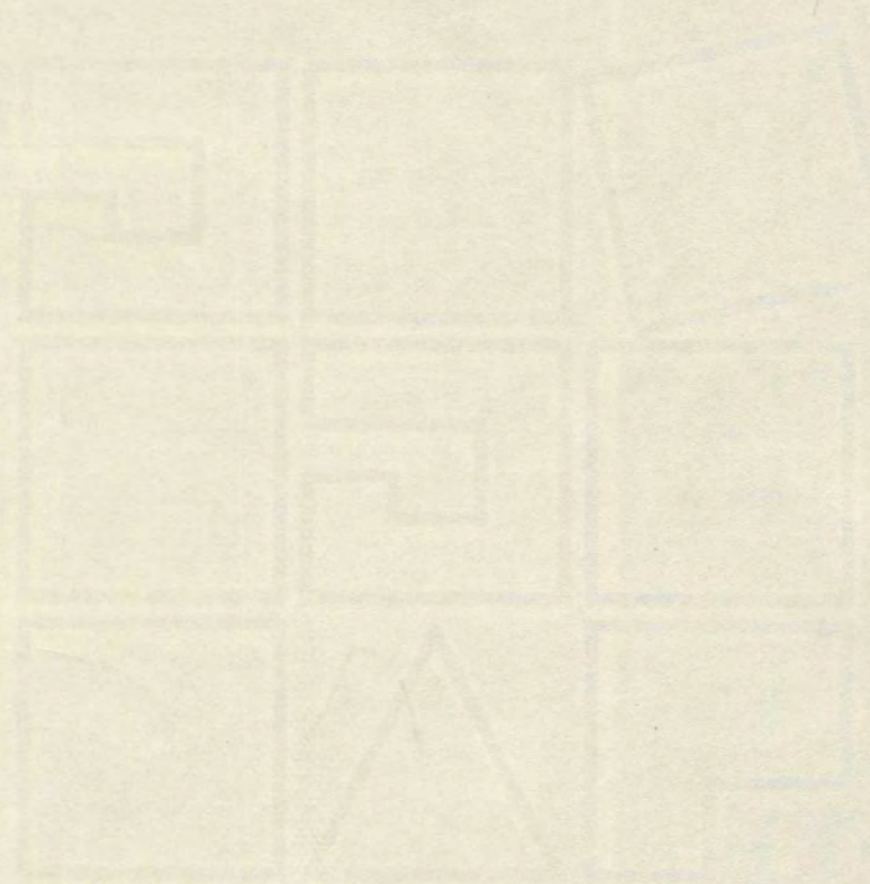
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CONTENTS

Semiconductors

- Analysis of Deposits Evaporated from Sb-Doped Si Melts 3305 Xinming HUANG, Kazutaka TERASHIMA, Eiji TOKIZAKI, Hitoshi SASAKI and Shigeyuki KIMURA
- Reabsorption of Visible Luminescence in Porous Si 3310 Kazuro MURAYAMA, Seiichi MIYAZAKI and Masataka HIROSE
- Third-Order Piezoresistance Coefficients in p-Type Si 3314 Yamichi OHMURA
- Formation Kinetics and Infrared Absorption of Carbon-Oxygen Complexes in Czochralski Silicon 3319 Hideki YAMANAKA
- Defects in SiO₂/Si Structures Probed by Using a Monoenergetic Positron Beam 3330 Akira UEDONO, Long WEI, Shoichiro TANIGAWA and Yuzuru OHJI
- Confirmation of Aluminum-Induced Negative Charge in Thermally Oxidized Silicon Wafers Using AC Surface Photovoltage Method 3335 Hirofumi SHIMIZU and Chusuke MUNAKATA
- Detection of Intermediates in Thermal Chemical Vapor Deposition Process Using Tetraethoxysilane 3339 Tetsuya SATAKE, Tetsuji SORITA, Hirofumi FUJIOKA, Hiroshi ADACHI and Hiroyuki NAKAJIMA
- High-Performance In_{0.3}Ga_{0.7}As/In_{0.29}Al_{0.71}As/GaAs Metamorphic High-Electron-Mobility Transistor 3343 Pascal WIN, Yves DRUELLE, Yvon CORDIER, Didier ADAM, Jacques FAVRE and Alain CAPPY
- Passivation of Shallow and Deep Levels by Hydrogen Plasma Exposure in AlGaAs Grown by Molecular Beam Epitaxy 3348 Antonio BOSACCHI, Secondo FRANCHI, Enos GOMBIA, Roberto MOSCA, Alberto BIGNAZZI, Emanuele GRILLI, Mario GUZZI and Riccardo ZAMBONI
- V/III Flux Ratio Dependence of InAs Epilayers Grown on GaAs Substrates by Molecular Beam Epitaxy 3354 Kotaro OKAMOTO and Ryoji HANANOKI
- Doping Properties of Zinc in InAlGaAs Grown by Low-Pressure Metal-Organic Vapor-Phase Epitaxy 3359 Masayoshi TSUJI, Kikuo MAKITA and Kenko TAGUCHI
- Analysis of P and Sb Diffusion during Thermal Oxidation in Silicon 3362 Takahisa OKINO and Masami ONISHI
- Reduction Mechanism of Threading Dislocation Density in GaAs Epilayer Grown on Si Substrate by High-Temperature Annealing 3368 Yasufumi TAKAGI, Hiroo YONEZU, Yoshiaki HACHIYA and Kangsa PAK
- Alloyed and Non-Alloyed Ohmic Contacts for AlInAs/InGaAs High Electron Mobility Transistors 3373 Naohito YOSHIDA, Yoshitsugu YAMAMOTO, Hirozou TAKANO, Takuji SONODA, Saburo TAKAMIYA and Shigeru MITSUI
- Changes in Collector and Base Currents for AlGaAs/GaAs Heterojunction Bipolar Transistors 3377 Norio IIZUKA, Tohru SUGIYAMA and Masao OBARA
- Properties of Sputter-Deposited CdS/CdTe Heterojunction Photodiode 3383 Yasuhiro TOMITA, Toshiaki KAWAI and Yoshinori HATANAKA
- Light Trapping for Thin-Film Silicon Solar Cells Fabricated on Insulator 3389 Hajime SASAKI, Hiroaki MORIKAWA, Yoshinori MATSUNO, Mikio DEGUCHI, Takashi ISHIHARA, Hisao KUMABE, Toshio MUROTANI and Shigeru MITSUI
- Optical Beam Induced Current Techniques for Failure Analysis of Very Large Scale Integrated Circuits Devices 3393 Hirotaka KOMODA and Katsusuke SHIMIZU
- Low-Temperature Formation of Palladium Silicided Shallow p⁺n Junctions Using Implant through Metal Technology 3402 Cheng-Tung LIN, Pei-Fen CHOU and Huang-Chung CHENG
- Homogeneous Nucleation of Misfit Dislocations in Strained Layers 3409 Hyo-Hoon PARK and Jeong Yong LEE
- Formation of Cubic GaN on (111)B GaAs by Metal-Organic Vapor-Phase Epitaxy with Dimethylhydrazine (Short Note) 3415 Noriyuki KUWANO, Kenki KOBAYASHI, Kensuke OKI, Seiro MIYOSHI, Hiroyuki YAGUCHI, Kentaro ONABE and Yasuhiro SHIRAKI
- Kinetic Study of Metallic Silver Photoinduced Surface Deposition Phenomenon (Short Note) 3417 Takeshi KAWAGUCHI and Shigeo MARUNO

Superconductors

- Critical Current Dependence on Deformation Kinetics in Textured YBa₂Cu₃O_x Superconductor 3419 Youhe ZHANG, Venkat SELVAMANICKAM, Dominic F. LEE and Kamel SALAMA
- Observations of Structure, Phase and Composition on Unidirectional Solidified Y-Ba-Cu-O Samples 3424 Jun-ichiro KASE, Jun-ichi SHIMOYAMA, Eiji YANAGISAWA and Takeshi MORIMOTO
- Characterization by Chemical Etching for Superconducting Bi₂Sr₂CaCu₂O₈ Crystals Grown by CO₂-Laser Melting 3429 Katsuei ISHIDA, Takuya TSUTSUMI, Masamori IIDA, Ichiroh NAKADA and Kazuo KURODA
- Fabrication and Characterization of Nb-(Nb Nanoconstrictions)-NbN Short Weak Links 3435 Hiroya ABE, Katuyoshi HAMASAKI, Kazuaki KOJIMA and Masayuki SASAKI

Magnetism

- Coercivity of Melt-Spun Nd-Fe-B-Ti Alloys with Large Volume Fraction of Free-Iron Dispersoid 3443 June-Min YAO, Tsung-Shune CHIN, Cheng-Hao LIN and Tsung-Yao CHU

Alignment of Crystallites in Obliquely Deposited Cobalt Films	3448	Kazuhiro HARA, Kikuo ITOH, Masao KAMIYA, Hiroshi FUJIWARA, Kunito OKAMOTO and Takashi HASHIMOTO
Optics and Quantum Electronics		
Positive- and Negative-Image Processings Based on Photoinduced Anisotropy in Methylred-doped Polyvinyl Alcohol Film	3453	Tomoaki TAKEDA, Hirofumi FUJIWARA and Kazuo NAKAGAWA
Harmonics of Thomson Backscattered X-Rays	3459	Jizhong CHEN, Masayuki FUJITA, Kazuo IMASAKI, Chiyoe YAMANAKA, Makoto ASAKAWA, Tatsuya YAMAMOTO, Sadao NAKAI and Takashi ASAKUMA
Ionization Energy Levels of Divalent Cations and Transition Metal Cations in $Y_3Fe_5O_{12}$ Single Crystals	3464	Yasunori FURUKAWA, Masayoshi SATO and Steven A. MARKGRAF
Analysis of Charge-Controlled Gray Scale in Ferroelectric Liquid Crystal Optically Addressed Spatial Light Modulator	3469	Yukio TANAKA, Akio TAKIMOTO and Hisahito OGAWA
Waveguiding Characteristics of Optical Waveguide with Claddings Having Negative Nonlinear Refractive Coefficient (Short Note)	3478	Shigeaki OHKE, Yutaka SATOMURA, Tokuo UMEDA and Yoshio CHO
Electrical Properties of Condensed Matter		
Deep Impurity Centers in CdS Single Crystals Studied by Spectral Analysis of Deep Level Transient Spectroscopy (Short Note)	3480	Junya YOSHINO, Kazuyoshi TANAKA, Yoichi OKAMOTO, Jun MORIMOTO and Toru MIYAKAWA
Structure and Mechanical and Thermal Properties of Condensed Matter		
Determination of Rotational Viscosity of Nematic Liquid Crystals from Transient Current: Numerical Analysis and Experiment	3482	Masahiro IMAI, Hiroyoshi NAITO, Masahiro OKUDA and Akihiko SUGIMURA
X-Ray Photoelectron Spectroscopy and X-Ray Absorption Near Edge Structure Study of Structural Change of Perhydropolysilazane to Silicon Nitride by Heat Treatment	3488	Yasuharu YOKOYAMA, Kazunaga HORIUCHI, Tsugio MAESHIMA and Toshiaki OHTA
Crystallization and Growth Process of Lead Titanate Fine Particles from Alkoxide-Prepared Powders	3495	Kenji ISHIKAWA, Nagaya OKADA, Kazumasa TAKADA, Takashi NOMURA and Minoru HAGINO
Low-Temperature Selective Epitaxial Growth of GaAs Using Triethylgallium and Amino-As in Metalorganic Molecular Beam Epitaxy	3500	Tadachika HIDAKA and Ikuo SUEMUNE
Gas Source Molecular Beam Epitaxial Growth of ZnSe Using Metal Zn and H_2Se	3505	Masayuki IMAIZUMI, Yasuyuki ENDOH, Ken-ichi OHTSUKA and Toshiro ISU
Growth and Characterization of $K_3Li_{2-x}Nb_{5+x}O_{15+2x}$ Micro Single Crystals Formed by the μ -Pulling Down Method for Blue SHG Applications	3510	Dae-Ho YOON, Makiko HASHIMOTO and Tsuguo FUKUDA
Surface Wave Measurements during Gelation Process of Tungstic Acid	3514	Kazuhiro MOTONAGA, Hirotaka OKABE, Kazuhiro HARA and Kazumi MATSUSHIGE
Stroboscopic Observation in Antiferroelectric Liquid Crystals under Application of Very Short Reverse Pulse Voltage (Short Note)	3518	Hiroyuki OKADA, Manabu WATANABE, Hiroyoshi ONNAGAWA and Kazuo MIYASHITA
Surfaces, Interfaces, and Films		
Remote Plasma SiO_2 Deposition by Tetraethoxysilane with Chemical-ly and Energetically Different Atomic Species	3520	Sunil WICKRAMANAYAKA, Akinori MATSUMOTO, Yoichiro NAKANISHI, Naokichi HOSOKAWA and Yoshinori HATANAKA
Preparation of Oriented Large Domains of Diacetylene Monolayer at the Air-Water Interface	3528	Susumu YAMADA, Eiji HATTA and Kōichi MUKASA
$ZrAl_3$ Intermetallic Compound Thin Film as a Diffusion Barrier between Al and Au Layers	3531	Jin-Kuo HO and Kwang-Lung LIN
Step Structure Transformation Induced by DC on Vicinal Si(111)	3538	Akiko NATORI
Ge Epitaxial Overlayers on Si(001) Studied by Surface-Sensitive X-Ray Absorption Fine Structure: Evidence for Strain-Induced Surface Rearrangement	3545	Hiroyuki OYANAGI, Kunihiro SAKAMOTO, Ryu SHIODA and Tsunenori SAKAMOTO
Crystallographic Investigation of Columnar Grain Structure in Obliquely Deposited Fe-Co Films	3553	Takashi HASHIMOTO, Kunito OKAMOTO, Hiroshi FUJIWARA, Kikuo ITOH, Masao KAMIYA and Kazuhiro HARA
Asymmetric Thin Film of Poly(<i>p</i> -phenylene) Prepared by Vacuum Deposition	3558	Toshihide ASAKURA and Naoki TOSHIMA
Ion-Assisted Crystal Growth by Post Irradiation as Applied to Nitride Formation	3566	Kyung-youll MIN, Masayoshi TARUTANI, Masahiko INOUE and Ryuichi SHIMIZU
Emission Energy Shift in GaInAs/GaInAsP Strained Quantum-Box Structures Due to 0-Dimensional Quantum-Box Effect	3571	Hideki HIRAYAMA, Kazuhisa MATSUNAGA, Masahiro ASADA, Tsukasa KAKINUMA and Machiya KUMAZAWA
Nuclear Science, Plasmas, and Electric Discharges		
Plasma-Sheath Boundary in Plasmas Containing Thermal and Beam Electrons	3578	James W. BRADLEY and Hiroshi AMEMIYA
Removal Conditions of Films Deposited on Probe Surface	3586	Isamu KATO, Tsuyoshi SHIMODA and Toshihiro YAMAGISHI
Measurement of Anisotropic Soft X-Ray Emission during Radio-Frequency Current Drive in the JFT-2M Tokamak	3590	Hisato KAWASHIMA, Mitsuru HASEGAWA, Gerhard FUCHS, Tohru MATOBA, Yoshihiko UESUGI, Katsumichi HOSHINO, Tomohide KAWAKAMI and Takumi YAMAMOTO

Atoms, Molecules, and Chemical Physics

- Electrical Conduction by Percolation Process in Insulating Polymer Containing Small Amount of Conducting Polymer 3597 Xiao Hong YIN, Katsumi YOSHINO, Hideo YAMAMOTO, Toshiro WATANUKI, Isao ISA, Shinichi NAKAGAWA and Mikio ADACHI
- Cross Section Measurements for Electron-Impact Dissociation of CHF_3 into Neutral and Ionic Radicals 3602 Masashi GOTO, Keiji NAKAMURA, Hirotaka TOYODA and Hideo SUGAI
- Plasma Cleaning and Etching Using Quartz Bell Jar with SnO_2 Transparent Thin-Film Heater in CHF_3 - SiO_2 Microwave Etching System 3608 Seiichi WATANABE

Instrumentation, Measurement, and Fabrication Technology

- Microwave Measurements of Low Pulp Concentration in Papermaking Process 3614 Shigeru NAKAYAMA
- Modified Lumped Parameter Method for Measurements of Dielectric Susceptibility in Ferroelectrics 3617 Shaoping LI, Jyh SHEEN, Sei-Joo JANG, Amar S. BHALLA, Robert E. NEWNHAM and L. Eric CROSS
- Energy Spectra of Displaced Atoms in High-Energy Electron-Irradiated Si: Views on Electron Beam Doping and Damage Factor 3622 Kyoichiro YASUDA and Takao WADA
- Effect of III/V-Compound Epitaxy on Si Metal-Oxide-Semiconductor Circuits 3628 Andreas LUBNOW, Guang-Ping TANG, Hergo-Heinrich WEHMANN, Erwin PEINER and Andreas SCHLACHETZKI
- Blister Formation at Photoresist-Substrate Interface 3635 Hitoshi NAGATA, Akira KAWAI, Hiroaki MORIMOTO and Masasuke TAKATA
- New Silylation Bi-layer Resist System Employing Photochemical Selective Resist Silylation 3640 Yoshiaki MIMURA and Isamu KOTAKA

Cross-Disciplinary Areas

- Effects of External Body Accelerations on Blood Flow 3648 Lalit M. SRIVASTAVA, U. E. EDEMEKA and Vijai P. SRIVASTAVA

Cumulative Author Index of Volume 33, 1994, Part 1

v

Contents of Oyo Buturi

xv

Contents of Journal of the Physical Society of Japan

xvi

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xix

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Light Trapping for Thin-Film Silicon Solar Cells Fabricated on Insulator

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We have developed a new solar cell using thin-film silicon supported by a silicon substrate etched in a grid form. The light-trapping structures of this cell have been studied by considering rear surface light reflections, electrical power loss and mechanical strength. High rear reflectance can be obtained by employing a multi-layer rear electrode. The pattern of the rear substrate is designed to provide sufficient mechanical strength and to minimize the electrical power loss, taking account of the current flow path. A conversion efficiency of 14.2% for a practical size of $10 \times 10 \text{ cm}^2$ is obtained by applying these calculated parameters using a single-crystal silicon substrate.

KEYWORDS: thin-film silicon solar cell, light trapping, light reflection, silicon on insulator, zone melting recrystallization

1. Introduction

Many types of thin-film silicon solar cells have been developed over the last 15 years, because of their potential to lower cost and provide higher efficiency. Chu *et al.*¹⁾ fabricated thin-film silicon solar cells on a carbon substrate with 9.75% efficiency for a small size of 9 cm^2 . Kendall *et al.*²⁾ reported cells with 10.9% efficiency for a practical cell size of 100 cm^2 on a conductive ceramic substrate.

For the realization of high conversion efficiency, highly efficient optical confinement and high crystal quality of silicon films are essential for thin-film solar cells. However, since the rear surface of conventional structures is entirely covered with the substrate, highly reflective structures at the rear surface might not be easily formed. There was an attempt to form a textured structure on the surface of the supporting substrate to increase total reflection,³⁾ but the process to form this structure resulted in high cost, and the rough substrate surface was disadvantageous for active layer formation.

The cells recently developed in our laboratory⁴⁾ have overcome these problems. The crystallographic quality of the thin-film active layer supported by an insulator-coated substrate is improved by the zone melting recrystallization (ZMR) method. The contact of the rear electrode is obtained by partial substrate etching, and this opening of the substrate makes it possible to form a highly reflective structure. This cell fabrication method and the structure will be described in detail elsewhere.⁵⁾

On the other hand, many studies have been made on optical confinement of conventional photovoltaic devices,^{6,7)} assuming a flat-plate wafer whose entire rear surface can be designed for optical trapping; however, since the rear structure of our cell is composed of both openings and frames, it requires a new analysis technique to determine its light-trapping ability. This paper is concerned with the design of a new type of thin-film silicon solar cells considering not only light trapping but also mechanical strength and electrical power loss. Finally, the performance of the thin-film silicon solar cell will be described.

2. Results and Discussion

Figure 1 shows the structure of the thin-film solar cell. The thin-film silicon active layer is formed by ZMR and epitaxial growth on an insulator-coated $\sim 600\text{-}\mu\text{m}$ -thick heat-resistive substrate. In this study, single-crystal silicon is used as a substrate. In order to obtain the rear contact and light reflection, partial openings are fabricated on the rear surface by selective etching of the substrate. The cell size is $10 \times 10 \text{ cm}^2$. Rear surface texturing is not performed in this study. The main points of the light-trapping design for this cell structure are as follows.

- Light reflection at the rear opening.
- Light reflection at the rear frame.
- Mechanical strength in handling.
- Electrical power loss at the upper part of the frame.

In order to fully utilize the rear light reflection, a larger area of the opening is desired. However, a larger area leads to decrease in mechanical strength. Consequently, items a)–d) require comprehensive optimization.

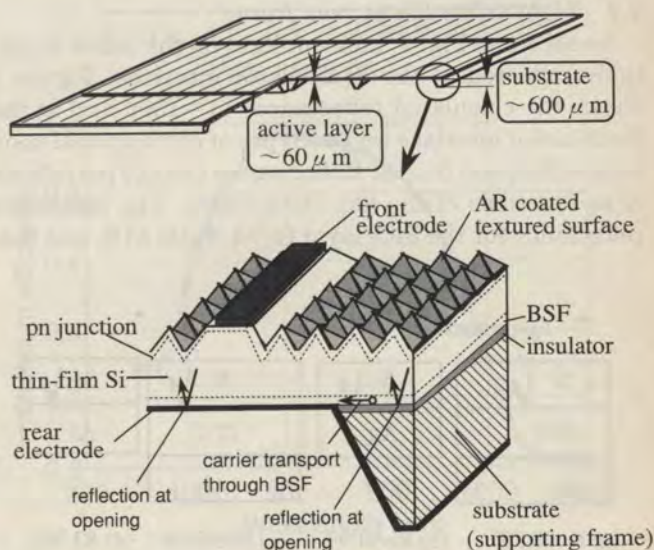


Fig. 1. Cell structure of thin-film silicon solar cell fabricated on insulator-coated substrate by zone melting recrystallization.

tion. From this point of view, each item above is discussed in the following sections.

2.1 Light reflection at rear opening

As shown in Fig. 1, this cell structure can be used to achieve high light reflectivity using rear surface treatments such as a textured structure or deposition of highly reflective metals. The requirements on the rear structure of the cell include high reflectivity as well as electrical conductivity. In order to realize reflectivity higher than that of conventional aluminum (Al) metal, we have adopted silver (Ag) metal and a transparent conductive indium tin oxide (ITO) film inserted between the thin Si film and Ag layer. This ITO film also plays the important role of an ohmic contact to the p^+ (BSF: back surface field) of the silicon film.

In Fig. 2, the results of the reflectance calculated at $\lambda=1000$ nm are shown, which includes the expected rear surface configuration for four different conditions. The matrix method^{8,9)} was used for the calculation, and calculated thickness of the ITO film was 900 Å. Comparing the result obtained using only Al film ($R=83.3\%$), the Ag film can increase the reflectance to $R=94.9\%$. Furthermore, insertion of the ITO film between Si and Ag makes it possible to obtain a sufficiently high reflectance of $R=98.5\%$. It is roughly estimated that the internal quantum efficiency, which is the light absorption, at $\lambda=1000$ nm is 0.319 ($R=0\%$), 0.525 ($R=94.9\%$) and 0.533 ($R=98.5\%$), and also that the enhancement of the short-circuit current density (J_{sc}) by the reflection of the rear electrode is 1.55 mA/cm² with Ag in comparison with the case of $R=0\%$, and is 1.6 mA/cm² with the ITO/Ag electrode. On the other hand, for low-cost fabrication (using the less-expensive Al electrode), insertion of the ITO film can improve the reflectance from $R=83.3\%$ to $R=95.2\%$. Since we have applied the ITO film, which has high electrical conductivity and high transparency as the inserted film, electrical and optical losses in the ITO layer are negligible.

2.2 Light reflection at rear frame

As shown in Fig. 1, incident light on the frame is partially reflected at the Si-insulator interface. Figure 3 shows the calculated reflectances ($\lambda=1000$ nm) at the Si-insulator interface for two types of conventional insulators (SiO_2 and Si_3N_4). Reflectances change periodically as functions of the film thicknesses. The maximum reflectance for the SiO_2 layer ($n=1.45$) is 51% and that

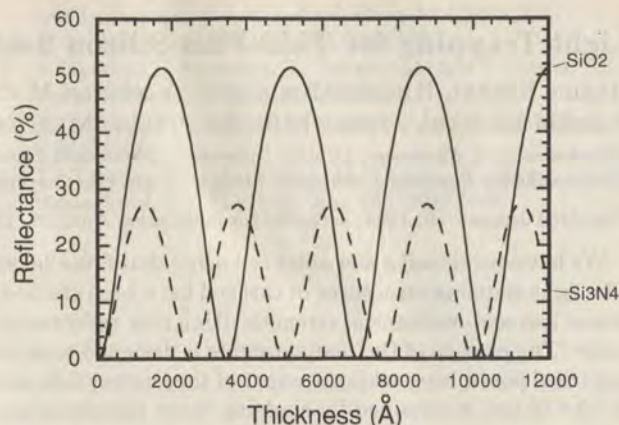


Fig. 3. Calculated reflectances at the upper part of the frame. Solid and dashed lines show reflectances of SiO_2 and Si_3N_4 , respectively.

for Si_3N_4 ($n=2.0$) is 28%. This is because the reflectance tends to be higher for a larger difference of refractive indices between the silicon and insulator than for a lower one. Therefore, SiO_2 is a better material for use as the insulator of the thin-film cell. If the material of the insulator can withstand the high-temperature ZMR process, air or highly reflective metals are more suitable than insulators to obtain higher reflection, because such materials have large refractive index differences with silicon. The calculated result shows the maximum reflectance of 51% for SiO_2 at thicknesses of about 1700 Å, 5200 Å, 8600 Å, and 12000 Å. In the case of thin films (less than 2000 Å), high-quality silicon film is difficult to obtain due to its tendency to aggregate or form holes in the insulator. On the other hand, thick films (more than 10000 Å) lead to more cracks or surface roughening, aside from their higher costs. Therefore, 5200 Å or 8600 Å is a suitable thickness for the insulator of this cell.

2.3 Mechanical strength

In industry, conventional solar cells use about 200- μm -thick silicon wafers with the size of 10 cm square because of the ease of wafer handling without wafer fracture. In this regard, we have evaluated the strength of thin-film solar cells using a three-point bending rupture test analysis.

The fracture limit (P_c) of a plate is expressed as

$$P_c = \frac{2W\zeta t^2}{3L}, \quad (1)$$

where W is the cell width, L is the cell length, ζ is the stress limit of silicon, and t is the substrate thickness. Although the fracture limit of the supporting frame shown in Fig. 1 has a complicated form, the strength of the plate must be proportional to the area of the frame as a first approximation. Moreover, in the case of a synthesized structure (a thin film is mounted on a thick substrate), if the film is sufficiently thin compared to the substrate, the stress caused by the thin film is negligible in this calculation. Considering these assumptions, Fig. 4 shows the results of the allowable area of the opening for handling during fabrication as a function of

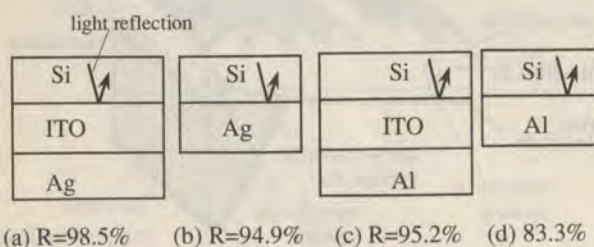


Fig. 2. Calculated reflectances for four different conditions of rear reflectors at opening.

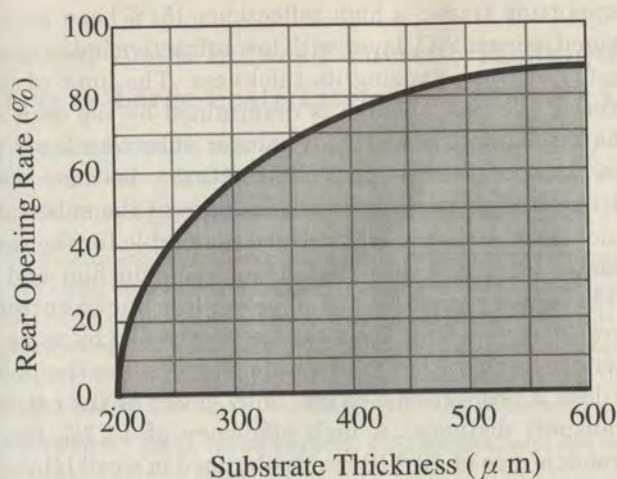


Fig. 4. Calculated possible rear opening area as a function of substrate thickness. Shaded part indicates possible range for handling.

the substrate thickness. The curve indicates that the strength of the cell is equal to that of the 200- μm -thick wafer. For example, the result shows that 84% of the area can be opened for a 600- μm -thick substrate. The shaded part shows the possible range for handling. Equation (1) suggests that the strength of the cell is proportional to the square of the substrate thickness; thus it is advantageous to employ a thicker substrate.

Now we consider the pattern of the frame. Possible basic patterns are honeycomb, circle and grid. In the case of a honeycomb pattern, it is flexible in the transverse direction, resulting in higher stress on the thin film. A circular pattern cannot achieve high packing density, resulting in a small area of the opening. Therefore we concluded that the simple grid pattern is suitable for thin-film solar cells.

2.4 Electrical power losses

As shown in Fig. 5, carriers generated at the upper part of the frame travel laterally to the rear electrode at the opening through a BSF layer, causing electric power loss. We calculate this power loss approximately using

$$P_{\text{loss}} = 8 \left(\frac{W}{L_f} \right)^2 \int_0^{W/2} \left(J_{\text{ph}} \cdot x \cdot \frac{L_f}{2} \right)^2 \cdot \frac{\rho_{\text{BSF}}}{d_{\text{BSF}} \cdot \frac{L_f}{2}} dx$$

$$= \frac{J_{\text{ph}}^2 \cdot W^2 \cdot W_f^3 \cdot \rho_{\text{BSF}}}{6 \cdot L_f \cdot d_{\text{BSF}}}, \quad (2)$$

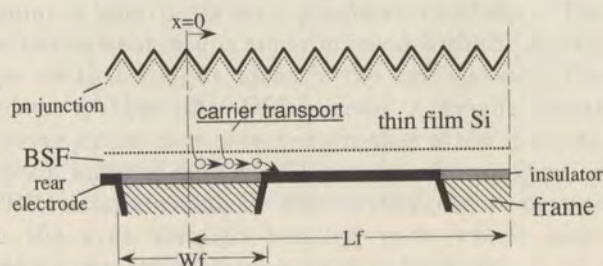


Fig. 5. Schematic of the generated carrier transport through the BSF layer on the upper part of the frame.

where W_f is the width of the frame, L_f is the center-to-center spacing of frames, W is the cell size, ρ_{BSF} is the resistivity of BSF, d_{BSF} is thickness of BSF and J_{ph} is short-circuit electric current density.

Figure 6 shows calculated results of electrical power loss as a function of the rate of the opening area for two

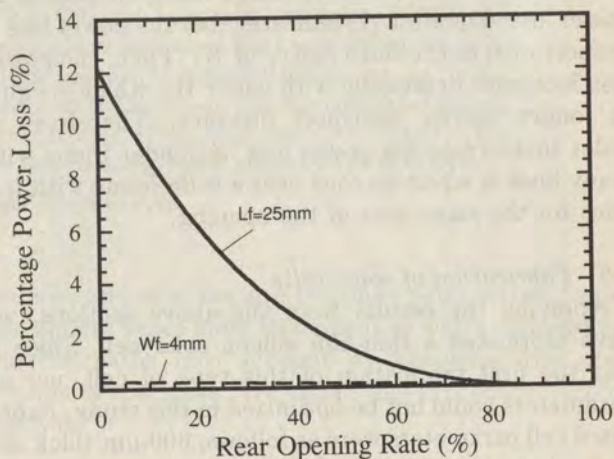


Fig. 6. Calculated power loss as a function of the rate of the rear opening area.

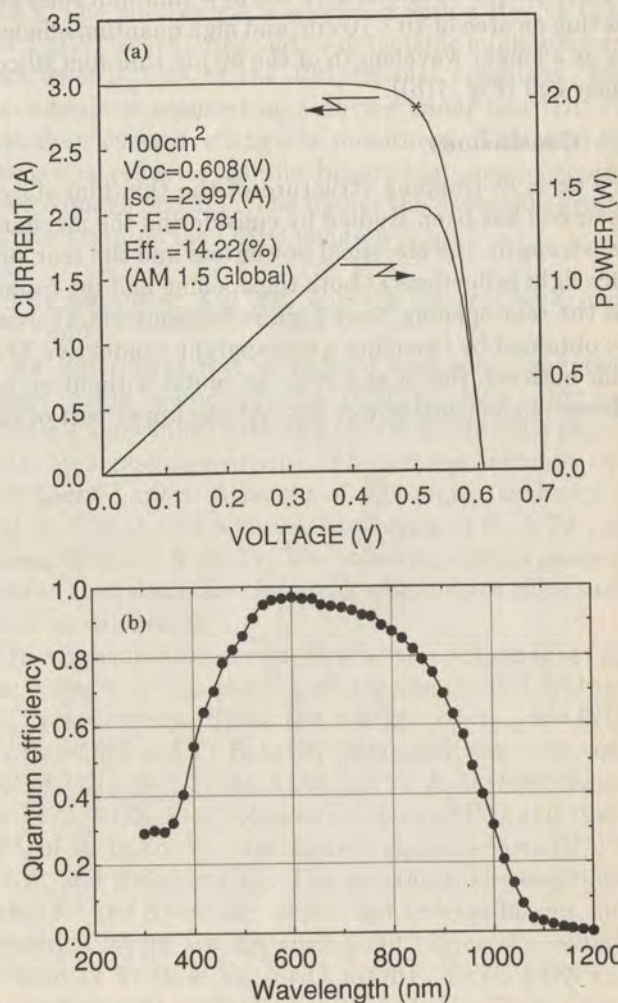


Fig. 7. I - V characteristics (a) and spectral response (b) of a thin-film silicon solar cell with a cell size of $10 \times 10 \text{ cm}^2$ under simulated AM1.5, 100 mW/cm^2 .

cases: one with the width of the frame (W_f) fixed at 4 mm and the other with the center-to-center spacing (L_f) fixed at 25 mm. In this calculation, $\rho_{BSF}=10^{-3} \Omega \cdot \text{cm}$, $d_{BSF}=3 \mu\text{m}$, $W=10 \text{ cm}$ and $J_{ph}=35 \text{ mA/cm}^2$ are assumed. The decrease of the opening area leads to the increase of power loss. The large power loss at the region of the small opening area for $L_f=25 \text{ mm}$ indicates that a wide W_f of more than 4 mm generates large power loss. Equation (2) indicates that the power loss is proportional to the third power of W_f . Then, the power loss increases drastically with wider W_f , which is equal to longer carrier transport distance. Therefore, in order to decrease the power loss, a slender frame with many lines is advantageous over a wide frame with few lines for the same area of the opening.

2.5 Fabrication of solar cells

Applying the results from the above sections, we have fabricated a thin-film silicon solar cell. Since it was the first fabrication of this type of cell, not all parameters could not be optimized in this study. Fabricated cell parameters were as follows: 600- μm -thick silicon substrate, ITO (900 Å)/Ag rear electrode at the openings, SiO_2 layer as an insulator (1 μm thick), $W_f=4 \text{ mm}$, $L_f=25 \text{ mm}$, and rate of the opening area was 60%. As shown in Fig. 7(a), a high efficiency of 14.2% can be obtained with the new thin-film solar cell having an area of $10 \times 10 \text{ cm}^2$ and high quantum efficiency at a longer wavelength of the 60 μm thin-film silicon solar cell (Fig. 7(b)).

3. Conclusions

The light-trapping structure of the thin-film silicon solar cell has been studied by considering the mechanical strength, the electrical power loss and the rear surface light reflections at both the opening and the frame. At the rear opening, very high reflectance (98.5%) can be obtained by inserting a transparent conductive ITO film between the Si and rear Ag metal without an increase of electrical power loss. At the upper part of the

supporting frame, a high reflectance (51%) can be obtained using a SiO_2 layer with low refractive index as an insulator by optimizing its thickness. The limit of the area of the rear opening is determined by the limit of the mechanical strength. A thicker substrate leads to fewer occurrences of cell fracture, because cell strength is proportional to the square of the substrate thickness. A simple grid pattern is suitable for the rear frame, leading to low damage of the thin film and a wide opening area. Electrical power loss due to current flow through a BSF layer can be suppressed by using a slender frame rather than a wide one, because the power loss is proportional to the third power of the carrier transport distance. A high efficiency of 14.2% for a practical size of $10 \times 10 \text{ cm}^2$ is obtained in a cell fabrication applying these calculated parameters.

Acknowledgement

This work is partly supported by New Energy and Industrial Technology Development Organization (NEDO) as a part of the New Sunshine Program under the Ministry of International Trade and Industry.

- 1) T. L. Chu, S. S. Chu and E. D. Stokes: *Sol. Energy Mater.* **2** (1979/1980) 265.
- 2) C. L. Kendall, J. C. Checchi, M. L. Lock, R. B. Hall and A. M. Barnett: *Proc. 21st IEEE Photovoltaic Specialists Conf., Florida, 1990* (IEEE, New York, 1990) p. 604.
- 3) J. A. Rand, R. B. Hall and A. M. Barnett: *Proc. 9th E.C. Photovoltaic Solar Energy Conf., Freiburg, 1989* (Kluwer Academic Publishers, Dordrecht, 1989) p. 309.
- 4) T. Ishihara, S. Arimoto, H. Morikawa, H. Kumabe, T. Murotani and S. Mitsui: *Appl. Phys. Lett.* **63** (1993) 3604.
- 5) T. Ishihara: in preparation for publication.
- 6) P. Campbell and M. A. Green: *J. Appl. Phys.* **62** (1987) 243.
- 7) A. Goetzberger: *Proc. 15th IEEE Photovoltaic Specialists Conf., Florida, 1981* (IEEE, New York, 1981) p. 867.
- 8) M. Born and E. Wolf: *Principles of Optics* (Pergamon, New York, 1964) Chap. 4.8, p. 69.
- 9) J. Zhao and M. A. Green: *IEEE Trans. Electron Devices* **ED-38** (1991) 1925.

ATTACHMENT E-3

Light Trapping for Thin-Film Silicon Solar Cells Fabricated on Insulator

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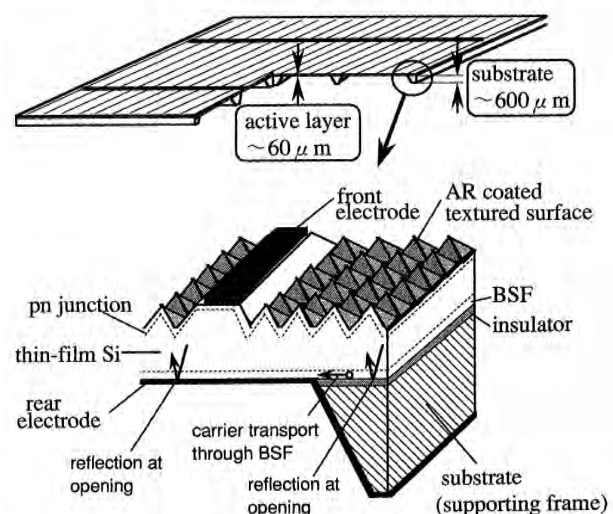


Fig. 1. Cell structure of thin-film silicon solar cell fabricated on insulator-coated substrate by zone melting recrystallization.

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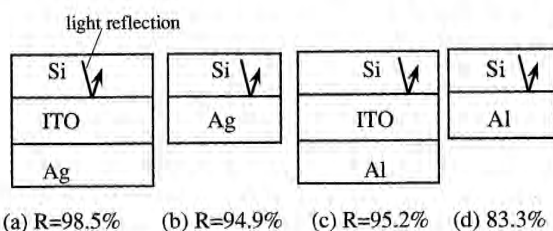


Fig. 2. Calculated reflectances for four different conditions of rear reflectors at opening.

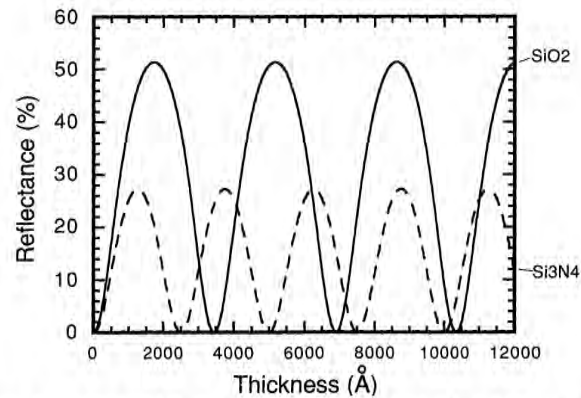


Fig. 3. Calculated reflectances at the upper part of the frame. Solid and dashed lines show reflectances of SiO_2 and Si_3N_4 , respectively.

for Si_3N_4 ($n=2.0$) is 28%. This is because the reflectance tends to be higher for a larger difference of refractive indices between the silicon and insulator than for a lower one. Therefore, SiO_2 is a better material for use as the insulator of the thin-film cell. If the material of the insulator can withstand the high-temperature ZMR process, air or highly reflective metals are more suitable than insulators to obtain higher reflection, because such materials have large refractive index differences with silicon. The calculated result shows the maximum reflectance of 51% for SiO_2 at thicknesses of about 1700 Å, 5200 Å, 8600 Å, and 12000 Å. In the case of thin films (less than 2000 Å), high-quality silicon film is difficult to obtain due to its tendency to aggregate or form holes in the insulator. On the other hand, thick films (more than 10000 Å) lead to more cracks or surface roughening, aside from their higher costs. Therefore, 5200 Å or 8600 Å is a suitable thickness for the insulator of this cell.

2.3 Mechanical strength

In industry, conventional solar cells use about 200- μm -thick silicon wafers with the size of 10 cm square because of the ease of wafer handling without wafer fracture. In this regard, we have evaluated the strength of thin-film solar cells using a three-point bending rupture test analysis.

The fracture limit (P_c) of a plate is expressed as

$$P_c = \frac{2W\zeta t^2}{3L}, \quad (1)$$

where W is the cell width, L is the cell length, ζ is the stress limit of silicon, and t is the substrate thickness. Although the fracture limit of the supporting frame shown in Fig. 1 has a complicated form, the strength of the plate must be proportional to the area of the frame as a first approximation. Moreover, in the case of a synthesized structure (a thin film is mounted on a thick substrate), if the film is sufficiently thin compared to the substrate, the stress caused by the thin film is negligible in this calculation. Considering these assumptions, Fig. 4 shows the results of the allowable area of the opening for handling during fabrication as a function of

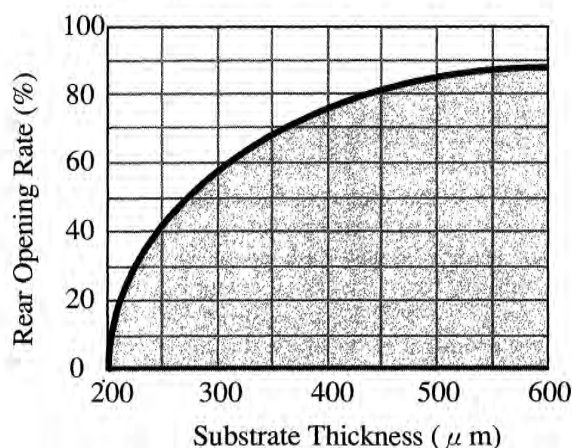


Fig. 4. Calculated possible rear opening area as a function of substrate thickness. Shaded part indicates possible range for handling.

the substrate thickness. The curve indicates that the strength of the cell is equal to that of the 200- μm -thick wafer. For example, the result shows that 84% of the area can be opened for a 600- μm -thick substrate. The shaded part shows the possible range for handling. Equation (1) suggests that the strength of the cell is proportional to the square of the substrate thickness; thus it is advantageous to employ a thicker substrate.

Now we consider the pattern of the frame. Possible basic patterns are honeycomb, circle and grid. In the case of a honeycomb pattern, it is flexible in the transverse direction, resulting in higher stress on the thin film. A circular pattern cannot achieve high packing density, resulting in a small area of the opening. Therefore we concluded that the simple grid pattern is suitable for thin-film solar cells.

2.4 Electrical power losses

As shown in Fig. 5, carriers generated at the upper part of the frame travel laterally to the rear electrode at the opening through a BSF layer, causing electric power loss. We calculate this power loss approximately using

$$P_{\text{loss}} = 8 \left(\frac{W}{L_f} \right)^2 \int_0^{W_f/2} \left(J_{\text{ph}} \cdot x \cdot \frac{L_f}{2} \right)^2 \cdot \frac{\rho_{\text{BSF}}}{d_{\text{BSF}} \cdot \frac{L_f}{2}} dx$$

$$= \frac{J_{\text{ph}}^2 \cdot W^2 \cdot W_f^3 \cdot \rho_{\text{BSF}}}{6 \cdot L_f \cdot d_{\text{BSF}}}, \quad (2)$$

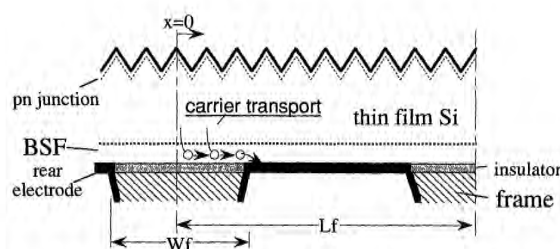


Fig. 5. Schematic of the generated carrier transport through the BSF layer on the upper part of the frame.

where W_f is the width of the frame, L_f is the center-to-center spacing of frames, W is the cell size, ρ_{BSF} is the resistivity of BSF, d_{BSF} is thickness of BSF and J_{ph} is short-circuit electric current density.

Figure 6 shows calculated results of electrical power loss as a function of the rate of the opening area for two

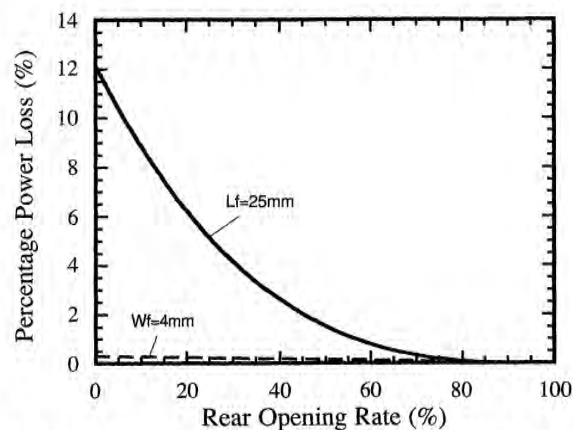


Fig. 6. Calculated power loss as a function of the rate of the rear opening area.

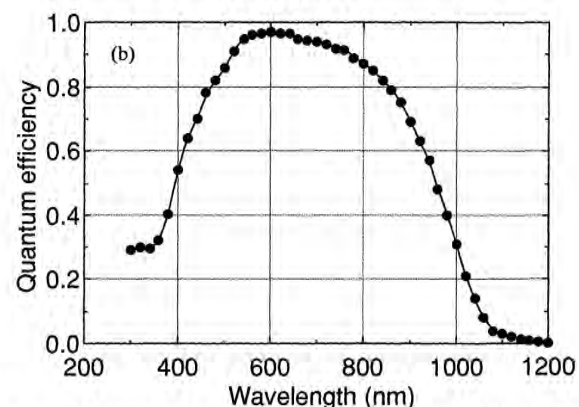
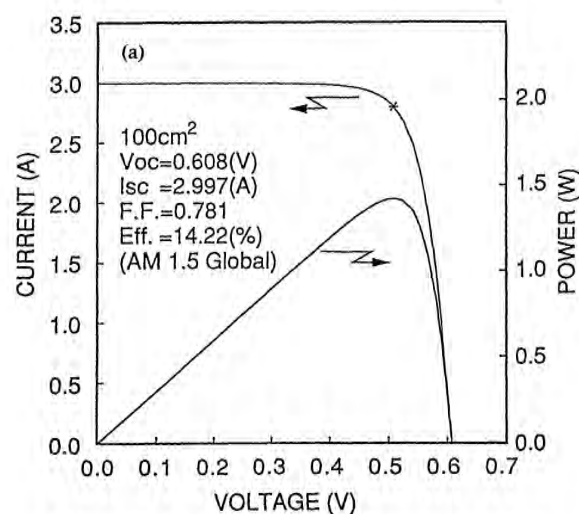


Fig. 7. I - V characteristics (a) and spectral response (b) of a thin-film silicon solar cell with a cell size of $10 \times 10 \text{ cm}^2$ under simulated AM1.5, 100 mW/cm^2 .

cases: one with the width of the frame (W_f) fixed at 4 mm and the other with the center-to-center spacing (L_f) fixed at 25 mm. In this calculation, $\rho_{BSF}=10^{-3} \Omega \cdot \text{cm}$, $d_{BSF}=3 \mu\text{m}$, $W=10 \text{ cm}$ and $J_{ph}=35 \text{ mA/cm}^2$ are assumed. The decrease of the opening area leads to the increase of power loss. The large power loss at the region of the small opening area for $L_f=25 \text{ mm}$ indicates that a wide W_f of more than 4 mm generates large power loss. Equation (2) indicates that the power loss is proportional to the third power of W_f . Then, the power loss increases drastically with wider W_f , which is equal to longer carrier transport distance. Therefore, in order to decrease the power loss, a slender frame with many lines is advantageous over a wide frame with few lines for the same area of the opening.

2.5 Fabrication of solar cells

Applying the results from the above sections, we have fabricated a thin-film silicon solar cell. Since it was the first fabrication of this type of cell, not all parameters could not be optimized in this study. Fabricated cell parameters were as follows: 600- μm -thick silicon substrate, ITO (900 Å)/Ag rear electrode at the openings, SiO_2 layer as an insulator (1 μm thick), $W_f=4 \text{ mm}$, $L_f=25 \text{ mm}$, and rate of the opening area was 60%. As shown in Fig. 7(a), a high efficiency of 14.2% can be obtained with the new thin-film solar cell having an area of $10 \times 10 \text{ cm}^2$ and high quantum efficiency at a longer wavelength of the 60 μm thin-film silicon solar cell (Fig. 7(b)).

3. Conclusions

The light-trapping structure of the thin-film silicon solar cell has been studied by considering the mechanical strength, the electrical power loss and the rear surface light reflections at both the opening and the frame. At the rear opening, very high reflectance (98.5%) can be obtained by inserting a transparent conductive ITO film between the Si and rear Ag metal without an increase of electrical power loss. At the upper part of the

supporting frame, a high reflectance (51%) can be obtained using a SiO_2 layer with low refractive index as an insulator by optimizing its thickness. The limit of the area of the rear opening is determined by the limit of the mechanical strength. A thicker substrate leads to fewer occurrences of cell fracture, because cell strength is proportional to the square of the substrate thickness. A simple grid pattern is suitable for the rear frame, leading to low damage of the thin film and a wide opening area. Electrical power loss due to current flow through a BSF layer can be suppressed by using a slender frame rather than a wide one, because the power loss is proportional to the third power of the carrier transport distance. A high efficiency of 14.2% for a practical size of $10 \times 10 \text{ cm}^2$ is obtained in a cell fabrication applying these calculated parameters.

Acknowledgement

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- 1) T. L. Chu, S. S. Chu and E. D. Stokes: *Sol. Energy Mater.* **2** (1979/1980) 265.
- 2) C. L. Kendall, J. C. Checchi, M. L. Lock, R. B. Hall and A. M. Barnett: *Proc. 21st IEEE Photovoltaic Specialists Conf., Florida, 1990* (IEEE, New York, 1990) p. 604.
- 3) J. A. Rand, R. B. Hall and A. M. Barnett: *Proc. 9th E.C. Photovoltaic Solar Energy Conf., Freiburg, 1989* (Kluwer Academic Publishers, Dordrecht, 1989) p. 309.
- 4) T. Ishihara, S. Arimoto, H. Morikawa, H. Kumabe, T. Murotani and S. Mitsui: *Appl. Phys. Lett.* **63** (1993) 3604.
- 5) T. Ishihara: in preparation for publication.
- 6) P. Campbell and M. A. Green: *J. Appl. Phys.* **62** (1987) 243.
- 7) A. Goetzberger: *Proc. 15th IEEE Photovoltaic Specialists Conf., Florida, 1981* (IEEE, New York, 1981) p. 867.
- 8) M. Born and E. Wolf: *Principles of Optics* (Pergamon, New York, 1964) Chap. 4.8, p. 69.
- 9) J. Zhao and M. A. Green: *IEEE Trans. Electron Devices* **ED-38** (1991) 1925.

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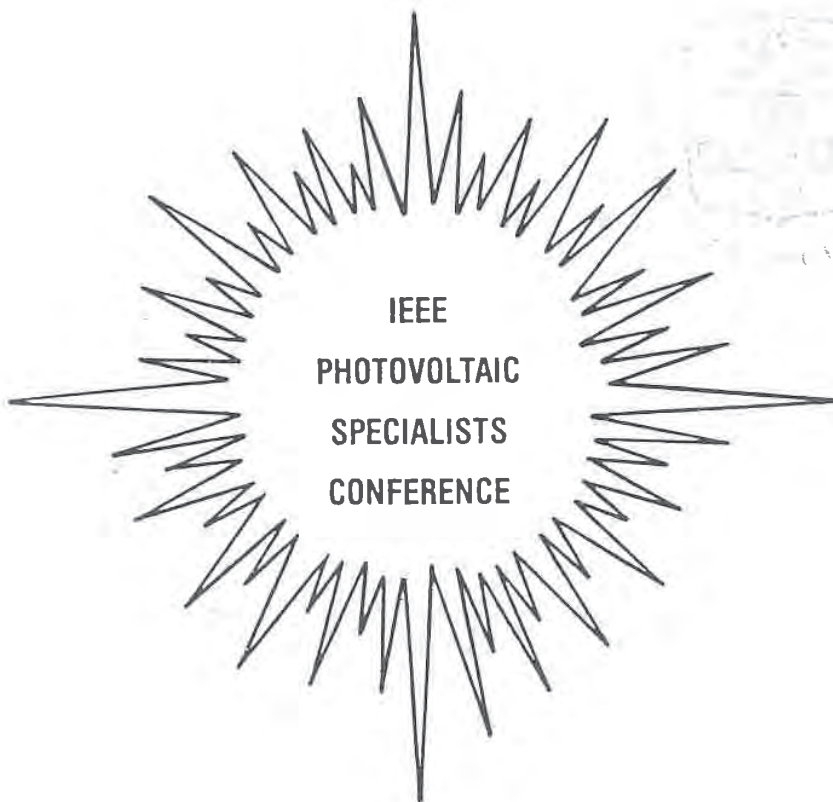
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TABLE OF CONTENTS

VOLUME I

William Cherry Award

Chairpersons:

J.D. Meakin

E.L. Ralph

Photovoltaics: Coming of Age

1

M.A. Green

High Efficiency Crystalline Cells and Materials

Overview of Recent Photovoltaic Developments

Chairperson:

J.D. Meakin

Organizer:

R.J. Schwartz

Photovoltaics: Meeting the Environmental Imperatives of Clean Air and Climate Change

9

W. Moomaw

Solar Photovoltaic Power: A U.S. Electric Utility R&D Perspective

16

E.A. DeMeo, F.R. Goodman, Jr., T.M. Peterson and J.C. Schaefer

Recent Advances in High Efficiency GaInP₂/GaAs Tandem Solar Cells

24

J.M. Olson, S.R. Kurtz, A. E. Kibbler and P. Faine

Photovoltaic Power for Space Station Freedom

30

C.R. Baraona

Advances in a-Si:H Alloys for High Efficiency Devices

36

A. Catalano

III-V Single and Multijunction Cells

Chairpersons:

S.P. Tobin

M. Yamaguchi

Organizer:

J.M. Gee

The Potential Performance of GaAs-Based Mechanically Stacked, Multijunction Solar Concentrator Cells

41

J.M. Gee and C.J. Chiang

Mechanically Stacked Two-Tandem Concentrator Solar Cell Concept

47

B. Beaumont, P. Garabedian, G. Nataf, J.C. Guillaume, P. Gibart and C. Verie

High-Efficiency GaAs/CuInSe₂ and AlGaAs/CuInSe₂ Thin-Film Tandem Solar Cells

53

R.P. Gale, R.W. McClelland, B.D. Dingle, J.V. Gormley, R.M. Burgess, N.P. Kim, R.A. Mickelsen and B.J. Stånbery

AlGaAs Top Solar Cell for Mechanical Attachment in a Multi-Junction Tandem Concentrator Solar Cell Stack

58

L.C. DiNetta, G.H. Negley, M.H. Hannon, J.R. Cummings, J.B. McNeely and A.M. Barnett

Monolithic Tandem Solar Cell Based on GaAlAs-GaAs System

64

L. Mayet, M. Gavand, B. Montégu, J.P. Boyeaux and A. Laugier

Graded-Band-Gap AlGaAs Solar Cells for AlGaAs/Ge Cascade Cells

68

M.L. Timmons, R. Venkatasubramanian, T.S. Colpitts, J.S. Hills, J.A. Hutchby, P.A. Iles and C.L. Chu

Development of Low Bandgap Ge and Si_{0.07}Ge_{0.93} Solar Cells for Monolithic and Mechanically-Stacked Cascade Applications

73

R. Venkatasubramanian, M.L. Timmons, R.T. Pickett, T.S. Colpitts, J.S. Hills, J.A. Hutchby, P.A. Iles and C.L. Chu

Large Scale, High Efficiency GaAs/Ge Cell Production

79

Y.C.M. Yeh, C. Cheng, F. Ho and H. Yoo

Large Area Shunt Defect Free GaAs Solar Cells

84

L.C. Kilmer and A.M. Barnett

A GaAs-ON-Si Solar Cell for Space Use

89

Y. Ohmachi, T. Ohara and Y. Kadota

New Results in Hetero-Epitaxy of GaAs/Ge/Si for High Efficiency in III-V Solar Cells on Low Cost Substrates

95

A. Leycuras, M.F. Vilela, J.C. Grenet, M. Leroux, G. Strobl, G. Neu and C. Verie

Back Contacted Emitter GaAs Solar Cells

99

G.L. Araujo, A. Marti and C. Algora

Application of InAlAs/GaAs Superlattice Alloys to GaAs Solar Cells

105

T.L. Drummond, J.M. Gee, F.L. Terry and R. Weng

Peeled Film GaAs Solar Cell Development

111

D.M. Wilt, R.D. Thomas, S.G. Bailey, G.A. Landis, D.J. Brinker, F.L. DeAngelo and N.S. Fatemi

An Evaporated Aluminum Metallization for High Efficiency GaAs Solar Cells

115

M. Ladle Ristow, M.S. Kuryla, H.F. MacMillan, N.R. Kaminar, G.F. Virshup, H.C. Hamaker, J.G. Werthen and K.A. Bertness

An Analysis of the Contact Sintering Process in III-V Solar Cells	119
V.G. Weizer and N.S. Fatemi	
Photovoltaic Characteristics of n⁺pp⁺InP Solar Cells by OMVPE	125
S. Tyagi, K. Singh, H. Bhimnathwala, S.K. Ghandhi and J.M. Borrego	
Study of Surface Passivation as a Function of InP Closed Ampoule Solar Cell Fabrication Processing Variables	130
Maria Faur, Mircea Faur, M. Goradia, C. Goradia, P. Jenkins, D. Jayne, S. Bailey and I. Weinberg	
High Efficiency GaAs Solar Cells Using GaInP₂ Window Layers	138
S.R. Kurtz, J.M. Olson and A.E. Kibbler	

LATE NEWS

Emitter Structures in MOCVD InP Solar Cells	141
C.J. Keavney, V.E. Haven and S.M. Vernon	
High Efficiency Thin Film GaAs Bifacial Solar Cells	145
R.W. McClelland, J.C.C. Fan, R.P. Gale and B.D. Dingle	
High Efficiency 1.0-eV GaInAs Bottom Solar Cell for 3-Junction Monolithic Stack	148
J.C. Schultz, M.E. Klausmeier-Brown, M.L. Ristow and M.M. Al-Jassim	

High Efficiency III-V Cells

Chairpersons:

J. Benner
C. Verie

Organizer:

J.M. Borrego

Buried Homo Junction Solar Cells Formed in p-InP During Sputter Deposition and Hydrogen Plasma Processing	153
T.A. Gessert, X. Li, M.W. Wanlass and T.J. Coutts	
Advances in High-Efficiency GaAs Solar Cells	158
S.P. Tobin, S.M. Vernon, S.J. Wojtczuk, C. Bajgar, M.M. Sanfalcon and T.M. Dixon	
High Efficiency GaAs and AlGaAs Solar Cells Grown by Molecular Beam Epitaxy	163
M.R. Melloch, S.P. Tobin, C. Bajgar T.B. Stellwag, A. Keshavarzi, M.S. Lundstrom and K. Emery	
High Voltage, Monolithically Interconnected GaAs Thin Film Solar Submodules	168
R.W. McClelland, B.D. Dingle, R.P. Gale and J.C.C. Fan	
Development of High-Performance GaInAsP Solar Cells for Tandem Solar Cell Applications	172
M.W. Wanlass, J.S. Ward, G.S. Horner, T.A. Gessert, K.A. Emery, T.J. Coutts, G.F. Virshup and M.L. Ristow	

27.6% (1-Sun, Air Mass 1.5 G) Monolithic Two-Junction AlGaAs/GaAs Solar Cell and 25% Three-Junction AlGaAs/GaAs/InGaAs Cascade Solar Cell	179
B.C. Chung, G.F. Virshup and J.C. Schultz	
Progress Toward a 30% Efficient, Monolithic, Three-Junction, Two-Terminal Concentrator Solar Cell for Space Applications	184
L.D. Partain, B.C. Chung, G.F. Virshup, J.C. Schultz, H.F. MacMillan, M. Ladle Ristow, M.S. Kuryla, K.A. Bertness, M.E. Klausmeyer-Brown, M.W. Wanlass and T.J. Coutts	
Over 35% Efficient GaAs/GaSb Stacked Concentrator Cell Assemblies for Terrestrial Applications	190
L.M. Fraas, J.E. Avery, V. Sundaram, V.T. Dinh, T.M. Davenport, J.W. Yerkes, J.M. Gee and K.A. Emery	

High Efficiency Solar Cells

Chairperson:

R.M. Swanson

Organizer:

P.A. Basore

A Review of Indium Phosphide Space Solar Cell Fabrication Technology	196
M.B. Spitzer, B. Dingle, J. Dingle and R. Morrison	
Recent Improvements in Silicon Solar Cell and Module Efficiency	207
M.A. Green, S.R. Wenham, J. Zhao, J. Zolper and A.W. Blakers	
Experimental Study of Solar Cell Performance Versus Dislocation Density	211
S.M. Vernon, S.P. Tobin, M. M. Al-Jassim, R.K. Ahrenkiel, K.M. Jones and B.M. Keyes	

Silicon Solar Cells

Chairpersons:

R. Mertens
D.R. Lillington

Organizer:

R.M. Swanson

Crystalline Photovoltaic Cell Research, Status and Future Direction	217
D.E. Hasti, D.L. King and J.D. McBrayer	
Cost Effectiveness of High Efficiency Cell Processes as Applied to Cast Polycrystalline Silicon	221
J.H. Wohlgemuth, S. Narayanan and R. Brenneman	
Passivated Emitters in Silicon Solar Cells	227
R.R. King, P.E. Gruenbaum, R.A. Sinton and R.M. Swanson	
Surface Passivation of High Efficiency Silicon Solar Cells	233
A. Aberle, W. Warta, J. Knobloch and B. Voss	

UV Radiation Hardness of Silicon Inversion Layer Solar Cells	239	The Effects of Different Diffusion Sources on Silicon Solar Cell Recombination Properties	311
R. Hezel		D.S. Ruby and J.D. McBrayer	
Polysilicon Emitters for Silicon Concentrator Solar Cells	245	Stable Passivations for High-Efficiency Silicon Solar Cells	317
J.-Y. Gan and R.M. Swanson		P.E. Gruenbaum, J.Y. Gan, R.R. King and R.M. Swanson	
Deeply-Grooved Silicon Concentrator Solar Cells for use with Prismatic Covers	251	Advancements in Silicon Buried Contact Solar Cells	323
J.S. Culik, E.L. Jackson and A.M. Barnett		S.R. Wenham, F. Zhang, C.M. Chong and M.A. Green	
Super Self-Aligned Technology for Backside Contact Solar Cells: A Route to Low Cost and High Efficiency	257	Point- and Planar-Junction PIN Silicon Solar Cells for Concentration Applications, Fabrication, Performance and Stability	327
P. Verlinden, B. Lafontaine, P. Jacquemin, E. Goutain and A. Crahay		A. Cuevas, R.A. Sinton and R.M. Swanson	
Light Trapping in Thin Crystalline Silicon Solar Cells	263	24% Efficient PERL Structure Silicon Solar Cells	333
J.A. Rand, R.B. Hall and A.M. Barnett		J. Zhao, A. Wang and M.A. Green	
Fermi Degeneracy and Quantum Collection Efficiency in Heavily Doped Silicon Solar Cells	269		
A. Morales-Acevedo			
Silane Glow Discharge Based Double Antireflection Coatings for cr-Si Solar Cells	275		
G. Willeke, E. Demesmaeker, J. Nijs and R. Mertens			
Development of a Multi-Purpose, Pulsed-Laser System for Solar Cell Processing Applications	278		
D.L. King, B.R. Hansen and W.M. Lehrer			
Electrical Parameter Changes in Silicon Solar Cells Induced by Thermal Donor Formation	284		
J.M. Ruiz and M. Cid			
Series Resistance Calculations in Silicon Solar Cells at Very High Concentration	289		
I. Tobias and A. Luque			
Annealing and Temperature Effects on Minority Carriers in Ion Implanted Silicon Solar Cells	295		
P. Nubile, A.F. Beloto, N. Veissid, B. Waldman, I. Pereyra and A.M. Andrade			
LATE NEWS			
Characterization of Very-Thin High-Efficiency Corrugated Silicon Solar Cells	299		
T. Uematsu, K. Kanda, S. Kokunal, T. Warabisako, S. Iida and T. Saitoh			
Developments in Module Ready Si Backside-Contact Solar Cells	302		
R.A. Sinton, R.A. Crane, S. Beckwith, A. Cuevas, P.E. Gruenbaum, D.E. Kane, J.Y. Gan, R.R. King, N. Midkiff and R.M. Swanson			
High Efficiency Silicon Solar Cells			
Chairpersons:			
A. Luque			
R.A. Sinton			
Organizer:			
R.M. Swanson			
Electro-Epitaxial Growth of Thin Film Silicon	307		
D.W. Cunningham, M.G. Mauk, J.P. Curran and A.M. Barnett			
		Modeling and Characterization of Single Crystal Solar Cells	
		Chairpersons:	
		A. Cuevas	
		G.F. Virshup	
		Organizer:	
		J.L. Gray	
		Temperature Coefficients of Multijunction Solar Cells	336
		G.F. Virshup, B.C. Chung, M. Ladle Ristow, M.S. Kuryla and D. Brinker	
		Modeling of Two-Junction, Series-Connected Tandem Solar Cells Using Top-Cell and Coating Thicknesses as Adjustable Parameters	339
		P. Faine, S.R. Kurtz and J.M. Olson	
		Numerical Model for Tunnel Junctions with Application to Cascade Solar Cells	345
		J.L. Gray	
		OBIC Studies: Classification of Structural Defects and Their Influence on the Performance of MOCVD Grown GaAs Solar Cells	348
		X. Tang, P.J.M. Boots and L.J. Giling	
		Intensity Effects in Minority Carrier Lifetime Measurements	353
		D.C. Marvin and L.F. Halle	
		Transient Photoluminescence Decay Investigations of LPE GaAs Heteroface Solar Cells	357
		W. Wetling, A. Ehrhardt, A. Bett and F. Lutz	
		Characterization of Antireflection Films for Surface-Passivated Crystalline Silicon Solar Cells Using Spectroscopic Ellipsometry	363
		O. Kamataki, T. Saitoh, S. Iida and T. Uematsu	
		Detailed Analysis of the Factors Affecting Emitter Recombination in Solar Cells Through the Small-Signal Voltage Decay Method	368
		K. Joardar, D.K. Schroder and C.E. Backus	
		Microwave-Detected Photoconductance Decay	374
		P.A. Basore and B.R. Hansen	

Experimental Measurement of the Intrinsic Carrier Concentration of Silicon	380
A.B. Sproul and M.A. Green	
Key Factors Limiting the Open Circuit Voltage of n^+pp^+ Indium Phosphide Solar Cells	386
C. Goradia, W. Thesling and I. Weinberg	
Lifetime Measurements by Open Circuit Voltage Decay in GaAs and InP Diodes	394
H. Bhimnathwala, S. Bothra, S. Tyagi, S.K. Ghandhi and J.M. Borrego	
Measurement of Surface Recombination Velocity on Heavily Doped InP	399
P. Jenkins, S.G. Bailey, Mircea Faur, M. Ghalla-Goradia and Maria Faur	
Surface Recombination Velocity and Lifetime in InP Measured by Transient Microwave Reflectance	404
S. Bothra, S. Tyagi, S.K. Ghandhi and J.M. Borrego	
Energy and Free Energy Analyses of Photovoltaic Energy Conversion	409
J.E. Parrott	
PC-ID Modeling of Depletion Layer Recombination in GaAs Solar Cells	415
L.C. Olsen, D.A. Huber, G. Dunham and F.W. Addis	
Non-Solar Photovoltaic Cells	420
P.A. Iles	

Modeling and Characterization of Single Crystal Solar Cells

Chairpersons:

P.A. Basore
J.L. Gray

Organizer:

R.A. Sinton

Texture: A Ray Tracing Program for the Photovoltaic Community	426
A.W. Smith, A. Rohatgi and S.C. Neel	
Design of High Efficiency GaAs Solar Cells by Photoluminescence Studies	432
R.K. Ahrenkiel, D.J. Dunlavy, B. Keyes, S.M. Vernon, S.P. Tobin and T.M. Dixon	
Physical Parameters of Highly Injected Silicon in the Modelling of Concentrator Solar Cells	437
D.E. Kane, R.A. Sinton, J.Y. Gan and R.M. Swanson	
Effects of Perimeter Recombination on GaAs-Gated Solar Cells	442
T.B. Stellwag, P.E. Dodd, M.S. Carpenter, M.S. Lundstrom, R.F. Pierret, M.R. Melloch, E. Yablonovitch and T.J. Gmitter	
Reverse I-V Characteristics of GaAs Cells	448
P.A. Iles, H. Yoo, C. Chu, J. Krogen and K.I. Chang	
Effects of Heavy Impurity Doping on the np Product in p-GaAs	455
M.E. Klausmeier-Brown, M.R. Melloch and M.S. Lundstrom	

Polycrystalline Solar Cells

Thin Film Compound Semiconductors

Chairpersons:

J.E. Phillips
K.W. Mitchell

Organizer:

C. Eberspacher

Polycrystalline Thin Film Photovoltaics	458
K. Zweibel, H.S. Ullal and R.L. Mitchell	
Key Issues and Cost Estimates for the Fabrication of CuInSe₂ (CIS) PV Modules by the Two-Stage Process	467
V.K. Kapur and B.M. Basol	
A Novel Electrochemical Technique for Insitu Deposition of Photoactive CuInSe₂ Thin Films for Solar Cells	471
P. Garg, J.C. Garg and A.C. Rastogi	
A Low Cost Method for Large Area Production of CuInSe₂/(CdZn)S Devices	477
H. Oumous, A. Knowles, M.H. Badawi, M.J. Carter and R. Hill	
Improvement of Cu(Ga,In)Se₂ Based Solar Cells by Etching the Absorber	481
R. Klenk, R. Menner, D. Cahen and H.W. Schock	
Photovoltaic Performance of p-AgGaSe₂/n-CdS Thin Film Heterojunction	487
Y.S. Murthy, O.M. Hussain, B.S. Naidu and P.J. Reddy	
Junctions Mode Using p-CdTe Films with Ion-Assisted Doping	493
P. Sharps, A.L. Fahrenbruch, A. Lopez-Otero, M. Schöfthaler and R.H. Bube	
CdS/CdTe Solar Cells by the Screen-Printing-Sintering Technique	498
N. Suyama, T. Arita, Y. Nishiyama, N. Ueno, S. Kitamura and M. Murozono	
Effects of Preheat Treatment of CdS on MOCVD CdTe/Cds Solar Cell Performance	504
R. Sudharsanan and A. Rohatgi	
Cd_{1-x}Zn_xTe Films Obtained by the Solid-State Reaction of Elemental Layers	509
B.M. Basol, V.K. Kapur and R.L. Mitchell	
Polycrystalline Thin Films of Mercury Zinc Telluride for Use in Multijunction Solar Cells	514
S. Arshed, R.W. Miles and R. Hill	
Improvement of ZnO/WSe₂ Solar Cells by Doping?	519
M. Vogt, M.Ch. Lux-Steiner, P. Dolatzoglou, W. Reetz, B. Bumuller and E. Bucher	
Ionized Cluster Beam Deposition of GaAs Thin Films for Solar Cells	525
D. Bonnet and S. Oelting	

LATE NEWS

- Reactor Analysis of Copper Indium Selenization** 529
R.D. Varrin, Jr., S. Verma, R.W. Birkmire, B.E. McCandless and T.W.F. Russell

- 4-CM² CuInGaSe₂ Based Solar Cells** 535
W.E. Devaney, J.M. Stewart and W.S. Chen

- Correlations of Single-Crystal CuInSe₂ Surface Processing with Defect Levels and Cell Performance** 541
F.A. Abou-Elfotouh, L.L. Kazmerski, A.A.J. Al-Douri and A.M. Bakry

Thin Film Compound Semiconductors

Chairpersons:

R. Noufi
R. Hill

Organizer:

B. Basol

- CuInSe₂ Thin Films and High-Efficiency Solar Cells Obtained By Selenization of Metallic Layers** 546
B.M. Basol and V.K. Kapur

- Options for Fabrication and Design of CuInSe₂ Based Solar Cells** 550
R.W. Birkmire, W.N. Shafarman and R.D. Varrin

- Individual Losses in Thin-Film CdTe Solar Cells** 556
H. Tavakolian and J.R. Sites

- A Study on the Optical and Microstructural Characteristics of Quaternary CU(In,Ga)Se₂ Polycrystalline Thin Films** 562
D. Albin, J. Tuttle, G.D. Mooney, J.J. Carapella, A. Duda, A. Mason and R. Noufi

- The Use of CuIn_{1-x}Ga_xSe₂ Layers to Improve the Performance of CuInSe₂ Cells** 570
R.J. Schwartz and J.L. Gray

- Towards High Efficiency Electrodeposited CdS/CdTe Thin Film Cells** 575
G.C. Morris, P.G. Tanner and A. Tottszer

Polycrystalline Solar Cells

Chairpersons:

T.J. Coutts
C. Eberspacher

Organizer:

T.J. Coutts

- Doping and Oxygen Dependence of Efficiency of EFG Silicon Solar Cells** 581
A. Rohatgi, W.A. Doolittle, A.W. Smith, F.V. Wald, R.O. Bell and C.E. Dube

- Thin Film CdTe Solar Cells—A Review** 588
B. Basol

- Advances in Large Area CuInSe₂ Thin Film Modules** 595
J.H. Ermer, J. Hummel, C.L. Jensen, C.V. Fredric, D. Pier, D. Tarrant and K. Mitchell

Polycrystalline Silicon

Chairpersons:

D.K. Schroder
A.M. Barnett

Organizer:

R. Hall

- Status of the Direct Solidification of Silicon Wafers by RAFT** 600
A. Beck, J. Geibler and D. Helmreich

- 10% Efficient Commercial-Scale Silicon-Film Solar Cells** 604
C.L. Kendall, J.C. Checchi, M.L. Rock, R.B. Hall and A.M. Barnett

- Improvements in Direct-Cast Semicrystalline Silicon Solar Cells** 608
H. Somberg

- Development of the E.P.R. Technology for an Oriented Crystal Growth of Semiconductor Wafers** 610
A. Chibani, S. Sof, M. Hamoud, R. Gauthier, P. Pinard and K. Marsh

- Recent Results in Optical Processing of Silicon Sheet** 615
J.M. Serra and A.M. Vallera

- Effects of Encapsulation on the Performance of Silicon Solar Cells** 618
B.L. Sopori

- Improved Contact Metallization for High Efficiency EFG Polycrystalline Silicon Solar Cells** 624
C.E. Dubé and R.C. Gonsiorawski

- Rapid Thermal Processing Effect on the Intragrain and Grain Boundaries Properties of Multicrystalline Silicon Solar Cells** 629
J.P. Boyeaux, K. Masri, G. Chaussemy, L. Mayet and A. Laugier

- Process Induced Improvements in Polycrystalline Silicon-Film Solar Cells** 634
M.L. Rock, D.W. Cunningham, C.L. Kendall, R.B. Hall and A.M. Barnett

- Hydrogen Passivation of Polycrystalline Silicon Solar Cells by Plasma Deposition of Silicon Nitride** 638
P.P. Michiels, L.A. Verhoef, J.C. Stroom, R.J.C. van Zolingen, C.M.M. Denisse, M. Hendriks and W.C. Sinke

- Defect Generation/Passivation by Low Energy Hydrogen Implant for Silicon Solar Cells** 644
B.L. Sopori, T.Q. Zhou and G.A. Rozgonyi

- Improved Backside Hydrogenation on Semicrystalline Silicon Solar Cells by RF Plasma** 650
M.A.G. Soler, I. Pereyra, F.J. Fonseca and A.M. Andrade

- One Sun Crystalline Silicon Materials Research: Current Direction and Future Needs** 653
B.L. Sopori, J. Benner and J.D. McBrayer

- Formation of PN Junction with Hydrogenated Microcrystalline Silicon** 659
K. Kawabata, H. Morikawa, T. Ishihara, K. Sato, H. Sasaki, T. Itagaki, M. Deguchi, S. Hamamoto and M. Aiga

LATE NEWS

- Cast Polycrystalline Silicon Solar Cell with Grooved Surface** 664
T. Nunoi, S. Okamoto, K. Nakajima, S. Tanaka, N. Shibuya, K. Okamoto, T. Nammoni and H. Itoh
- Ink Jet Printing for Metallization on Very Thin Solar Cells** 666
H. Somberg
- Large Area High Efficiency Multicrystalline Silicon Solar Cell** 668
K. Shirasawa, H. Yamashita, K. Fuku, M. Takayama, K. Okada, K. Masuri and H. Watanabe
- Cold Crucible Induction Casting of Semi-Conductor Silicon for Solar Cell** 674
K. Kaneko, T. Misawa and K. Tabata

Polycrystalline Silicon

Chairpersons:

R.B. Hal
A. Goetzberger

Organizer:

T. Gessert

- 18% Efficient Polycrystalline Silicon Solar Cells** 678
S. Narayanan, J. Zolper, F. Yun, S.R. Wenham, A.B. Sproul, C.M. Chong and M.A. Green
- Correlation Between Impurities, Defects and Cell Performance in Semicrystalline Silicon** 681
W.A. Doolittle, A. Rohatgi and R. Brenneman
- The Effects of Chromium on Edge-Defined Film-Fed Growth (EFG) Polycrystalline Silicon Solar Cells** 687
B. Bathey, C.E. Dubé, J.P. Kalajs and F.V. Wald
- Hydrogen Passivation of Polycrystalline Silicon Solar Cells by Means of Catalytic Reactions** 691
M. Kaiser and R. Schindler
- Manufacture of SI Ribbons by the S-Web Technique** 695
R. Falckenberg, J.G. Grabmaier, K.H. Eisenrith, B. Freienstein, A. Lerchenberger, R. Schindler and F. Lutz
- Mass-Production of High Quality Polycrystalline Silicon Sheets by the New Spin Cast Process** 700
M. Suzuki, I. Hide, T. Matsuyama, H. Yamashita, T. Suzuki, T. Moritani and Y. Maeda

Polycrystalline Materials and Device Characterization

Chairperson:

B.J. Stanbery

Organizer:

C. Eberspacher

- Lateral Distribution of Metallic Impurities in Silicon Bicrystals Investigated by Scanning MCTS** 705
T. Heiser, A. Mesli and P. Siffert
- Physical and Electrical Investigation of Silicide Precipitates in EFG Polycrystalline Silicon Intentionally Contaminated with Chromium** 711
J.B. Mohr, S.H. Park, S.N. Schauer, D.K. Schroder and J. Kalejs
- Influence of Oxygen on Polycrystalline Silicon Sheet** 717
I. Hide, T. Matsuyama, M. Suzuki, H. Yamashita, T. Suzuki, T. Moritani and Y. Maeda
- DLTS Study of EFG Solar Cells** 721
S. Mil'shtein, J.T. Borenstein, J.I. Hanoka and Y. Yang
- Automated Defect, Inclusion and Morphological Analysis of Solarex Polycrystalline Silicon** 726
R. Brenneman, D. Ramsey and D. Angell
- Modeling of the Grain Boundary Potential for Poly-Si** 731
Z. Chen and L.C. Burton
- Investigation of Conventional and Pregettered Multicrystalline Silicon Cells in Terms of Lifetime, Diffusion Length and Defects** 737
I. Perichaud, G. Mathian, S. Martinuzzi, M. Pasquinelli and J. Gervais
- Effect of Oxidation-Reduction Heat Treatments on CuInSe₂/CdS Device Behavior** 743
M. Roy and J.E. Phillips
- Secondary and Polymorphic Phase Behavior of Thin Film CuInSe₂: Ramifications on the Device Performance** 748
J.R. Tuttle, D.S. Albin, J. Goral and R. Noufi
- Nomarski Contrast Microscopy of CuBSe₂/Mo (B = In, Ga) Films** 755
L. Margulis, A. Jakubowicz, G. Hodes and D. Cahen
- Raman Scattering Study of CuInSe₂ Films Prepared by Three-Source RF-Sputtering and by Selenization of Cu/In/Se Stacked Layers** 758
S. Yamanaka, M. Tanda, K. Horino, K. Ito, A. Yamada, M. Konagai and K. Takahashi
- Deposition of CuInSe₂ by the Hybrid Sputtering and Evaporation Method** 764
A. Rockett, C.J. Kiely, G. Kenshole, L. Chung Yang, H. Talieh, L.C. Yang, E. Banda and A. Agarwal
- Preparation of Nonstoichiometric CuInSe₂ Crystals by the Bridgman Method** 768
L.S. Yip, W.S. Weng, I. Shih and C.H. Champness

LATE NEWS

- Shunt Effects in Polycrystalline GaAs Solar Cells** 772
C. Honsberg and A.M. Barnett
- Thin Film CdTe Homojunctions by MOCVD** 777
T.L. Chu, S.S. Chu, C. Ferekides, J. Britt and C.W. Wu

Polycrystalline Materials and Device Characterization

Chairpersons:

B.L. Soporì
G.C. Morris

Organizer:

T. Coutts

- Determination of Diffusion Length with Bi-Facial
Spectral Response** 782
J.E. Phillips
- Advanced X-Ray Analysis of Polycrystalline CuInSe₂
Thin Films** 787
H. Dittrich, R. Menner and H.W. Schock
- In-Depth Characterization of Si Solar Cells** 793
L.A. Verhoef, F.J. Bisschop, J.C. Stroom and W. Sinke
- Hot Spots and Heavily Dislocated Regions in Multi-
crystalline Silicon Cells** 800
A. Simo and S. Martinuzzi

VOLUME II

Terrestrial Systems and Technology

Utility PV Systems and Concentration Technology

Chairpersons:

A.B. Maish
D.L. King

Organizers:

S. Hester
R. McConnell

Analysis of the Value of Photovoltaics for Demand Side Management	809
S. Rahman, J. Jockell and S. Lahouar	
A Utility Strategy for Photovoltaics	815
C. Herig, G. Atmaram and B. Marion	
Performance of a 15 kWp Amorphous Silicon Photovoltaic System	821
G.H. Atmaram, B. Marion and C. Herig	
Effect of Central Station Photovoltaic Plants on Power System Security	831
B.H. Chowdhury	
Photovoltaics in the Utility Distribution System: The Evaluation of System and Distributed Benefits	836
D.S. Shugar	
Carrisa Plains PV Power Plant Performance	844
H. Wenger, C. Jennings and J. Iannucci	
Problems and Countermeasures on Safety of Utility Grid with a Number of Small Scale PV Systems	850
H. Kobayashi, K. Takigawa, E. Hashimoto, A. Kitamura and H. Matsuda	
Early Applications of Photovoltaics in the Electric Utility Industry	856
J.E. Bigger and E.C. Kern, Jr.	
A Twenty Percent Efficient Photovoltaic Concentrator Module	861
C. Chiang and E. Richards	
Performance of a Self-Aligning Solar Array Tracking Controller	864
A.B. Maish	
The Photovoltaic Concentrator Initiative	870
J.L. Chamberlin and D.L. King	
Design and Construction of an Extruded, Curved, Linear Focus, Fresnel Lens	876
N.R. Kaminar and D. Curchod	
Performance Testing and Qualification of Sandia's Third Baseline Photovoltaic Concentrator Module	881
E. Richards, C. Chang and M. Quintana	

LATE NEWS

Sandia's Concept-90 Photovoltaic Concentrator Module	887
C. Chiang and M. Quintana	

Utility Applications and Testing

Chairpersons:

A.D. Krantz
R. McConnell

Organizers:

S. Hester
R. DeBlasio

Maximizing the Benefit Derived from PV Plants: Selecting the Best Plant Design and Plant Location	892
T. Hoff and J.J. Iannucci	
Lessons Learned with Residential Photovoltaic Systems	898
M.C. Russell and E.C. Kern, Jr.	
Results from Arizona Public Service Company's Star Center	903
T.L. Lepley	
Lessons Learned from Testing Utility Connected PV Systems	909
S.J. Durand, D.R. Bowling and V.V. Risser	
PG&E'S Cost-Effective Photovoltaic Installations	914
C. Jennings	
Photovoltaic Power Conditioning: Status and Needs	919
P. Steitz, T.S. Key and F.R. Goodman, Jr.	
Optimizing the Component Mix of a Mini-Utility	926
T. Hoff and J.J. Iannucci	
Utility Use of PV System Ratings	932
K. Firor, C.M. Whitaker and C. Jennings	

Terrestrial Systems & Array Technology

Chairperson:

L. Herwig

Organizer:

A.D. Krantz

PVUSA: Lessons Learned from Startup and Early Operation	937
S.L. Hester, T.U. Townsend, W.J. Stolte and W.T. Clements	

Photovoltaic Concentrator Technology Development 944
E.C. Boes

Objectives and Results of the PEP '87 Round-Robin Calibration of Reference Solar Cells and Modules 952
J. Metzdorf, T. Wittchen, K. Heidler, K. Denhe, R. Shimokawa, F. Nagamine, H. Ossenbrink, L. Fornarini, C. Goodbody, M. Davies, K. Emery and R. DeBlasio

Terrestrial Systems, Applications and Technology

Chairpersons:
K. Emery
C.J. Chiang

Organizers:
P. Garvison
A.D. Krantz

Synthesis of Worldwide Solar Isolation Data for Photovoltaic System Sizing 960
P.A. Hutchinson, D.E. Andersen and V.V. Risser

The Synthesis of Solar Radiation Data for Sizing Stand-Alone Photovoltaic Systems 965
R.N. Chapman

Optimum Switching Points for Array Reconfiguration Controller 971
Z. Salameh and C. Liang

Photovoltaic Applications for Electric Vehicles 977
R.J. King

The ANCIPA Project—PV Plant to Power Four Sliding Gates and Trash-Rack Rake 982
A. Previ, A. Iliceto, S. Righi and S. Guastella

Lessons Learned from Testing Photovoltaic Vaccine Refrigerators 985
D. Kilfoyle, B. Marion and G.G. Ventre

Photovoltaic Powered Lights for Indian Villages 991
N.P. Singh and B. Bhargava

Two Examples of Photovoltaic Generators on a High-Voltage Overhead Line 994
J. Alzieu, Y. Le Cunff, J. Maire and Y. Moller

A Simple Way to Implement the Direct Coupling of PV Generator and Battery in Energy Simulation Models 999
A.P. van Dijk, E.A. Alsema, K. Blok and W.C. Turkenburg

Analysis of Photovoltaic Modules with Protection Diodes in Presence of Mismatching 1005
A. Abete, E. Barbisio, F. Cane and P. Demartini

Development of Photovoltaic in China: Status and Future 1011
C.R. Qiang, Y.J. Huan, Z.F. Xin, L.W. Zhe and W.S. Chen

Photovoltaic Environmental, Health and Safety Electronic Bulletin Board Service 1014
A.F. Meinhold and P.D. Moskowitz

PV Module Performance and Testing

Chairpersons:
C.E. Backus
P. Garvison

Organizers:
R. DeBlasio
R. McConnell

A New Approach for the Performance Evaluation of Solar Cells Under Realistic Reporting Conditions 1017
K. Heidler, A. Raicu and H.R. Wilson

PV Module Performance Outdoors at PG&E 1023
C. Jennings and C. Whitaker

Seasonal Performance of Three Grid-Connected PV Systems 1030
B. Marion and G. Atmaram

Outdoor Stability Performance of CIS and CdTe Photovoltaic Modules at SERI 1038
L.C. Mrig and S. Rummel

Health and Safety Issues Related to the Production, Use and Disposal of Cadmium-Based Photovoltaic Modules 1040
P.D. Moskowitz, V.M. Fthenakis and K. Zweibel

Long-Term Photothermal/Humidity Testing of Photovoltaic Module Polymer Insulations and Cover Films 1043
G. Mon., C. Gonzalez, P. Willis, E. Jetter, R. Sugimura and R. Ross, Jr.

PV System Performance and Measurement

Chairperson:
M.J. O'Neill

Organizers:
R. DeBlasio
A. Maish

Case Study of a Central-Station Grid-Intertie Photovoltaic System with V-Trough Concentration 1051
J. Freilich and J.M. Gordon

Comparative Short Term/Long Term Field Test Performance and Stability of Tandem and Single Junction a-Si Modules 1057
M.J. Hahn, W.B. Berry and L. Mrig

Primary Reference Cell Calibrations at SERI: History and Methods 1062
C.R. Osterwald, K.A. Emery, D.R. Myers and R.E. Hart

PV Performance Measurement Algorithms, Procedures and Equipment 1068
K.A. Emery and C.R. Osterwald

Reliability of Photovoltaic Concentrator Modules 1074
E. Richards and C. Chiang

Study of the Long Run Field Degradation of Flat Plate Photovoltaic Module	1080
P.K. Koner and J.C. Joshi	
What is an Air Mass 1.5 Spectrum?	1085
C. Riordan and R. Hulstrom	
A Simple Method to Analyze and Present Performance Data of the 300 kW Delphos PV PLant	1089
A. Sarno, S. LiCausi, F. Apicella and M. Guerra	
Toward the Photovoltaic Farm	1095
D. Coiante	
Comparison Between Pyranometers and Encapsulated Solar Cells as Reference PV Sensors. Outdoor Measurements in Real Conditions	1099
F. Chenlo, N. Vela and J. Olivares	
A Versatile Microprocessor Based Controller for Solar Tracking	1105
A.K. Saxena and V. Dutta	
LATE NEWS	
Solar Spectral Irradiance Under Overcast Skies	1110
S. Nann and C. Riordan	
Mixing Optical Beams for Solar Simulation—A New Approach	1116
B.L. Sopori, C. Marshall and K. Emery	
Stand Alone Systems and Concentrator Modules/Arrays	
Chairpersons:	
M. Prince	
K. Collier	
Organizers:	
P. Garvison	
A. Maish	
Performance of Battery Charge Controllers: An Interim Test Report	1122
W.L. Bower, J.P. Dunlop and C.W. Maytrott	
Terrestrial Photovoltaics Systems for U.S. Military Applications	1130
R. Ducey, G. Smith, L. Humble, L. Strother, K. Agi, A. Seiss and J.F. Hoelscher	
Production of the Alpha Solarco Proof-of-Concept Array	1136
D. Carroll, E. Schmidt and B. Bailor	
22.7% Efficient 1000X GaAs Concentrator Module	1142
M.S. Kuryla, N.R. Kaminar, H.F. MacMillan, M. Ladle Ristow, G.F. Virshup, M.R. Klausmeier-Brown and L.D. Partain	
Fabrication, Installation & Initial Operation of the 2,000 SQ.M. Linear Fresnel Lens Photovoltaic Concentrator System at 3M/Austin (Texas)	1147
M.J. O'Neill, R.R. Walters, J.L. Perry, A.J. McDanal, M.C. Jackson and W.J. Hesse	

Space Systems and Technology

Flight Experiments and Results

Chairperson:

R.D. Williams

Organizer:

D.J. Brinker

Multijunction Component Cells on LIPS III	1153
J.G. Werthen, G.F. Virshup, M.E. Klausmeier-Brown, B.C. Chong, M. Ladle Ristow and N.R. Kaminar	
Results of the MBB LIPS III Experiment	1159
H. Kulms, G.J. LaRoche and B. Czap	
An Analysis of Spaceflight Performance of Several Types of Silicon Solar Cells on the LIPS III Satellite	1164
D. Warfield and J. Silver	
Recent Results from the InP Homo Junction Cell Module on the LIPS III Spacecraft	1167
D.J. Brinker and I. Weinberg	
Radiation and Flight Testing of ITO/InP Solar Cells	1172
N.M. Pearsall, C. Goodbody, N. Robson, I. Forbes and R. Hill	
Forward-Biased Current Annealing of Radiation Degraded Indium Phosphide and Gallium Arsenide Solar Cells	1178
S. Michael, C. Cypranowski and B. Anspaugh	
The Solar Cell Experiment of the First Brazilian Complete Space Mission Satellite	1184
N. Veissid, P. Nubile, A.F. Beloto and A.M. Andrade	
The Design and Performance of the Hughes HS 393C Satellite Solar Arrays Featuring Large Area Solar Cells	1188
J.S. Fodor, S.W. Gelb, L.J. Goldhammer and D.W. Moffett	
Electrical Design and Performance of the British Satellite Broadcast Spacecraft	1193
D.W. Moffett, S.W. Gelb, L.J. Goldhammer and B.D. Edwards	

LATE NEWS

First Space Flight of InP Solar Cells	1198
M. Yamaguchi, T. Hayashi, A. Ushirokawa, Y. Takahashi, M. Koubata, M. Hashimoto, H. Okazaki, T. Takamoto, M. Ura, M. Ohmori, S. Ikegami, H. Arai and T. Orii	
High Altitude AMO Testing of PV Concentrator Lens Elements	1203
M.F. Piszczor, D.J. Brinker, E.O. Boyer, R.C. McKnight, R.J. Ranado, M.J. O'Neill and A.J. McDanal	

Space Environmental Effects

Chairperson:

J.W. Koch

Organizer:

R.W. Francis

- Systematic Anomalies in Experiment Data from LIPS III** 1208
J.G. Severns, T.G. Stern, D.K. Conway, R.M. Hobbs
and R.W. Conway
- Preliminary Results from the Advanced Photovoltaic
Experiment Flight Test** 1213
D.J. Brinker, R.E. Hart, Jr. and J.R. Hickey
- Space Proven GaAs Solar Cells—Main Power
Generation for CS-3** 1219
N. Takata, H. Kurakata, S. Matsuda, T. Okuno, S.
Yoshida, H. Matsumoto, M. Goto, M. Ohkubo and M.
Ohmura
- In-Flight Performance of the SBS-1A Solar Array,
Featuring Ultrathin High Efficiency Solar Cells** 1226
R.D. Williams, S.W. Gelb and J.S. Fodor
- 16%-Efficient GaAs Solar Cell After 10^{15} cm⁻², 1-MeV
Radiation** 1231
K.A. Bertness, M. Ladle Ristow, M.E. Klausmeier-
Brown, M. Grounner, M.R. Kurlya and J.G. Werthen
- Effects of Radiation on InP Cells Epitaxially Grown on Si
and GaAs Substrates** 1235
I. Weinberg, C.K. Swartz, D.J. Brinker and D.M. Wilt

Space Systems and Technology

Chairpersons:

D.Flood

L.M. Fraas

Organizer:

B. Anspaugh

- Recent Solar Flare Activity and Its Effect on In-Orbit
Solar Arrays** 1241
L.J. Goldhammer
- Measurement Techniques for Multijunction Solar Cells** 1249
G.F. Virshup

Space Solar Arrays and Components

Chairpersons:

D.J. Brinker

P.A. White

Organizer:

L. Goldhammer

- Design Considerations for Lunar Base Photovoltaic
Power Systems** 1256
J.M. Hickman, H. Curtis and G.A. Landis
- Design Considerations for Mars Photovoltaic Power
Systems** 1263
G.A. Landis and J. Appelbaum
- The Mini-Dome Fresnel Lens Photovoltaic Concentrator
Array: Current Status of Component & Prototype Panel
Testing** 1271
M.F. Piszczor, C.K. Swartz, M.J. O'Neill, A.J.
McDanal and L.M. Fraas
- Lightweight Concentrator Module with 30% AMO
Efficient GaAs/GaSb Tandem Cells** 1277
J.E. Avery, L.M. Fraas, V. Sundaram, N. Mansori, J.W.
Yerkes, D.J. Brinker, H.B. Curtis and M.J. O'Neill
- Investigation of the Reverse Biasing of Solar Cells in a
Space Array** 1282
R. Kimber, R. Hill and N.M. Pearsall
- The Bypass Diode Assembly: Solar Cell Protection for
Space Station Freedom** 1288
T.W. Woike, S.C. Stotlar and L.M. Woods
- Direct Glassing of Silicon Space Solar Cells: Approach
and Manufacturing Experiences** 1294
J.W. Koch and P.A. White
- A Coverglass for Gallium Arsenide Solar Cells** 1300
P.A. White
- A Light Trapping Solar Cell Coverglass** 1304
G.A. Landis
- HST Solar Generator Design for a Decade in Orbit** 1308
L. Gerlach, A. Fournier-Sicre, A. Fromberg and S.
Korehnert
- Stability of GaAs/Ge Solar Cells with Standard Front
Contacts After Long-Term, High-Temperature
Exposure** 1314
S. Gasner, G. Pack, M. Gates and R. Given
- Application of the GaSb Solar Cell to Isotope-Heated
Power Systems** 1320
A.C. Day, W.E. Horne and M.D. Morgan
- Reappraisal of Solid Selective Emitters** 1326
D.L. Chubb

LATE NEWS

Electrical and Thermal Behavior of GSPG Type Solar Array 1334

J.P. David, J. Duveau, J. Guerin, A. Michel, E. Rapp, M. Roussel and L. Pelenc

Performance Evaluation of CLEFT GaAs/CuInSe₂ Tandem Cell Circuits Through Solar Simulator Testing and Computer Modeling 1340

R. Burgess, C. Flora and M. Schneider

23.5% Thin-Film Space Concentrator Cells 1346

B.D. Dingle, R.P. Gale, R.W. McClelland, M.B. Spitzer, H.B. Curtis and D.J. Brinker

Effect of Emitter Parameter Variation on the Performance of Heteroepitaxial Indium Phosphide Solar Cells 1350

R.K. Jain and D.J. Flood

Advanced Array Technology

Chairpersons:

M. Kruer
K.P. Bogus

Organizer:

R. Patterson

Photovoltaic Superiority for Space Station Freedom Power in the 21st Century 1356

S.G. Bailey, G.A. Landis and M.A. Perino

Mission Applications for Advanced Photovoltaic Solar Arrays 1362

P.M. Stella, J.L. West, R.G. Chave, D.P. McGee and A.S. Yen

Retractable Planar Space Photovoltaic Array 1369

E.L. Ralph, M. A. Chung and K.C. Reinhardt

Large Area Space Solar Cells—Si or GaAs 1374

S. Khemthong, H. Yoo, N. Hansen, C. Chu, P. Iles and J. Krogen

Development of 2.7 Mil BSF and BSFR Silicon Wrapthrough Solar Cells 1378

A.V. Mason, J.R. Kukulka, S.M. Bunyan and L.M. Woods

High Efficiency, Rugged, Lightweight GaAs Solar Cells 1383

F.H. Ho, P.A. Iles, C. Chu, Y.C.M. Yeh, J. Krogen, W. Patterson and B. Reed

Amorphous Silicon Based Solar Cells

Amorphous Silicon Cells and Modules

Chairpersons:

D. Morel
H. Sakai

Organizer:

M. Prince

The Density of States (DOS) of I-Layers in a-Si:H Based pin Cells Determined by CPM Measurements 1389

H. Rübel, R. Geyer, B. Scheppat, P. Lechner, M. Gorn, and N. Kniffler

New Type Structures on A-Si Solar Cell Submodules Fabricated by Microscopic Hole Spacing Technique 1394

M. Ohnishi, H. Shibuya, N. Okuda, H. Inoue, Y. Kishi, S. Kiyama, H. Kawata, S. Tsuda, S. Nakano, Y. Kuwano and S. Okamoto

High Effective Area Amorphous Silicon Solar Cell Using Eximer Laser Process 1400

M. Abe, H. Shinohara, Y. Arai, N. Ishida, A. Satake, K. Nishi, S. Kugawa, S. Nakajima, Y. Uehara, M. Ishii and S. Yamazaki

Outdoor Performance Studies of a-Si Alloy Multi-Junction Solar Cells Using Simulated Solar Illumination 1403

J. Burdick and T. Glatfelter

Status of the DOE/SERI Amorphous Silicon Research Project: Recent Advances and Future Directions 1409

B.L. Stafford, W. Luft, B. von Rodern and W.L. Wallace

Hydrogen-Plasma Reactive Flushing for a-Si:H and A-SiGe:H Solar Cell Fabrication 1416

Y.S. Tsuo, Y. Xu, R.S. Crandall, D. Han, C. Qiu and J.I. Pankove

a-Si/poly-Si Two- and Four-Terminal Tandem Type Solar Cells 1420

Y. Matsumoto, K. Miyagi, H. Takakura, H. Okamoto and Y. Hamakawa

A Three Dimensional Design Approach for a-Si:h Multijunction Solar Cells 1426

M.M. Alkansi and A.Z. Sadik

Power Optimization for Large-Area a-Si:H Solar Modules 1432

F. Willing, S. Wiedeman, J. Newton, J. O'Dowd and K. Jansen

Two Source Simulator for Improved Solar Simulation 1438

M. Bennett and R. Podlesny

Advances in Large Area Si:H Thin Film Modules 1443

D.R. Willett, S.A. Vasquez and D.P. Tanner

High Reliability Three-Stacked Amorphous-Silicon Solar Cell 1449

S. Moriuchi, Y. Inoue, H. Sannomiya, A. Yokota, M. Itoh, Y. Nakata and H. Itoh

Amorphous Silicon Based Cells

Chairpersons:

S. Wagner
G.H. Bauer

Organizer:

R. Arga

High Performance Interconnected Amorphous Silicon Based Modules 1455

J. Morris, R.R. Arya, C. Poplawski, A. Catalano, R. Podlesny, J.L. Newton, A. Wilczynski and T. Lommas-son

Role of Film Thickness in Amorphous Silicon Solar Cell Cell Characterization 1459

P. McElheny, S. Nag, S.J. Fonash, C.R. Wronski, M. Bennett and R. Arya

Sub-Bandgap Photocurrent in Reverse Based p-i-n a-Si:H Solar Cells 1465

A. Mittiga, P. Fiorini, S. Korepanov, M. Sebastiani and F. Evangelisti

High Efficiency A-Si/a-Si Tandem Solar Cells 1471

D.S. Shen, R.E. Schropp, H. Chatham, R.E. Hollingsworth, J. Xi and P.K. Bhat

A Stable 10% Solar Cell with a-Si/a-Si Double-Junction Structure 1475

Y. Ichikawa, S. Fujikake, T. Yoshida, T. Hama and H. Sakai

41.5 Watt, 10.5% Si:H/CuInSe₂ Tandem Thin Film Modules 1481

K.W. Mitchell, D.R. Willett, C. Eberspacher, J.H. Ermer, D.N. Pier and K.L. Pauls

Amorphous Silicon

Chairpersons:

B. Baron
M. Konagai

Organizer:

S. Fonash

Instabilities In A-Si:H Solar Cells: Materials and Device Issues 1487

C.R. Wronski

a-SiGe:H Alloy Material Limitations and Device Considerations 1493

C.M. Fortmann

A 10 MWp A-Si:H Module Processing Line 1501

J. Macnell, A.E. Delahoy, F. Kampas, F. Ellis, E. Eser and A. Varvar

Modeling and Stability of Amorphous Silicon Alloys

Chairpersons:

V.L. Dalai
S.S. Hegedus

Organizer:

C. Wronski

Evaluation of Degradation in Amorphous Silicon Solar Cells 1506

D. Redfield and R.H. Bube

1.00 MEV Proton Radiation Resistance Studies of Single-Junction and Single Gap Dual-Junction Amorphous-Silicon Alloy Solar Cells 1510

S. Abdulaziz, Y. Li, J.S. Payson, Y. Li and J.R. Woodyard

A Technique for Determining Urbach Edge, Midgap States and Electric Field in a-Si:H and A-(Si,Ge):H Devices 1516

V.L. Dalal, R.D. Knox and B. Moradi

An Extended "Collection Length Model" for the Description of the keV-Electron Induced Degradation and Thermal Recovery of p-i-n Solar Cells 1521

U. Schneider and B. Schroder

Optimum Band Gap for Amorphous Silicon Based Solar Cells 1526

P. Fiorini, A. Mittiga, I. Chamboueyron and F. Evangelisti

Optical Losses in Multi-Junction a-Si:H Based Solar Cells and Modules 1529

S. Wiedeman, J. Morris and L. Yang

Computer Modeling of a-SiC:H/a-Si:H Heterojunction Solar Cell Performance as a Function of the Apportionment of the Bandgap Discontinuity 1535

J.Y. Hou, J.K. Arch and S.J. Fonash

Sensitivity of the Spectral Response of a-Si:H Schottky Barriers to the Density of States Profile: A Computer Simulation 1540

P.J. McElheny and S.J. Fonash

Capacitance Studies of a-SiGe:H p-i-n Solar Cells 1544

S.S. Hegedus

Modelling of Transport and Recombination of Photoexcited Carriers in a-Si:H and a-SiGe:H 1550

C.D. Abel and G.H. Bauer

Superlattice Contact Layers for High Open Circuit Voltage A-Si:h Solar Cells 1555

A. Rothwarf and A. Varonides

Measurement of Ambipolar Mobility-Lifetime Product and its Significance for Amorphous Silicon Solar Cells 1560

E. Sauvain, A. Shah and J. Hubin

LATE NEWS

- Staeble-Wronski Effect in a-Ge:H Films** 1564
C.F. de O. Graeff, P.V. Santos, G. Marcand and I. Chambouleyron
- Performance of Large Area Thin Film Si:H Modules: A Link Between Shunting and Stability** 1569
R.D. Wieting, M. Boelingen, J.A. Anderson and D.R. Willett

Amorphous Silicon: Materials and Processing

Chairpersons:

R. Arya
B.L. Stafford

Organizer:

L. Kazmerski

- Silicon Carbon Alloy Thin Film Depositions Using Electron Cyclotron Resonance Microwave Plasmas** 1574
Y.H. Shing and F.S. Pool
- Bulk Photoconductivity of a-Ge:H Films from Spectral Measurements** 1579
H. Pfeleiderer, F. Schmeling, W. Kusian, F.H. Karg and W. Kruhler
- Effect of Hydrogen Plasma Treatment on SnO₂:F Films for Use in a-Si Solar Cells** 1584
K. Sato, Y. Gotoh, Y. Hayashi and H. Nishimura
- Effect of the Deposition Parameters on the Electro-optical Properties and Morphology of Microcrystalline Hydrogenated Silicon Alloys** 1588
E.T. Dirani, I. Pereyra, A.M. Andrade, A.M. Soler and R. Martins
- Ion-Beam Hydrogenation of Sputter-Deposited Amorphous Silicon and Amorphous Silicon-Germanium Alloys** 1591
X.J. Deng, Y.S. Tsuo and J.U. Trefny
- Studies of Substrate Induced Disorder in Amorphous Silicon by In-Situ-Raman Backscattering During Film Growth** 1595
M.B. Schubert and G.H. Bauer
- Tin Oxide Electrode for A-Si:H Solar Cells Deposited by a Spray Pyrolysis Technique** 1601
A. Antonaia, S. Aprea and P.T. Menna
- Ambipolar Diffusion Length in a-Si:H(F) and a-Si,Ge:H,F Measured with the Steady-State Photocurrent Grating Technique** 1606
J.Z. Liu, X. Li, P. Roca i Cabarrocas, J.P. Conde, A. Maruyama, H. Park, S. Wagner and A.E. Delahoy
- Improving Tin Oxide/Hydrogenated Amorphous Silicon Interfaces for Solar Cell Applications** 1610
P. Roca i Cabarrocas, S. Ramprasad, J.Z. Liu, V. Chu, A. Maruyama and S. Wagner

LATE NEWS

- Intrinsic Microcrystalline Silicon Deposited by Remote PECVD: A New Thin-Film Photovoltaic Material** 1614
C. Wang and G. Lucovsky
- A-(Si,Ge):H Alloys: Status and Issues** 1619
B. Stafford, B.N. Baron, V. Dalal and M. Silver

Modeling and Stability of Amorphous Silicon

Chairpersons:

R.S. Crandall
S. Guha

Organizer:

S. Fonash

- The Mobility Gaps in a-Si:H and its Effect on Solar Cell Performance** 1624
S. Lee, J.K. Arch, S.J. Fonash and C.R. Wronski
- Band Bending Due to Charged Dangling Bonds in Amorphous Silicon P-i-N Solar Cells** 1630
R.S. Crandall and H.M. Branz
- First Principles Computer Model Showing the Effect of p-Layer Thickness and Front Contact Barrier Height on the Performance of a-Si:H p-i-n Solar Cells** 1636
J.K. Arch, F.A. Rubinelli, J. Hou and S.J. Fonash
- Saturation Behavior of the Light-Induced Defect Density in Hydrogenated Amorphous Silicon** 1642
H.R. Park, J.Z. Liu, P. Roca i Cabarrocas, A. Maruyama, M. Isomura and S. Wagner
- Deposition Conditions, Hydrogen Content, and the Staebler-Wronski Effects in Amorphous Silicon** 1648
C.M. Fortmann, T. Zhou, C. Malone, M. Gunes and C.R. Wronski
- Improved Stability in Amorphous Silicon Germanium Solar Cells Made from Hydrogen-Diluted Silane and Germane** 1653
M.S. Bennett, A. Catalano, K. Rajan and R.R. Arya

Amorphous Silicon: Materials and Processing

Chairpersons:

C. Scherring
H. Aulich

Organizer:

C. Fortmann

High Absorption-Coefficient and Stable a-Si for High Efficiency Solar Cells 1656

S. Nakano, S. Okamoto, T. Takahama, M. Nishikuni,
K. Ninomiya, N. Nakamura, S. Tsuda, M. Ohnishi, Y.
Kishi and Y. Kuwano

Electrical and Structural Properties of a-Ge:H Alloys 1662

J.L. Newton and K. Kritikson

Production of 20 A/Sec⁻¹ a-Si Alloys for Use in Solar Cells 1667

P. Nath, K. Hoffman, J. Call, G. DiDio and S.R.
Ovshinsky

Large Area Deposition of a-Si PV Modules 1670

L. Boman, A. Bubenzer, J. Meot, J.P.M. Schmitt and
J.M. Siefert

POLYSILICON EMITTERS FOR SILICON CONCENTRATOR SOLAR CELLS

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ABSTRACT

Polysilicon emitters with a thermally grown interfacial oxide are examined in great detail. Both J_o and ρ_c are measured for the polysilicon emitter (contact) which is annealed under various conditions. $J_o \leq 5 \times 10^{-14}$ A/cm² and $\rho_c \sim 1 \times 10^{-5}$ Ω -cm² are obtained for both n- and p-type polysilicon emitters. The results also indicate that the interfacial oxide is only broken by a very small fraction in order to have $\rho_c \sim 1 \times 10^{-5}$ Ω -cm². Under such a condition, J_o is primarily dominated by the recombination at the oxide interface.

INTRODUCTION

Polysilicon emitters, because of their important applications in high speed bipolar transistors, have been widely studied. It was found that, between the polysilicon and the substrate, there always exists a very thin oxide (interfacial oxide), which can be as a by-product of the cleaning process or is grown intentionally [1,2,3,4,5,6,7]. In either case, the oxide is not thermally stable; i.e., it tends to break up during high temperature anneals [1,2,3,4,5,6,7]. The breakup of the interfacial oxide has direct impact on both majority and minority carrier transport in the polysilicon emitter. This can be seen from the dependence of the specific contact resistivity (ρ_c) [6] and the emitter saturation current density (J_o) [1,2,3,4,5,6,7] upon either the anneal condition or the oxide integrity. When the effect of the interfacial oxide is negligible, such as when the interfacial oxide loses its integrity in high temperature anneals, the ρ_c is low ($\sim 2 \times 10^{-7}$ Ω -cm²) [6] and the J_o is high ($\sim 1 \times 10^{-12}$) [1,3]. Conversely, when both carriers are mostly blocked by the interfacial oxide, like for an intact chemical oxide (~ 15 Å), the ρ_c is high and the J_o is low. Typically, $\rho_c \geq 1 \times 10^{-4}$ Ω -cm², and the corresponding $J_o \sim 1 \times 10^{-14}$

A/cm² have been observed on the n-type polysilicon emitter [1,5,6].

With the extent of the oxide breakup between these two extremes, various combinations of ρ_c and J_o can be obtained. It is of particular interest to know the ρ_c and the corresponding J_o when only a small fraction of the interfacial oxide is broken. For silicon solar cells operated under high concentrated sunlight, the emitter recombination is one of the main recombination that limit the solar cell performance [8]. This is because the diffused-emitter, which is formed with dopant diffusion into the base (substrate), has high J_o ($= 4.5 \times 10^{-13}$ A/cm²). Consequently, the cell performance can be improved if the diffused-emitter is replaced with the polysilicon emitter, of which the J_o is less than 4.5×10^{-13} A/cm² and the ρ_c is low enough.

In this paper, detailed calibrations for the polysilicon emitter with a thermally grown interfacial oxide is presented. Compared with the the chemical oxide, the thermal oxide appears to be more robust to the high temperature anneal. Consequently, this lends more controllability on the oxide breakup process. In addition, two separate anneal steps were used in order to avoid any possible interference from the dopant diffusion. It has been reported that the interfacial oxide tends to break up more rapidly with the existence of dopant [3,5]. Moreover, J_o also depends on the surface dopant concentration and the emitter depth [9]. In order to see the effect of the oxide breakup on J_o and ρ_c alone, it is therefore desirable to separate these two processes. The first-step anneal, which serves to break the oxide, was performed at higher temperature than that for the second-step anneal which aims for the dopant drive-in.

EXPERIMENTAL

Procedures

In this work, the J_o and ρ_c were measured independently for each type of polysilicon emitter (or contact). J_o was measured with photoconductivity decay method which has been reported elsewhere [10]. Because high bulk lifetime is needed for such a measurement, the samples were prepared with high resistivity ($>100 \Omega\text{-cm}$) FZ wafers. In contrast, ρ_c was measured on devices made on CZ wafers of which resistivity is 0.28 and $0.5 \Omega\text{-cm}$ for p- and n- type respectively. The device for ρ_c -measurement is shown in Fig. 1 schematically. Except for the pattern-definition steps which were not required for J_o -measurement samples, the two sets of wafers were always processed together. The process sequence is shown as followings:

1. Field oxidation ($2000 \text{ \AA}$)*.
2. Polysilicon-substrate contact opening*.
3. Thin thermal oxide growth at 800°C *. (10-minute oxygen flow)
4. Polysilicon deposition ($6000 \text{ \AA}$) and first-step anneal (1050°C)*.
5. First-step anneal*.
6. Polysilicon finger definition.
7. Undoped glass deposition ($2000 \text{ \AA}$).
8. Metal-polysilicon and metal-substrate contact opening.
9. Doped glass deposition on both sides of the wafer*.
10. Drive-in; $900\text{-}1000^\circ\text{C}$ *.
11. Doped glass stripping and Al-1% Si alloy deposition.
12. Metal finger definition.

Note that the steps marked with “*” are the steps for J_o -measurement samples. In addition, the J_o -samples are divided into two sets; one set of samples had an additional 400°C -30 min forming gas anneal (FGA), the other did not. The growth of thin oxide was carried out with 200 sccm oxygen and 5 slm argon mixture. Typically, oxide thickness less than $20 \text{ \AA}$ was measured with ellipsometer. In step 2, a series of square contacts of size between 1 and $64 \mu\text{m}$ are opened for polysilicon-substrate contacts.

ρ_c Measurement

As shown in Fig. 1, the voltage difference, V_{ab} , between probe A and B is caused by several components of the series resistance along the current loop. They are the resistance imposed by the bulk of the polysilicon and the wafer, the metal-polysilicon contact resistance, and the polysilicon-substrate contact resistance. The potential drop across the polysilicon film is conceivably negligible because the film is heavily doped and very thin. The metal-polysilicon contact resistance is actually measured on the similar device (four-terminal resistor [11]) next to the device shown in the figure. Typi-

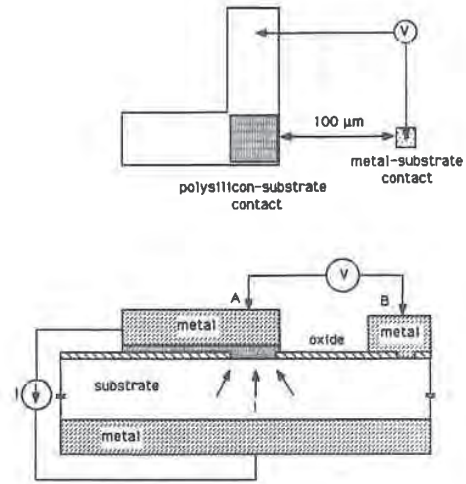


Figure 1: The device structure for the specific contact resistivity measurement.

cally, the ρ_c of the metal-polysilicon contact is less than $1 \times 10^{-6} \Omega\text{-cm}^2$. With such low ρ_c and large contact area between the metal and the polysilicon, the metal-polysilicon contact resistance can be ignored as well. As a result, the series resistance derived from V_{ab}/I is essentially determined by two terms; the bulk resistance of the silicon substrate and the polysilicon-substrate contact resistance. Such a series resistance can be expressed as a function of the size of the polysilicon-substrate square contact.

$$R = C \frac{\rho}{d} + \frac{\rho_c}{d^2}, \quad (1)$$

or

$$R_c = R \times d^2 = \rho_c + C \rho d; \quad (2)$$

where C is a constant that accounts for the contact geometry factor, ρ is the substrate resistivity, d is the width of the square contact, and ρ_c is the specific contact resistivity of the polysilicon-substrate contact. The contact size dependence of the last term in Eqn. (2) results from the crowding effect as the current flows toward the polysilicon-substrate contact. It is obvious that, from Eqn. (2), the ρ_c can be derived from the plot of R_c versus d which is obtained by measuring the series resistance of contacts of different sizes.

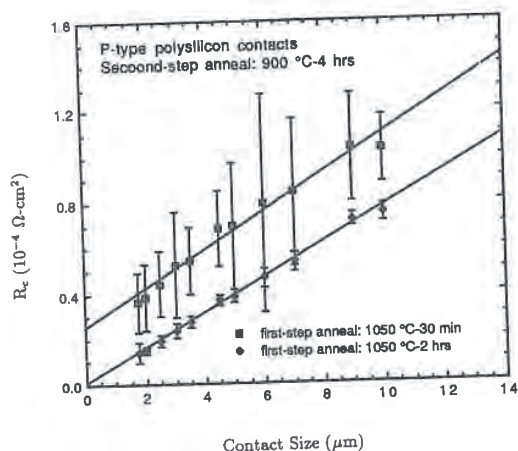


Figure 2: The R_c versus the contact size for p-type polysilicon contacts of different first-step anneals.

RESULTS AND DISCUSSIONS

Fig. 2 shows two R_c -plots for the p-type polysilicon contacts. One has the first-step anneal at 1050 °C for 30 minutes, the other has 1050 °C for 2 hours. Each data point is the average of 16 measurements across the wafer and the error bar is drawn with 4 standard deviations. Since devices were made on the wafers of about the same resistivity, the slopes of the linear-fit lines are almost identical. Note that, the devices that received a 30-minute first-step anneal have higher intercepts than those that received a 2-hour first-step anneal. This indicates that more oxide breakup occurs when the anneal time increases. Another characteristic of the interfacial oxide breakup can also be seen from the spread in the data (the length of the error bar). The magnitude of the error bar is not due to the measurement uncertainty; instead, it results from the random distribution of the oxide breakup. When only a very small fraction of the interfacial oxide is broken, it is possible that the interfacial oxide on each contact may not be broken equally. Consequently, this gives rise to the fluctuation of the resistance measured. On the other hand, the fluctuation will be subdued when more oxide is broken. This explains the different appearance of error bars observed between these two sets of data.

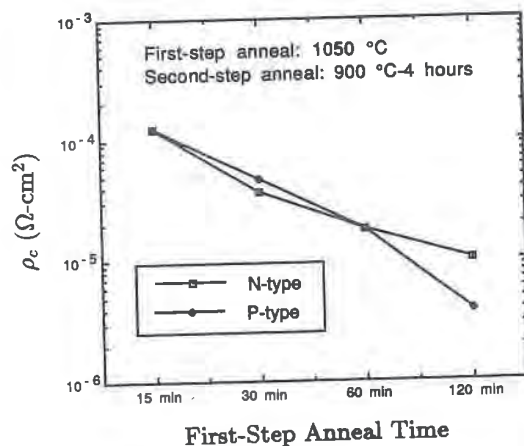


Figure 3: ρ_c of both n- and p- type polysilicon-substrate contacts is shown as a function of the time of the first-step anneal.

To see how the J_o and the ρ_c is affected by the first-step anneal, one set of samples (and device wafers) were first annealed at 1050 °C for various lengths of time (first-step anneal). After the doped-glass deposition, they were all annealed at 900 °C for 4 hours. The ρ_c measured from the device and the J_o measured from the photoconductivity decay are presented in the following figures.

In Fig. 3, ρ_c is plotted against the time of the first-step anneal for both types. Note that the ρ_c decreases as the anneal time increases. In addition, ρ_c measured from both n- and p- type devices are more or less the same, except those annealed with 120 minutes. The similarity of ρ_c between the n- and the p- type contact also indicates that the interaction between the dopant and the interfacial oxide is negligible; since such an interaction, if exists, would cause the ρ_c of the p-type to be lower [6].

The effects of the first-step anneal on J_o are presented in Fig. 4 and 5 for the n-type and the p-type polysilicon emitters respectively. In each figure, two sets of data are shown: the one with an FGA, and the one without. For the samples with an FGA, the J_o is significantly less than that without FGA for the same anneal condition. This indicates that the recombination

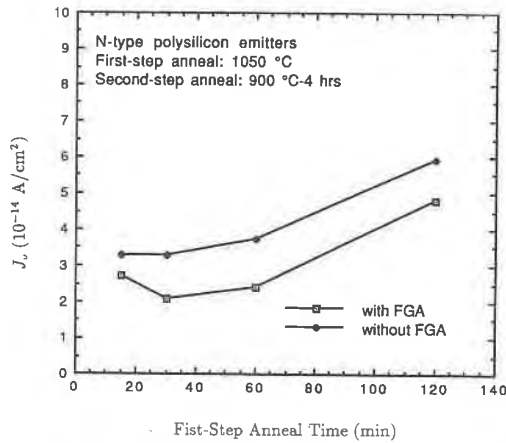


Figure 4: The J_o versus the first-step anneal time for n-type polysilicon emitters.

at the oxide interface is, at least, one of the dominant mechanisms for the emitter recombination. It is also important to note that the J_o of the p-type polysilicon emitter (Fig 5) appears to be much lower than what has been previously reported [1]. This may have to do to the use of thermal oxide as the interfacial layer in our samples. Either the thermal oxide is most robust during the high temperature anneal or the thermal oxide has lower interface defect state density (D_{it}) compared to the chemical oxide. Another interesting thing in these figures is that the J_o of the sample that received a 15-minute anneal is higher than the sample that received a 30-minute anneal. Moreover, such a behavior occurs in both the n- and the p- type samples. The possible explanation is that the interfacial oxide quality is improved by the high temperature anneal. This is not too surprising because the oxide was grown around 800 °C, in which higher D_{it} is expected [12,13]. Other than that, the J_o of both types appears to increase slowly with the anneal time. In addition, because the dominant recombination is likely at the oxide interface, it implies that the oxide must only be broken by very a small fraction, which is in consistent with what was observed in Fig. 2.

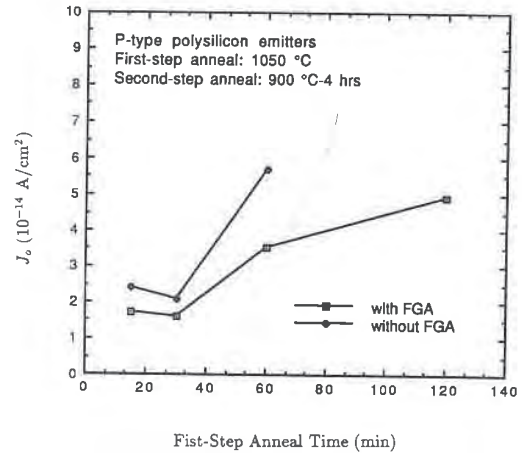


Figure 5: The J_o versus the first-step anneal time for p-type polysilicon emitters.

The effect of the second-step anneal (dopant drive-in) on both the J_o and the ρ_c were also investigated. All samples (and devices) received a first-step anneal at 1050 °C for one hour, followed with various treatments in the second-step anneal. The results are summarized in Table 1. The label on the right most column represents the second-step anneal condition of that sample. As shown in the table, the J_o increases with the temperature and time of the second-step anneal. In the meantime, the ρ_c decreases as the drive-in temperature increases. Considering the significant increase of J_o caused by increasing the drive-in temperature from 900 to 1000 °C, it is beneficial to use the two-step anneal to optimize J_o .

In Fig. 3, the decrease of ρ_c with the anneal time is what would be expected from the gradual breakup of the interfacial oxide. This is in consistent with the increase of J_o shown in Fig. 4 and Fig. 5, since J_o depends on the oxide integrity in the opposite way. This is especially clear when both ρ_c and J_o are plotted together. Fig. 6 is the ρ_c versus J_o plot for all the results obtained in this experiment. The inset is the list of the label

Table 1: The effect of the second-step anneal on J_o and ρ_c .

	N-type		P-type	
	$J_{o,e}$ ($\times 10^{-14}$ A/cm ²)	ρ_c ($\mu\Omega\text{-cm}^2$)	$J_{o,e}$ ($\times 10^{-14}$ A/cm ²)	ρ_c ($\mu\Omega\text{-cm}^2$)
900 °C-4 hour	2.4	18	3.5	18
1000 °C-30 min	4.5	~ 6	8.2	3.8
1000 °C-60 min	7.9		10.5	

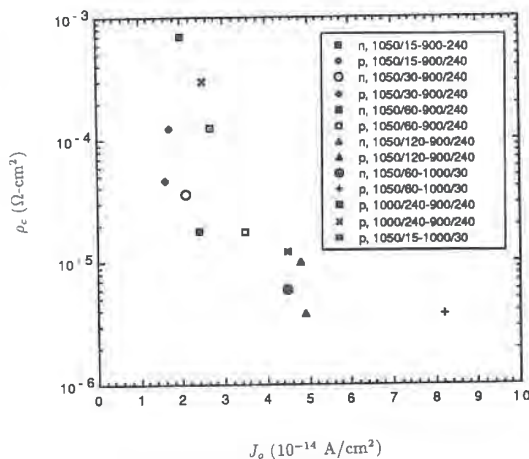


Figure 6: ρ_c - J_o of this work.

for each point. It specifies the type of polysilicon emitter, the first-step anneal (temperature/minute), and the second-step anneal (temperature/minute). As shown in the figure, the data runs from the upper-left corner to the lower-right corner which is similar to that reported by Crabbé [6] and is the typical trend when both ρ_c and J_o are regulated by the extent of oxide breakup. Nevertheless, from left to right, two distinct regimes are shown in the figure. In one regime, J_o is almost constant while ρ_c drops drastically. In the other regime, ρ_c decreases very slowly and J_o increases in much faster pace. In the first regime, that the J_o is inert to the oxide breakup is because the extent of the oxide breakup is very small such that the J_o is still dominated by the recombinations at the oxide interface and in the single-crystal outdiffusion. On the other hand, the drastic change of the ρ_c can be attributed to the transition of the majority carrier transport from the tunneling to the channel resistance. When the interfacial oxide is intact, tunneling is the only process available for the majority carriers to pass through the interfacial oxide. This usually results in a high contact resistance because of low tunneling probability. As the oxide starts to break up, additional highly conductive channels are created due to the intimate contacts formed between the polysilicon and the substrate in the broken regions [3,4,5]. A drastic change of ρ_c is observed when more currents flow through those channels. In the other regime, J_o starts to increase because the recombination in the polysilicon becomes comparable to the recombination mentioned

previously. On the other hand, the slow decrease of the ρ_c in this regime is because the majority carrier transport is completely dominated by the channel resistance. The increase of the oxide breakup can be thought as more parallel resistors added together; consequently, a significant change of ρ_c will not be observed.

The data shown in Fig. 6 are quite useful for silicon solar cells. First, most of J_o are below $5 \times 10^{-14} \text{ A/cm}^2$ which is about one order magnitude lower than that of diffused-emitters. Second, most of ρ_c are also lower than $5 \times 10^{-5} \text{ } \Omega\text{-cm}^2$. This means that the potential drop across the contact is negligible as long as the current density is less than 100 A/cm^2 . It is interesting to see how much of the cell efficiency can be improved with polysilicon emitters of characteristics given here. With the cell modeling, which is similar to the one reported by Sinton [8], more than one absolute percent of the cell efficiency is obtained for a backside contact solar cell with polysilicon emitters with characteristics shown here ($J_o = 2 \times 10^{-14} \text{ A/cm}^2$ for the n-type, $J_o = 3.5 \times 10^{-14} \text{ A/cm}^2$ for the p-type, and $\rho_c = 1 \times 10^{-5} \text{ } \Omega\text{-cm}^2$ for both types).

CONCLUSIONS

To conclude, we showed that polysilicon emitters with low J_o and ρ_c can be obtained with a very small fraction of interfacial oxide breakup. Typically, $\rho_c \sim 1 \times 10^{-5} \text{ } \Omega\text{-cm}^2$ and $J_o \leq 5 \times 10^{-14} \text{ A/cm}^2$ are obtained for both n- and p- type polysilicon emitters. From the cell modeling, polysilicon emitters with these qualities can be quite useful for silicon concentrator solar cells. Because only small fraction of interfacial oxide is broken, the J_o is primarily dominated by the recombination at the oxide interface and in the single-crystal diffusion region. Consequently, an interfacial oxide of good quality is important to obtain low J_o . Our results also indicates that ρ_c drops drastically when the oxide starts to breakup. This is explained by the transition of the dominant majority-carrier transport from the tunneling to the channel resistance.

This work was supported by the Electric Power Research Institute.

References

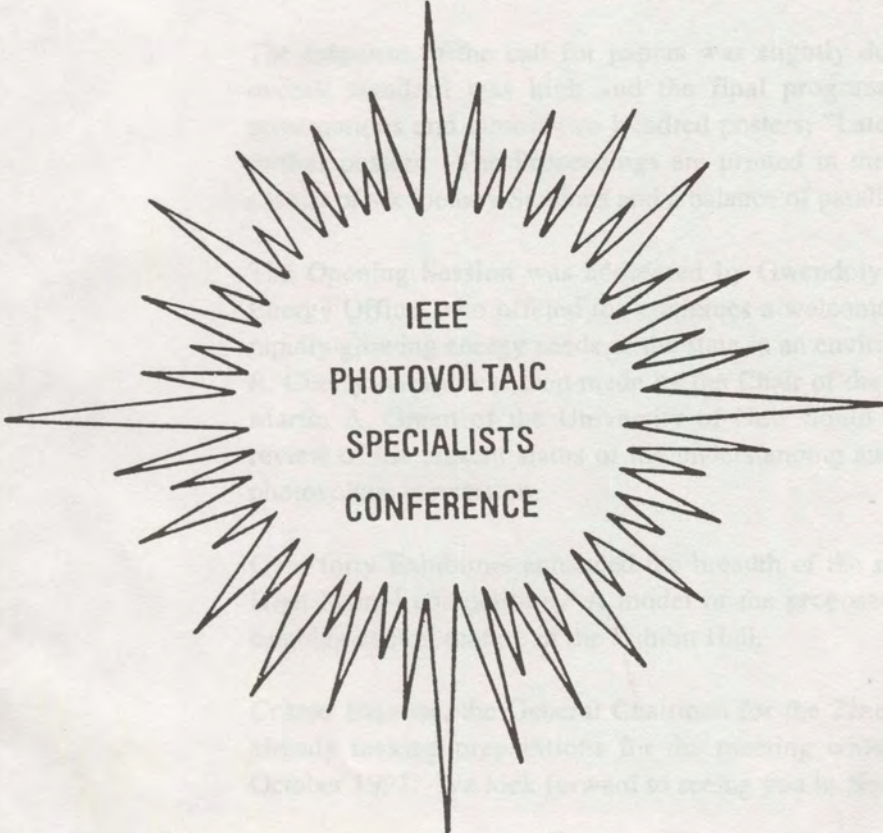
- [1] Y. Kwark, R. A. Sinton, and R. M. Swanson, "Low J_s Contact Structures Using SIPOS and Polysilicon Films," In *18th IEEE Photovoltaic Specialists Conference*, page 787, 1985.
- [2] H. C. de Graaff and J. G. de Groot, "The SIS Tunnel Emitter: A Theory Emitters with Thin Interface Lasers," *IEEE Trans. Electron Devices*, ED-26(11):1771, November 1979.
- [3] G. L. Patton, J. C. Bravman, and J. D. Plummer, "Impact of Processing Parameters on Base Current in Polysilicon Contacted Bipolar Transistors," In *IEDM Tech. Dig.*, page 30, 1985.
- [4] J. C. Bravman, G. L. Patton, and J. D. Plummer, "Structure and Morphology of Polycrystalline Silicon-Single Crystal Silicon Interfaces," *J. Appl. Phys.*, 57(8):2279, April 1987.
- [5] G. R. Wolstenholme, N. Jorgensen, P. Ashburn, and G. R. Booker, "An Investigation of the Thermal Stability of the Interfacial Oxide in Polycrystalline Silicon Emitter Bipolar Transistors by Comparing Device Results with High Resolution Electron Microscopy Observation," *J. Appl. Phys.*, 61(1):225, January 1987.
- [6] Emmanuel F. Crabbé, "Carrier Transport in Polysilicon Emitter Contacts for Scaled Bipolar Transistors," PhD thesis, Stanford University, 1988.
- [7] P. Ashburn and B. Soerowirdjo, "Comparison of Experimental and Theoretical Results on Polysilicon Emitter Bipolar Transistors," *IEEE Trans. Electron Devices*, ED-31(7):853, July 1984.
- [8] R. A. Sinton and R. M. Swanson, "An Optimization Study of Si Point-Contact Concentrator Solar Cells," In *19th IEEE Photovoltaic Specialists Conference*, page 1201, 1987.
- [9] R. R. King, R. A. Sinton and R. M. Swanson, "Studies of Diffused Phosphorus Emitters: Saturation Current, Surface Recombination Velocity, and Quantum Efficiency," *IEEE Trans. Electron Devices*, 37(2):365, February 1990.
- [10] D. E. Kane and R. M. Swanson, "Measurement of the Emitter Saturation Current by a Contactless Photoconductivity Decay Method," In *18th IEEE Photovoltaic Specialists Conference*, page 578, 1985.
- [11] Simon S. Cohen and Gennady SH. Gildenblat, editors. "Metal-Semiconductor Contacts and Devices," Volume 13 of *VLSI Electronics Microstructure Science*, Academic Press, 1986.
- [12] Reda R. Razouk and Bruce E. Deal, "Dependence of Interface State Density on Silicon Thermal Oxidation Process Variables," *J. Electrochem. Soc.*, 126(9):1573, September 1979.
- [13] M. Revitz, S. J. Raider, and R. A. Gdula, *J. Vac. Sci. Technol.*, 16(2):345, 1979.

ATTACHMENT F-2

THE CONFERENCE RECORD OF THE
**TWENTY FIRST IEEE
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VOLUME I

**Hyatt Orlando Hotel
Kissimmee, Florida
May 21-25, 1990**



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7/2, 91/18

CHAIR'S MESSAGE

Two groups of people deserve and most certainly have, my sincere appreciation for making the 21st Institute of Electrical and Electronics Engineers, Photovoltaic Specialists Conference a meeting worthy of our "coming of age". The authors and attendees provided the technical excellence and excitement that photovoltaics deserves and needs. The Executive and Program Committees, and everyone else who contributed to the organization and operation of the meeting, worked long and hard to ensure a smooth running and enjoyable week.

The recent Specialists Conferences have established an overall pattern that was followed at the 21st. On the Monday we held four Tutorials that certainly confirmed the popularity and demand for this type of session. This year the topics covered were Thin Film Solar Cells, Testing and Life Prediction of Solar Panels, High Efficiency Silicon Cells and Diagnostic Measurements.

The response to the call for papers was slightly down from the previous meeting but the overall standard was high and the final program featured just over one hundred oral presentations and almost two hundred posters; "Late News" submissions added twenty nine further posters. The Proceedings are printed in the order that the sessions took place and consist of six Plenary Sessions and a balance of parallel Oral or Poster Sessions.

The Opening Session was addressed by Gwendolyn Spencer, Director Florida Governor's Energy Office, who offered the conferees a welcome to Florida, and a challenge to meet the rapidly growing energy needs of the state in an environmentally acceptable way. The William R. Cherry Award was then made by the Chair of the Cherry Committee, Eugene L. Ralph, to Martin A. Green of the University of New South Wales. Dr. Green gave an impressive review of the present status of the understanding and practical realization of high efficiency photovoltaic conversion.

Over forty Exhibitors enhanced the breadth of the meeting and ten schools took part in the High School competition. A model of the proposed NASA Space Station provided an eye catching central feature in the Exhibit Hall.

Cosmo Baraona, the General Chairman for the 22nd Photovoltaic Specialists Conference, is already making preparations for the meeting which will take place in Las Vegas during October 1991. We look forward to seeing you in Nevada.

John D. Meakin
Chairman

TABLE OF CONTENTS

VOLUME I

William Cherry Award

Chairpersons:

J.D. Meakin
E.L. Ralph

Photovoltaics: Coming of Age

1

M.A. Green

High Efficiency Crystalline Cells and Materials

Overview of Recent Photovoltaic Developments

Chairperson:

J.D. Meakin

Organizer:

R.J. Schwartz

Photovoltaics: Meeting the Environmental Imperatives of Clean Air and Climate Change

9

W. Moomaw

Solar Photovoltaic Power: A U.S. Electric Utility R&D Perspective

16

E.A. DeMeo, F.R. Goodman, Jr., T.M. Peterson and J.C. Schaefer

Recent Advances in High Efficiency GaInP₂/GaAs Tandem Solar Cells

24

J.M. Olson, S.R. Kurtz, A. E. Kibbler and P. Faine

Photovoltaic Power for Space Station Freedom

30

C.R. Baraona

Advances in a-Si:H Alloys for High Efficiency Devices

36

A. Catalano

III-V Single and Multijunction Cells

Chairpersons:

S.P. Tobin
M. Yamaguchi

Organizer:

J.M. Gee

The Potential Performance of GaAs-Based Mechanically Stacked, Multijunction Solar Concentrator Cells

41

J.M. Gee and C.J. Chiang

Mechanically Stacked Two-Tandem Concentrator Solar Cell Concept

47

B. Beaumont, P. Garabedian, G. Nataf, J.C. Guillaume, P. Gibart and C. Verie

High-Efficiency GaAs/CuInSe₂ and AlGaAs/CuInSe₂ Thin-Film Tandem Solar Cells

53

R.P. Gale, R.W. McClelland, B.D. Dingle, J.V. Gormley, R.M. Burgess, N.P. Kim, R.A. Mickelsen and B.J. Stanbery

AlGaAs Top Solar Cell for Mechanical Attachment in a Multi-Junction Tandem Concentrator Solar Cell Stack

58

L.C. DiNetta, G.H. Negley, M.H. Hannon, J.R. Cummings, J.B. McNeely and A.M. Barnett

Monolithic Tandem Solar Cell Based on GaAlAs-GaAs System

64

L. Mayet, M. Gavand, B. Montégu, J.P. Boyeaux and A. Laugier

Graded-Band-Gap AlGaAs Solar Cells for AlGaAs/Ge Cascade Cells

68

M.L. Timmons, R. Venkatasubramanian, T.S. Colpitts, J.S. Hills, J.A. Hutchby, P.A. Iles and C.L. Chu

Development of Low Bandgap Ge and Si_{0.07}Ge_{0.93} Solar Cells for Monolithic and Mechanically-Stacked Cascade Applications

73

R. Venkatasubramanian, M.L. Timmons, R.T. Pickett, T.S. Colpitts, J.S. Hills, J.A. Hutchby, P.A. Iles and C.L. Chu

Large Scale, High Efficiency GaAs/Ge Cell Production

79

Y.C.M. Yeh, C. Cheng, F. Ho and H. Yoo

Large Area Shunt Defect Free GaAs Solar Cells

84

L.C. Kilmer and A.M. Barnett

A GaAs-ON-Si Solar Cell for Space Use

89

Y. Ohmachi, T. Ohara and Y. Kadota

New Results in Hetero-Epitaxy of GaAs/Ge/Si for High Efficiency in III-V Solar Cells on Low Cost Substrates

95

A. Leycuras, M.F. Vilela, J.C. Grenet, M. Leroux, G. Strobl, G. Neu and C. Verie

Back Contacted Emitter GaAs Solar Cells

99

G.L. Araujo, A. Marti and C. Algora

Application of InAlAs/GaAs Superlattice Alloys to GaAs Solar Cells

105

T.L. Drummond, J.M. Gee, F.L. Terry and R. Weng

Peeled Film GaAs Solar Cell Development

111

D.M. Wilt, R.D. Thomas, S.G. Bailey, G.A. Landis, D.J. Brinker, F.L. DeAngelo and N.S. Fatemi

An Evaporated Aluminum Metallization for High Efficiency GaAs Solar Cells

115

M. Ladle Ristow, M.S. Kuryla, H.F. MacMillan, N.R. Kaminar, G.F. Virshup, H.C. Hamaker, J.G. Werthen and K.A. Bertness

An Analysis of the Contact Sintering Process in III-V Solar Cells	119
V.G. Weizer and N.S. Fatemi	
Photovoltaic Characteristics of n⁺pp⁺InP Solar Cells by OMVPE	125
S. Tyagi, K. Singh, H. Bhimnathwala, S.K. Ghandhi and J.M. Borrego	
Study of Surface Passivation as a Function of InP Closed Ampoule Solar Cell Fabrication Processing Variables	130
Maria Faur, Mircea Faur, M. Goradia, C. Goradia, P. Jenkins, D. Jayne, S. Bailey and I. Weinberg	
High Efficiency GaAs Solar Cells Using GaInP₂ Window Layers	138
S.R. Kurtz, J.M. Olson and A.E. Kibbler	

LATE NEWS

Emitter Structures in MOCVD InP Solar Cells	141
C.J. Keavney, V.E. Haven and S.M. Vernon	
High Efficiency Thin Film GaAs Bifacial Solar Cells	145
R.W. McClelland, J.C.C. Fan, R.P. Gale and B.D. Dingle	
High Efficiency 1.0-eV GaInAs Bottom Solar Cell for 3-Junction Monolithic Stack	148
J.C. Schultz, M.E. Klausmeier-Brown, M.L. Ristow and M.M. Al-Jassim	

High Efficiency III-V Cells

Chairpersons:

J. Benner
C. Verie

Organizer:

J.M. Borrego

Buried Homojunction Solar Cells Formed in p-InP During Sputter Deposition and Hydrogen Plasma Processing	153
T.A. Gessert, X. Li, M.W. Wanlass and T.J. Coutts	
Advances in High-Efficiency GaAs Solar Cells	158
S.P. Tobin, S.M. Vernon, S.J. Wojtczuk, C. Bajgar, M.M. Sanfalcon and T.M. Dixon	
High Efficiency GaAs and AlGaAs Solar Cells Grown by Molecular Beam Epitaxy	163
M.R. Melloch, S.P. Tobin, C. Bajgar T.B. Stellwag, A. Keshavarzi, M.S. Lundstrom and K. Emery	
High Voltage, Monolithically Interconnected GaAs Thin Film Solar Submodules	168
R.W. McClelland, B.D. Dingle, R.P. Gale and J.C.C. Fan	
Development of High-Performance GaInAsP Solar Cells for Tandem Solar Cell Applications	172
M.W. Wanlass, J.S. Ward, G.S. Horner, T.A. Gessert, K.A. Emery, T.J. Coutts, G.F. Virshup and M.L. Ristow	

27.6% (1-Sun, Air Mass 1.5 G) Monolithic Two-Junction AlGaAs/GaAs Solar Cell and 25% Three-Junction AlGaAs/GaAs/InGaAs Cascade Solar Cell	179
B.C. Chung, G.F. Virshup and J.C. Schultz	
Progress Toward a 30% Efficient, Monolithic, Three-Junction, Two-Terminal Concentrator Solar Cell for Space Applications	184
L.D. Partain, B.C. Chung, G.F. Virshup, J.C. Schultz, H.F. MacMillan, M. Ladle Ristow, M.S. Kuryla, K.A. Bertness, M.E. Klausmeyer-Brown, M.W. Wanlass and T.J. Coutts	
Over 35% Efficient GaAs/GaSb Stacked Concentrator Cell Assemblies for Terrestrial Applications	190
L.M. Fraas, J.E. Avery, V. Sundaram, V.T. Dinh, T.M. Davenport, J.W. Yerkes, J.M. Gee and K.A. Emery	

High Efficiency Solar Cells

Chairperson:

R.M. Swanson

Organizer:

P.A. Basore

A Review of Indium Phosphide Space Solar Cell Fabrication Technology	196
M.B. Spitzer, B. Dingle, J. Dingle and R. Morrison	
Recent Improvements in Silicon Solar Cell and Module Efficiency	207
M.A. Green, S.R. Wenham, J. Zhao, J. Zolper and A.W. Blakers	
Experimental Study of Solar Cell Performance Versus Dislocation Density	211
S.M. Vernon, S.P. Tobin, M. M. Al-Jassim, R.K. Ahrenkiel, K.M. Jones and B.M. Keyes	

Silicon Solar Cells

Chairpersons:

R. Mertens
D.R. Lillington

Organizer:

R.M. Swanson

Crystalline Photovoltaic Cell Research, Status and Future Direction	217
D.E. Hasti, D.L. King and J.D. McBrayer	
Cost Effectiveness of High Efficiency Cell Processes as Applied to Cast Polycrystalline Silicon	221
J.H. Wohlgemuth, S. Narayanan and R. Brenneman	
Passivated Emitters in Silicon Solar Cells	227
R.R. King, P.E. Gruenbaum, R.A. Sinton and R.M. Swanson	
Surface Passivation of High Efficiency Silicon Solar Cells	233
A. Aberle, W. Warta, J. Knobloch and B. Voss	

UV Radiation Hardness of Silicon Inversion Layer Solar Cells	239	The Effects of Different Diffusion Sources on Silicon Solar Cell Recombination Properties	311
R. Hezel		D.S. Ruby and J.D. McBrayer	
Polysilicon Emitters for Silicon Concentrator Solar Cells	245	Stable Passivations for High-Efficiency Silicon Solar Cells	317
J.-Y. Gan and R.M. Swanson		P.E. Gruenbaum, J.Y. Gan, R.R. King and R.M. Swanson	
Deeply-Grooved Silicon Concentrator Solar Cells for use with Prismatic Covers	251	Advancements in Silicon Buried Contact Solar Cells	323
J.S. Culik, E.L. Jackson and A.M. Barnett		S.R. Wenham, F.Zhang, C.M. Chong and M.A. Green	
Super Self-Aligned Technology for Backside Contact Solar Cells: A Route to Low Cost and High Efficiency	257	Point- and Planar-Junction PIN Silicon Solar Cells for Concentration Applications, Fabrication, Performance and Stability	327
P. Verlinden, B. Lafontaine, P. Jacquemin, E. Goutain and A. Crahay		A. Cuevas, R.A. Sinton and R.M. Swanson	
Light Trapping in Thin Crystalline Silicon Solar Cells	263	24% Efficient PERL Structure Silicon Solar Cells	333
J.A. Rand, R.B. Hall and A.M. Barnett		J. Zhao, A. Wang and M.A. Green	
Fermi Degeneracy and Quantum Collection Efficiency in Heavily Doped Silicon Solar Cells	269	Modeling and Characterization of Single Crystal Solar Cells	
A. Morales-Acevedo		Chairpersons:	
Silane Glow Discharge Based Double Antireflection Coatings for cr-Si Solar Cells	275	A. Cuevas	
G. Willeke, E. Demesmaeker, J. Nijs and R. Mertens		G.F. Virshup	
Development of a Multi-Purpose, Pulsed-Laser System for Solar Cell Processing Applications	278	Organizer:	
D.L. King, B.R. Hansen and W.M. Lehrer		J.L. Gray	
Electrical Parameter Changes in Silicon Solar Cells Induced by Thermal Donor Formation	284	Temperature Coefficients of Multijunction Solar Cells	336
J.M. Ruiz and M. Cid		G.F. Virshup, B.C. Chung, M. Ladle Ristow, M.S. Kuryla and D. Brinker	
Series Resistance Calculations in Silicon Solar Cells at Very High Concentration	289	Modeling of Two-Junction, Series-Connected Tandem Solar Cells Using Top-Cell and Coating Thicknesses as Adjustable Parameters	339
I. Tobias and A. Luque		P. Faine, S.R. Kurtz and J.M. Olson	
Annealing and Temperature Effects on Minority Carriers in Ion Implanted Silicon Solar Cells	295	Numerical Model for Tunnel Junctions with Application to Cascade Solar Cells	345
P. Nubile, A.F. Beloto, N. Veissid, B. Waldman, I. Pereyra and A.M. Andrade		J.L. Gray	
LATE NEWS		OBIC Studies: Classification of Structural Defects and Their Influence on the Performance of MOCVD Grown GaAs Solar Cells	348
Characterization of Very-Thin High-Efficiency Corrugated Silicon Solar Cells	299	X. Tang, P.J.M. Boots and L.J. Giling	
T. Uematsu, K. Kanda, S. Kokunal, T. Warabisako, S. Iida and T. Saitoh		Intensity Effects in Minority Carrier Lifetime Measurements	353
Developments in Module Ready Si Backside-Contact Solar Cells	302	D.C. Marvin and L.F. Halle	
R.A. Sinton, R.A. Crane, S. Beckwith, A. Cuevas, P.E. Gruenbaum, D.E. Kane, J.Y. Gan, R.R. King, N. Midkiff and R.M. Swanson		Transient Photoluminescence Decay Investigations of LPE GaAs Heteroface Solar Cells	357
High Efficiency Silicon Solar Cells		W. Wettling, A. Ehrhardt, A. Bett and F.Lutz	
Chairpersons:		Characterization of Antireflection Films for Surface-Passivated Crystalline Silicon Solar Cells Using Spectroscopic Ellipsometry	363
A. Luque		O. Kamataki, T. Saitoh, S. Iida and T. Uematsu	
R.A. Sinton		Detailed Analysis of the Factors Affecting Emitter Recombination in Solar Cells Through the Small-Signal Voltage Decay Method	368
Organizer:		K. Joardar, D.K. Schroder and C.E. Backus	
R.M. Swanson		Microwave-Detected Photoconductance Decay	374
Electro-Epitaxial Growth of Thin Film Silicon	307	P.A. Basore and B.R. Hansen	
D.W. Cunningham, M.G. Mauk, J.P. Curran and A.M. Barnett			

Experimental Measurement of the Intrinsic Carrier Concentration of Silicon	380
A.B. Sproul and M.A. Green	
Key Factors Limiting the Open Circuit Voltage of n^+pp^++ Indium Phosphide Solar Cells	386
C. Goradia, W. Thesling and I. Weinberg	
Lifetime Measurements by Open Circuit Voltage Decay in GaAs and InP Diodes	394
H. Bhimnathwala, S.Bothra, S. Tyagi, S.K. Ghandhi and J.M. Borrego	
Measurement of Surface Recombination Velocity on Heavily Doped InP	399
P. Jenkins, S.G. Bailey, Mircea Faur, M. Ghalla-Goradia and Maria Faur	
Surface Recombination Velocity and Lifetime in InP Measured by Transient Microwave Reflectance	404
S. Bothra, S. Tyagi, S.K. Ghandhi and J.M. Borrego	
Energy and Free Energy Analyses of Photovoltaic Energy Conversion	409
J.E. Parrott	
PC-ID Modeling of Depletion Layer Recombination in GaAs Solar Cells	415
L.C. Olsen, D.A. Huber, G. Dunham and F.W. Addis	
Non-Solar Photovoltaic Cells	420
P.A. Iles	
 Modeling and Characterization of Single Crystal Solar Cells	
 Chairpersons:	
P.A. Basore	
J.L. Gray	
 Organizer:	
R.A. Sinton	
Texture: A Ray Tracing Program for the Photovoltaic Community	426
A.W. Smith, A. Rohatgi and S.C. Neel	
Design of High Efficiency GaAs Solar Cells by Photoluminescence Studies	432
R.K. Ahrenkiel, D.J. Dunlavy, B. Keyes, S.M. Vernon, S.P. Tobin and T.M. Dixon	
Physical Parameters of Highly Injected Silicon in the Modelling of Concentrator Solar Cells	437
D.E. Kane, R.A. Sinton, J.Y. Gan and R.M. Swanson	
Effects of Perimeter Recombination on GaAs-Gased Solar Cells	442
T.B. Stellwag, P.E. Dodd, M.S. Carpenter, M.S. Lundstrom, R.F. Pierret, M.R. Melloch, E. Yablonovitch and T.J. Gmitter	
Reverse I-V Characteristics of GaAs Cells	448
P.A. Iles, H. Yoo, C. Chu, J. Krogen and K.I. Chang	
Effects of Heavy Impurity Doping on the np Product in p-GaAs	455
M.E. Klausmeier-Brown, M.R. Melloch and M.S. Lundstrom	

Polycrystalline Solar Cells

Thin Film Compound Semiconductors

Chairpersons:

J.E. Phillips

K.W. Mitchell

Organizer:

C. Eberspacher

Polycrystalline Thin Film Photovoltaics	458
K. Zweibel, H.S. Ullal and R.L. Mitchell	
Key Issues and Cost Estimates for the Fabrication of CuInSe₂ (CIS) PV Modules by the Two-Stage Process	467
V.K. Kapur and B.M. Basol	
A Novel Electrochemical Technique for Insitu Deposition of Photoactive CuInSe₂ Thin Films for Solar Cells	471
P. Garg, J.C. Garg and A.C. Rastogi	
A Low Cost Method for Large Area Production of CuInSe₂/(CdZn)S Devices	477
H. Oumous, A. Knowles, M.H. Badawi, M.J. Carter and R. Hill	
Improvement of Cu(Ga,In)Se₂ Based Solar Cells by Etching the Absorber	481
R. Klenk, R. Menner, D. Cahen and H.W. Schock	
Photovoltaic Performance of p-AgGaSe₂/n-CdS Thin Film Heterojunction	487
Y.S. Murthy, O.M. Hussain, B.S. Naidu and P.J. Reddy	
Junctions Mode Using p-CdTe Films with Ion-Assisted Doping	493
P. Sharps, A.L. Fahrenbruch, A. Lopez-Otero, M. Schöfthaler and R.H. Bube	
CdS/CdTe Solar Cells by the Screen-Printing-Sintering Technique	498
N. Suyama, T. Arita, Y. Nishiyama, N. Ueno, S. Kitamura and M. Murozono	
Effects of Preheat Treatment of CdS on MOCVD CdTe/Cds Solar Cell Performance	504
R. Sudharsanan and A. Rohatgi	
Cd_{1-x}Zn_xTe Films Obtained by the Solid-State Reaction of Elemental Layers	509
B.M. Basol, V.K. Kapur and R.L. Mitchell	
Polycrystalline Thin Films of Mercury Zinc Telluride for Use in Multijunction Solar Cells	514
S. Arshed, R.W. Miles and R. Hill	
Improvement of ZnO/WSe₂ Solar Cells by Doping?	519
M. Vogt, M.Ch. Lux-Steiner, P. Dolatzoglou, W. Reetz, B. Bumuller and E. Bucher	
Ionized Cluster Beam Deposition of GaAs Thin Films for Solar Cells	525
D. Bonnet and S. Oelting	

LATE NEWS

- Reactor Analysis of Copper Indium Selenization** 529
R.D. Varrin, Jr., S. Verma, R.W. Birkmire, B.E. McCandless and T.W.F. Russell

- 4-CM² CuInGaSe₂ Based Solar Cells** 535
W.E. Devaney, J.M. Stewart and W.S. Chen

- Correlations of Single-Crystal CuInSe₂ Surface Processing with Defect Levels and Cell Performance** 541
F.A. Abou-Elfotouh, L.L. Kazmerski, A.A.J. Al-Douri and A.M. Bakry

Thin Film Compound Semiconductors

Chairpersons:

R. Noufi
R. Hill

Organizer:

B. Basol

- CuInSe₂ Thin Films and High-Efficiency Solar Cells Obtained By Selenization of Metallic Layers** 546
B.M. Basol and V.K. Kapur

- Options for Fabrication and Design of CuInSe₂ Based Solar Cells** 550
R.W. Birkmire, W.N. Shafarman and R.D. Varrin

- Individual Losses in Thin-Film CdTe Solar Cells** 556
H. Tavakolian and J.R. Sites

- A Study on the Optical and Microstructural Characteristics of Quaternary Cu(In,Ga)Se₂ Polycrystalline Thin Films** 562
D. Albin, J. Tuttle, G.D. Mooney, J.J. Carapella, A. Duda, A. Mason and R. Noufi

- The Use of CuIn_{1-x}Ga_xSe₂ Layers to Improve the Performance of CuInSe₂ Cells** 570
R.J. Schwartz and J.L. Gray

- Towards High Efficiency Electrodeposited CdS/CdTe Thin Film Cells** 575
G.C. Morris, P.G. Tanner and A. Tottszer

Polycrystalline Solar Cells

Chairpersons:

T.J. Coutts
C. Eberspacher

Organizer:

T.J. Coutts

- Doping and Oxygen Dependence of Efficiency of EFG Silicon Solar Cells** 581
A. Rohatgi, W.A. Doolittle, A.W. Smith, F.V. Wald, R.O. Bell and C.E. Dube

- Thin Film CdTe Solar Cells—A Review** 588
B. Basol

- Advances in Large Area CuInSe₂ Thin Film Modules** 595
J.H. Ermer, J. Hummel, C.L. Jensen, C.V. Fredric, D. Pier, D. Tarrant and K. Mitchell

Polycrystalline Silicon

Chairpersons:

D.K. Schroder
A.M. Barnett

Organizer:

R. Hall

- Status of the Direct Solidification of Silicon Wafers by RAFT** 600
A. Beck, J. Geibler and D. Helmreich

- 10% Efficient Commercial-Scale Silicon-Film Solar Cells** 604
C.L. Kendall, J.C. Checchi, M.L. Rock, R.B. Hall and A.M. Barnett

- Improvements in Direct-Cast Semicrystalline Silicon Solar Cells** 608
H. Somberg

- Development of the E.P.R. Technology for an Oriented Crystal Growth of Semiconductor Wafers** 610
A. Chibani, S. Sof, M. Hamoud, R. Gauthier, P. Pinard and K. Marsh

- Recent Results in Optical Processing of Silicon Sheet** 615
J.M. Serra and A.M. Vallera

- Effects of Encapsulation on the Performance of Silicon Solar Cells** 618
B.L. Sopori

- Improved Contact Metallization for High Efficiency EFG Polycrystalline Silicon Solar Cells** 624
C.E. Dubé and R.C. Gonsiorawski

- Rapid Thermal Processing Effect on the Intragrain and Grain Boundaries Properties of Multicrystalline Silicon Solar Cells** 629
J.P. Boyeaux, K. Masri, G. Chaussemy, L. Mayet and A. Laugier

- Process Induced Improvements in Polycrystalline Silicon-Film Solar Cells** 634
M.L. Rock, D.W. Cunningham, C.L. Kendall, R.B. Hall and A.M. Barnett

- Hydrogen Passivation of Polycrystalline Silicon Solar Cells by Plasma Deposition of Silicon Nitride** 638
P.P. Michiels, L.A. Verhoef, J.C. Stroom, R.J.C. van Zolingen, C.M.M. Denisse, M. Hendriks and W.C. Sinke

- Defect Generation/Passivation by Low Energy Hydrogen Implant for Silicon Solar Cells** 644
B.L. Sopori, T.Q. Zhou and G.A. Rozgonyi

- Improved Backside Hydrogenation on Semicrystalline Silicon Solar Cells by RF Plasma** 650
M.A.G. Soler, I. Pereyra, F.J. Fonseca and A.M. Andrade

- One Sun Crystalline Silicon Materials Research: Current Direction and Future Needs** 653
B.L. Sopori, J. Benner and J.D. McBraver

- Formation of PN Junction with Hydrogenated Microcrystalline Silicon** 659
K. Kawabata, H. Morikawa, T. Ishihara, K. Sato, H. Sasaki, T. Itagaki, M. Deguchi, S. Hamamoto and M. Aiga

LATE NEWS

- Cast Polycrystalline Silicon Solar Cell with Grooved Surface** 664
T. Nunoi, S. Okamoto, K. Nakajima, S. Tanaka, N. Shibuya, K. Okamoto, T. Nammori and H. Itoh
- Ink Jet Printing for Metallization on Very Thin Solar Cells** 666
H. Somberg
- Large Area High Efficiency Multicrystalline Silicon Solar Cell** 668
K. Shirasawa, H. Yamashita, K. Fuku, M. Takayama, K. Okada, K. Masuri and H. Watanabe
- Cold Crucible Induction Casting of Semi-Conductor Silicon for Solar Cell** 674
K. Kaneko, T. Misawa and K. Tabata

Polycrystalline Silicon

Chairpersons:

R.B. Hal
A. Goetzberger

Organizer:

T. Gessert

- 18% Efficient Polycrystalline Silicon Solar Cells** 678
S. Narayanan, J. Zolper, F. Yun, S.R. Wenham, A.B. Sproul, C.M. Chong and M.A. Green
- Correlation Between Impurities, Defects and Cell Performance in Semicrystalline Silicon** 681
W.A. Doolittle, A. Rohatgi and R. Brenneman
- The Effects of Chromium on Edge-Defined Film-Fed Growth (EFG) Polycrystalline Silicon Solar Cells** 687
B. Bathey, C.E. Dubé, J.P. Kalajs and F.V. Wald
- Hydrogen Passivation of Polycrystalline Silicon Solar Cells by Means of Catalytic Reactions** 691
M. Kaiser and R. Schindler
- Manufacture of SI Ribbons by the S-Web Technique** 695
R. Falckenberg, J.G. Grabmaier, K.H. Eisenrith, B. Freienstein, A. Lerchenberger, R. Schindler and F. Lutz
- Mass-Production of High Quality Polycrystalline Silicon Sheets by the New Spin Cast Process** 700
M. Suzuki, I. Hide, T. Matsuyama, H. Yarnashita, T. Suzuki, T. Moritani and Y. Maeda

Polycrystalline Materials and Device Characterization

Chairperson:

B.J. Stanbery

Organizer:

C. Eberspacher

- Lateral Distribution of Metallic Impurities in Silicon Bicrystals Investigated by Scanning MCTS** 705
T. Heiser, A. Mesli and P. Siffert
- Physical and Electrical Investigation of Silicide Precipitates in EFG Polycrystalline Silicon Intentionally Contaminated with Chromium** 711
J.B. Mohr, S.H. Park, S.N. Schauer, D.K. Schroder and J. Kalejs
- Influence of Oxygen on Polycrystalline Silicon Sheet** 717
I. Hide, T. Matsuyama, M. Suzuki, H. Yamashita, T. Suzuki, T. Moritani and Y. Maeda
- DLTS Study of EFG Solar Cells** 721
S. Mil'shtein, J.T. Borenstein, J.I. Hanoka and Y. Yang
- Automated Defect, Inclusion and Morphological Analysis of Solarex Polycrystalline Silicon** 726
R. Brenneman, D. Ramsey and D. Angell
- Modeling of the Grain Boundary Potential for Poly-Si** 731
Z. Chen and L.C. Burton
- Investigation of Conventional and Pregettered Multicrystalline Silicon Cells in Terms of Lifetime, Diffusion Length and Defects** 737
I. Perichaud, G. Mathian, S. Martinuzzi, M. Pasquinelli and J. Gervais
- Effect of Oxidation-Reduction Heat Treatments on CuInSe₂/CdS Device Behavior** 743
M. Roy and J.E. Phillips
- Secondary and Polymorphic Phase Behavior of Thin Film CuInSe₂: Ramifications on the Device Performance** 748
J.R. Tuttle, D.S. Albin, J. Goral and R. Noufi
- Nomarski Contrast Microscopy of CuBSe₂/Mo (B = In, Ga) Films** 755
L. Margulis, A. Jakubowicz, G. Hodes and D. Cahen
- Raman Scattering Study of CuInSe₂ Films Prepared by Three-Source RF-Sputtering and by Selenization of Cu/In/Se Stacked Layers** 758
S. Yamanaka, M. Tanda, K. Horino, K. Ito, A. Yamada, M. Konagai and K. Takahashi
- Deposition of CuInSe₂ by the Hybrid Sputtering and Evaporation Method** 764
A. Rockett, C.J. Kiely, G. Kenshole, L. Chung Yang, H. Talieh, L.C. Yang, E. Banda and A. Agarwal
- Preparation of Nonstoichiometric CuInSe₂ Crystals by the Bridgman Method** 768
L.S. Yip, W.S. Weng, I. Shih and C.H. Champness

LATE NEWS

- Shunt Effects in Polycrystalline GaAs Solar Cells** 772
C. Honsberg and A.M. Barnett
- Thin Film CdTe Homojunctions by MOCVD** 777
T.L. Chu, S.S. Chu, C. Ferekides, J. Britt and C.W. Wu

Polycrystalline Materials and Device Characterization

Chairpersons:

B.L. Sopori
G.C. Morris

Organizer:

T. Coutts

- Determination of Diffusion Length with Bi-Facial Spectral Response** 782
J.E. Phillips
- Advanced X-Ray Analysis of Polycrystalline CuInSe₂ Thin Films** 787
H. Dittrich, R. Menner and H.W. Schock
- In-Depth Characterization of Si Solar Cells** 793
L.A. Verhoef, F.J. Bisschop, J.C. Stroom and W. Sinke
- Hot Spots and Heavily Dislocated Regions in Multi-crystalline Silicon Cells** 800
A. Simo and S. Martinuzzi

POLYSILICON EMITTERS FOR SILICON CONCENTRATOR SOLAR CELLS

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ABSTRACT

Polysilicon emitters with a thermally grown interfacial oxide are examined in great detail. Both J_o and ρ_c are measured for the polysilicon emitter (contact) which is annealed under various conditions. $J_o \leq 5 \times 10^{-14}$ A/cm² and $\rho_c \sim 1 \times 10^{-5}$ Ω -cm² are obtained for both n- and p-type polysilicon emitters. The results also indicate that the interfacial oxide is only broken by a very small fraction in order to have $\rho_c \sim 1 \times 10^{-5}$ Ω -cm². Under such a condition, J_o is primarily dominated by the recombination at the oxide interface.

INTRODUCTION

Polysilicon emitters, because of their important applications in high speed bipolar transistors, have been widely studied. It was found that, between the polysilicon and the substrate, there always exists a very thin oxide (interfacial oxide), which can be as a by-product of the cleaning process or is grown intentionally [1,2,3,4,5,6,7]. In either case, the oxide is not thermally stable; i.e., it tends to break up during high temperature anneals [1,2,3,4,5,6,7]. The breakup of the interfacial oxide has direct impact on both majority and minority carrier transport in the polysilicon emitter. This can be seen from the dependence of the specific contact resistivity (ρ_c) [6] and the emitter saturation current density (J_o) [1,2,3,4,5,6,7] upon either the anneal condition or the oxide integrity. When the effect of the interfacial oxide is negligible, such as when the interfacial oxide loses its integrity in high temperature anneals, the ρ_c is low ($\sim 2 \times 10^{-7}$ Ω -cm²) [6] and the J_o is high ($\sim 1 \times 10^{-12}$) [1,3]. Conversely, when both carriers are mostly blocked by the interfacial oxide, like for an intact chemical oxide (~ 15 Å), the ρ_c is high and the J_o is low. Typically, $\rho_c \geq 1 \times 10^{-4}$ Ω -cm², and the corresponding $J_o \sim 1 \times 10^{-14}$

A/cm² have been observed on the n-type polysilicon emitter [1,5,6].

With the extent of the oxide breakup between these two extremes, various combinations of ρ_c and J_o can be obtained. It is of particular interest to know the ρ_c and the corresponding J_o when only a small fraction of the interfacial oxide is broken. For silicon solar cells operated under high concentrated sunlight, the emitter recombination is one of the main recombination that limit the solar cell performance [8]. This is because the diffused-emitter, which is formed with dopant diffusion into the base (substrate), has high J_o ($= 4.5 \times 10^{-13}$ A/cm²). Consequently, the cell performance can be improved if the diffused-emitter is replaced with the polysilicon emitter, of which the J_o is less than 4.5×10^{-13} A/cm² and the ρ_c is low enough.

In this paper, detailed calibrations for the polysilicon emitter with a thermally grown interfacial oxide is presented. Compared with the chemical oxide, the thermal oxide appears to be more robust to the high temperature anneal. Consequently, this lends more controllability on the oxide breakup process. In addition, two separate anneal steps were used in order to avoid any possible interference from the dopant diffusion. It has been reported that the interfacial oxide tends to break up more rapidly with the existence of dopant [3,5]. Moreover, J_o also depends on the surface dopant concentration and the emitter depth [9]. In order to see the effect of the oxide breakup on J_o and ρ_c alone, it is therefore desirable to separate these two processes. The first-step anneal, which serves to break the oxide, was performed at higher temperature than that for the second-step anneal which aims for the dopant drive-in.

EXPERIMENTAL

Procedures

In this work, the J_o and ρ_c were measured independently for each type of polysilicon emitter (or contact). J_o was measured with photoconductivity decay method which has been reported elsewhere [10]. Because high bulk lifetime is needed for such a measurement, the samples were prepared with high resistivity ($>100 \Omega\text{-cm}$) FZ wafers. In contrast, ρ_c was measured on devices made on CZ wafers of which resistivity is 0.28 and $0.5 \Omega\text{-cm}$ for p- and n- type respectively. The device for ρ_c -measurement is shown in Fig. 1 schematically. Except for the pattern-definition steps which were not required for J_o -measurement samples, the two sets of wafers were always processed together. The process sequence is shown as follows:

1. Field oxidation ($2000 \text{ \AA}$)*.
2. Polysilicon-substrate contact opening*.
3. Thin thermal oxide growth at 800°C *. (10-minute oxygen flow)
4. Polysilicon deposition ($6000 \text{ \AA}$) and first-step anneal (1050°C)*.
5. First-step anneal*.
6. Polysilicon finger definition.
7. Undoped glass deposition ($2000 \text{ \AA}$).
8. Metal-polysilicon and metal-substrate contact opening.
9. Doped glass deposition on both sides of the wafer*.
10. Drive-in; $900\text{-}1000^\circ\text{C}$ *.
11. Doped glass stripping and Al-1% Si alloy deposition.
12. Metal finger definition.

Note that the steps marked with “*” are the steps for J_o -measurement samples. In addition, the J_o -samples are divided into two sets; one set of samples had an additional 400°C -30 min forming gas anneal (FGA), the other did not. The growth of thin oxide was carried out with 200 sccm oxygen and 5 slm argon mixture. Typically, oxide thickness less than $20 \text{ \AA}$ was measured with ellipsometer. In step 2, a series of square contacts of size between 1 and $64 \mu\text{m}$ are opened for polysilicon-substrate contacts.

ρ_c Measurement

As shown in Fig. 1, the voltage difference, V_{ab} , between probe A and B is caused by several components of the series resistance along the current loop. They are the resistance imposed by the bulk of the polysilicon and the wafer, the metal-polysilicon contact resistance, and the polysilicon-substrate contact resistance. The potential drop across the polysilicon film is conceivably negligible because the film is heavily doped and very thin. The metal-polysilicon contact resistance is actually measured on the similar device (four-terminal resistor [11]) next to the device shown in the figure. Typi-

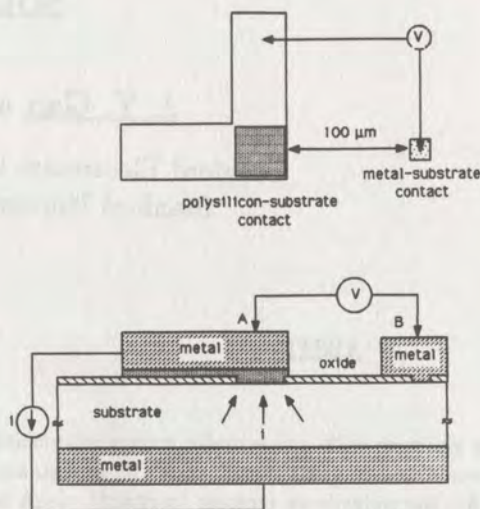


Figure 1: The device structure for the specific contact resistivity measurement.

cally, the ρ_c of the metal-polysilicon contact is less than $1 \times 10^{-6} \Omega\text{-cm}^2$. With such low ρ_c and large contact area between the metal and the polysilicon, the metal-polysilicon contact resistance can be ignored as well. As a result, the series resistance derived from V_{ab}/I is essentially determined by two terms; the bulk resistance of the silicon substrate and the polysilicon-substrate contact resistance. Such a series resistance can be expressed as a function of the size of the polysilicon-substrate square contact.

$$R = C \frac{\rho}{d} + \frac{\rho_c}{d^2}, \quad (1)$$

or

$$R_c = R \times d^2 = \rho_c + C \rho d; \quad (2)$$

where C is a constant that accounts for the contact geometry factor, ρ is the substrate resistivity, d is the width of the square contact, and ρ_c is the specific contact resistivity of the polysilicon-substrate contact. The contact size dependence of the last term in Eqn. (2) results from the crowding effect as the current flows toward the polysilicon-substrate contact. It is obvious that, from Eqn. (2), the ρ_c can be derived from the plot of R_c versus d which is obtained by measuring the series resistance of contacts of different sizes.

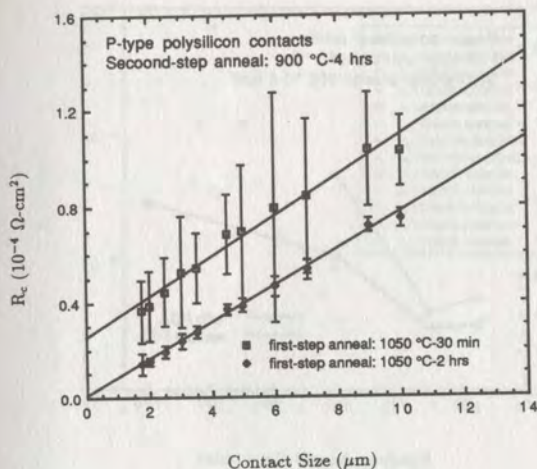


Figure 2: The R_c versus the contact size for p-type polysilicon contacts of different first-step anneals.

RESULTS AND DISCUSSIONS

Fig. 2 shows two R_c -plots for the p-type polysilicon contacts. One has the first-step anneal at 1050 °C for 30 minutes, the other has 1050 °C for 2 hours. Each data point is the average of 16 measurements across the wafer and the error bar is drawn with 4 standard deviations. Since devices were made on the wafers of about the same resistivity, the slopes of the linear-fit lines are almost identical. Note that, the devices that received a 30-minute first-step anneal have higher intercepts than those that received a 2-hour first-step anneal. This indicates that more oxide breakup occurs when the anneal time increases. Another characteristic of the interfacial oxide breakup can also be seen from the spread in the data (the length of the error bar). The magnitude of the error bar is not due to the measurement uncertainty; instead, it results from the random distribution of the oxide breakup. When only a very small fraction of the interfacial oxide is broken, it is possible that the interfacial oxide on each contact may not be broken equally. Consequently, this gives rise to the fluctuation of the resistance measured. On the other hand, the fluctuation will be subdued when more oxide is broken. This explains the different appearance of error bars observed between these two sets of data.

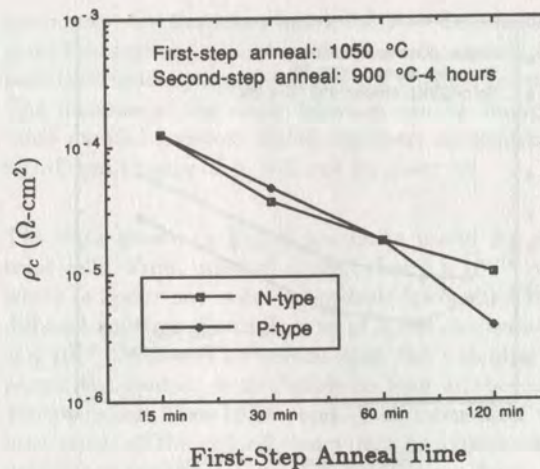


Figure 3: ρ_c of both n- and p- type polysilicon-substrate contacts is shown as a function of the time of the first-step anneal.

To see how the J_o and the ρ_c is affected by the first-step anneal, one set of samples (and device wafers) were first annealed at 1050 °C for various lengths of time (first-step anneal). After the doped-glass deposition, they were all annealed at 900 °C for 4 hours. The ρ_c measured from the device and the J_o measured from the photoconductivity decay are presented in the following figures.

In Fig. 3, ρ_c is plotted against the time of the first-step anneal for both types. Note that the ρ_c decreases as the anneal time increases. In addition, ρ_c measured from both n- and p- type devices are more or less the same, except those annealed with 120 minutes. The similarity of ρ_c between the n- and the p- type contact also indicates that the interaction between the dopant and the interfacial oxide is negligible; since such an interaction, if exists, would cause the ρ_c of the p-type to be lower [6].

The effects of the first-step anneal on J_o are presented in Fig. 4 and 5 for the n-type and the p-type polysilicon emitters respectively. In each figure, two sets of data are shown: the one with an FGA, and the one without. For the samples with an FGA, the J_o is significantly less than that without FGA for the same anneal condition. This indicates that the recombination

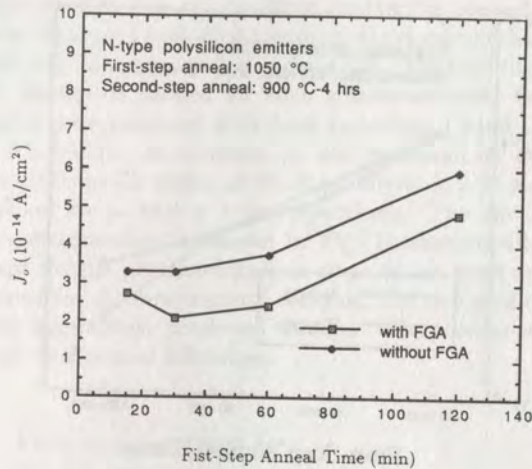


Figure 4: The J_o versus the first-step anneal time for n-type polysilicon emitters.

at the oxide interface is, at least, one of the dominant mechanisms for the emitter recombination. It is also important to note that the J_o of the p-type polysilicon emitter (Fig 5) appears to be much lower than what has been previously reported [1]. This may have to do to the use of thermal oxide as the interfacial layer in our samples. Either the thermal oxide is most robust during the high temperature anneal or the thermal oxide has lower interface defect state density (D_{it}) compared to the chemical oxide. Another interesting thing in these figures is that the J_o of the sample that received a 15-minute anneal is higher than the sample that received a 30-minute anneal. Moreover, such a behavior occurs in both the n- and the p- type samples. The possible explanation is that the interfacial oxide quality is improved by the high temperature anneal. This is not too surprising because the oxide was grown around 800 °C, in which higher D_{it} is expected [12,13]. Other than that, the J_o of both types appears to increase slowly with the anneal time. In addition, because the dominant recombination is likely at the oxide interface, it implies that the oxide must only be broken by very a small fraction, which is in consistent with what was observed in Fig. 2.

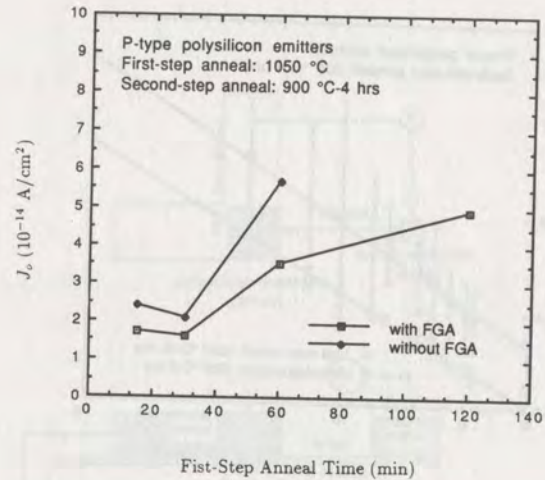


Figure 5: The J_o versus the first-step anneal time for p-type polysilicon emitters.

The effect of the second-step anneal (dopant drive-in) on both the J_o and the ρ_c were also investigated. All samples (and devices) received a first-step anneal at 1050 °C for one hour, followed with various treatments in the second-step anneal. The results are summarized in Table 1. The label on the right most column represents the second-step anneal condition of that sample. As shown in the table, the J_o increases with the temperature and time of the second-step anneal. In the meantime, the ρ_c decreases as the drive-in temperature increases. Considering the significant increase of J_o caused by increasing the drive-in temperature from 900 to 1000 °C, it is beneficial to use the two-step anneal to optimize J_o .

In Fig. 3, the decrease of ρ_c with the anneal time is what would be expected from the gradual breakup of the interfacial oxide. This is in consistent with the increase of J_o shown in Fig. 4 and Fig. 5, since J_o depends on the oxide integrity in the opposite way. This is especially clear when both ρ_c and J_o are plotted together. Fig. 6 is the ρ_c versus J_o plot for all the results obtained in this experiment. The inset is the list of the label

Table 1: The effect of the second-step anneal on J_o and ρ_c .

	N-type		P-type	
	$J_{o,e}$ ($\times 10^{-14}$ A/cm ^{2})	ρ_c ($\mu\Omega\text{-cm}^2$)	$J_{o,e}$ ($\times 10^{-14}$ A/cm ^{2})	ρ_c ($\mu\Omega\text{-cm}^2$)
900 °C-4 hour	2.4	18	3.5	18
1000 °C-30 min	4.5	~ 6	8.2	3.8
1000 °C-60 min	7.9		10.5	

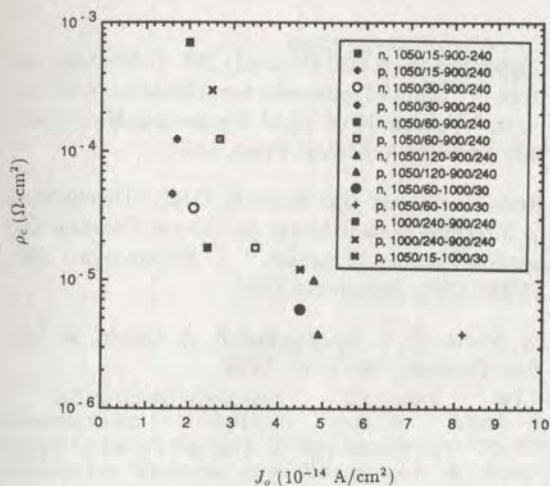


Figure 6: ρ_c - J_o of this work.

for each point. It specifies the type of polysilicon emitter, the first-step anneal (temperature/minute), and the second-step anneal (temperature/minute). As shown in the figure, the data runs from the upper-left corner to the lower-right corner which is similar to that reported by Crabbé [6] and is the typical trend when both ρ_c and J_o are regulated by the extent of oxide breakup. Nevertheless, from left to right, two distinct regimes are shown in the figure. In one regime, J_o is almost constant while ρ_c drops drastically. In the other regime, ρ_c decreases very slowly and J_o increases in much faster pace. In the first regime, that the J_o is inert to the oxide breakup is because the extent of the oxide breakup is very small such that the J_o is still dominated by the recombinations at the oxide interface and in the single-crystal outdiffusion. On the other hand, the drastic change of the ρ_c can be attributed to the transition of the majority carrier transport from the tunneling to the channel resistance. When the interfacial oxide is intact, tunneling is the only process available for the majority carriers to pass through the interfacial oxide. This usually results in a high contact resistance because of low tunneling probability. As the oxide starts to break up, additional highly conductive channels are created due to the intimate contacts formed between the polysilicon and the substrate in the broken regions [3,4,5]. A drastic change of ρ_c is observed when more currents flow through those channels. In the other regime, J_o starts to increase because the recombination in the polysilicon becomes comparable to the recombination mentioned

previously. On the other hand, the slow decrease of the ρ_c in this regime is because the majority carrier transport is completely dominated by the channel resistance. The increase of the oxide breakup can be thought as more parallel resistors added together; consequently, a significant change of ρ_c will not be observed.

The data shown in Fig. 6 are quite useful for silicon solar cells. First, most of J_o are below 5×10^{-14} A/cm² which is about one order magnitude lower than that of diffused-emitters. Second, most of ρ_c are also lower than 5×10^{-5} Ω-cm². This means that the potential drop across the contact is negligible as long as the current density is less than 100 A/cm². It is interesting to see how much of the cell efficiency can be improved with polysilicon emitters of characteristics given here. With the cell modeling, which is similar to the one reported by Sinton [8], more than one absolute percent of the cell efficiency is obtained for a backside contact solar cell with polysilicon emitters with characteristics shown here ($J_o=2 \times 10^{-14}$ A/cm² for the n-type, $J_o=3.5 \times 10^{-14}$ A/cm² for the p-type, and $\rho_c=1 \times 10^{-5}$ Ω-cm² for both types).

CONCLUSIONS

To conclude, we showed that polysilicon emitters with low J_o and ρ_c can be obtained with a very small fraction of interfacial oxide breakup. Typically, $\rho_c \sim 1 \times 10^{-5}$ Ω-cm² and $J_o \leq 5 \times 10^{-14}$ A/cm² are obtained for both n- and p- type polysilicon emitters. From the cell modeling, polysilicon emitters with these qualities can be quite useful for silicon concentrator solar cells. Because only small fraction of interfacial oxide is broken, the J_o is primarily dominated by the recombination at the oxide interface and in the single-crystal diffusion region. Consequently, an interfacial oxide of good quality is important to obtain low J_o . Our results also indicates that ρ_c drops drastically when the oxide starts to breakup. This is explained by the transition of the dominant majority-carrier transport from the tunneling to the channel resistance.

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References

- [1] Y. Kwark, R. A. Sinton, and R. M. Swanson, "Low J_0 Contact Structures Using SIPOS and Polysilicon Films," In *18th IEEE Photovoltaic Specialists Conference*, page 787, 1985.
- [2] H. C. de Graaff and J. G. de Groot, "The SIS Tunnel Emitter: A Theory Emitters with Thin Interface Layers," *IEEE Trans. Electron Devices*, ED-26(11):1771, November 1979.
- [3] G. L. Patton, J. C. Bravman, and J. D. Plummer, "Impact of Processing Parameters on Base Current in Polysilicon Contacted Bipolar Transistors," In *IEDM Tech. Dig.*, page 30, 1985.
- [4] J. C. Bravman, G. L. Patton, and J. D. Plummer, "Structure and Morphology of Polycrystalline Silicon-Single Crystal Silicon Interfaces," *J. Appl. Phys.*, 57(8):2279, April 1987.
- [5] G. R. Wolstenholme, N. Jorgensen, P. Ashburn, and G. R. Booker, "An Investigation of the Thermal Stability of the Interfacial Oxide in Polycrystalline Silicon Emitter Bipolar Transistors by Comparing Device Results with High Resolution Electron Microscopy Observation," *J. Appl. Phys.*, 61(1):225, January 1987.
- [6] Emmanuel F. Crabbé, "Carrier Transport in Polysilicon Emitter Contacts for Scaled Bipolar Transistors," PhD thesis, Stanford University, 1988.
- [7] P. Ashburn and B. Soerowirdjo, "Comparison of Experimental and Theoretical Results on Polysilicon Emitter Bipolar Transistors," *IEEE Trans. Electron Devices*, ED-31(7):853, July 1984.
- [8] R. A. Sinton and R. M. Swanson, "An Optimization Study of Si Point-Contact Concentrator Solar Cells," In *19th IEEE Photovoltaic Specialists Conference*, page 1201, 1987.
- [9] R. R. King R. A. Sinton and R. M. Swanson, "Studies of Diffused Phosphorus Emitters: Saturation Current, Surface Recombination Velocity, and Quantum Efficiency," *IEEE Trans. Electron Devices*, 37(2):365, February 1990.
- [10] D. E. Kane and R. M. Swanson, "Measurement of the Emitter Saturation Current by a Contactless Photoconductivity Decay Method," In *18th IEEE Photovoltaic Specialists Conference*, page 578, 1985.
- [11] Simon S. Cohen and Gennady SH. Gildenblat, editors. "Metal-Semiconductor Contacts and Devices," Volume 13 of *VLSI Electronics Microstructure Science*, Academic Press, 1986.
- [12] Reda R. Razouk and Bruce E. Deal, "Dependence of Interface State Density on Silicon Thermal Oxidation Process Variables," *J. Electrochem. Soc.*, 126(9):1573, September 1979.
- [13] M. Revitz, S. J. Raider, and R. A. Gdula, *J. Vac. Sci. Technol.*, 16(2):345, 1979.

ATTACHMENT F-3

POLYSILICON EMITTERS FOR SILICON CONCENTRATOR SOLAR CELLS

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ABSTRACT

Polysilicon emitters with a thermally grown interfacial oxide are examined in great detail. Both J_o and ρ_c are measured for the polysilicon emitter (contact) which is annealed under various conditions. $J_o \leq 5 \times 10^{-14}$ A/cm² and $\rho_c \sim 1 \times 10^{-5}$ Ω -cm² are obtained for both n- and p-type polysilicon emitters. The results also indicate that the interfacial oxide is only broken by a very small fraction in order to have $\rho_c \sim 1 \times 10^{-5}$ Ω -cm². Under such a condition, J_o is primarily dominated by the recombination at the oxide interface.

INTRODUCTION

Polysilicon emitters, because of their important applications in high speed bipolar transistors, have been widely studied. It was found that, between the polysilicon and the substrate, there always exists a very thin oxide (interfacial oxide), which can be as a by-product of the cleaning process or is grown intentionally [1,2,3,4,5,6,7]. In either case, the oxide is not thermally stable; *i.e.*, it tends to break up during high temperature anneals [1,2,3,4,5,6,7]. The breakup of the interfacial oxide has direct impact on both majority and minority carrier transport in the polysilicon emitter. This can be seen from the dependence of the specific contact resistivity (ρ_c) [6] and the emitter saturation current density (J_o) [1,2,3,4,5,6,7] upon either the anneal condition or the oxide integrity. When the effect of the interfacial oxide is negligible, such as when the interfacial oxide loses its integrity in high temperature anneals, the ρ_c is low ($\sim 2 \times 10^{-7}$ Ω -cm²) [6] and the J_o is high ($\sim 1 \times 10^{-12}$) [1,3]. Conversely, when both carriers are mostly blocked by the interfacial oxide, like for an intact chemical oxide (~ 15 Å), the ρ_c is high and the J_o is low. Typically, $\rho_c \geq 1 \times 10^{-4}$ Ω -cm², and the corresponding $J_o \sim 1 \times 10^{-14}$

A/cm² have been observed on the n-type polysilicon emitter [1,5,6].

With the extent of the oxide breakup between these two extremes, various combinations of ρ_c and J_o can be obtained. It is of particular interest to know the ρ_c and the corresponding J_o when only a small fraction of the interfacial oxide is broken. For silicon solar cells operated under high concentrated sunlight, the emitter recombination is one of the main recombination that limit the solar cell performance [8]. This is because the diffused-emitter, which is formed with dopant diffusion into the base (substrate), has high J_o ($= 4.5 \times 10^{-13}$ A/cm²). Consequently, the cell performance can be improved if the diffused-emitter is replaced with the polysilicon emitter, of which the J_o is less than 4.5×10^{-13} A/cm² and the ρ_c is low enough.

In this paper, detailed calibrations for the polysilicon emitter with a thermally grown interfacial oxide is presented. Compared with the chemical oxide, the thermal oxide appears to be more robust to the high temperature anneal. Consequently, this lends more controllability on the oxide breakup process. In addition, two separate anneal steps were used in order to avoid any possible interference from the dopant diffusion. It has been reported that the interfacial oxide tends to break up more rapidly with the existence of dopant [3,5]. Moreover, J_o also depends on the surface dopant concentration and the emitter depth [9]. In order to see the effect of the oxide breakup on J_o and ρ_c alone, it is therefore desirable to separate these two processes. The first-step anneal, which serves to break the oxide, was performed at higher temperature than that for the second-step anneal which aims for the dopant drive-in.

EXPERIMENTAL

Procedures

In this work, the J_o and ρ_c were measured independently for each type of polysilicon emitter (or contact). J_o was measured with photoconductivity decay method which has been reported elsewhere [10]. Because high bulk lifetime is needed for such a measurement, the samples were prepared with high resistivity ($>100 \Omega\text{-cm}$) FZ wafers. In contrast, ρ_c was measured on devices made on CZ wafers of which resistivity is 0.28 and $0.5 \Omega\text{-cm}$ for p- and n- type respectively. The device for ρ_c -measurement is shown in Fig. 1 schematically. Except for the pattern-definition steps which were not required for J_o -measurement samples, the two sets of wafers were always processed together. The process sequence is shown as followings:

1. Field oxidation ($2000 \text{ \AA}$)*.
2. Polysilicon-substrate contact opening*.
3. Thin thermal oxide growth at 800°C *. (10-minute oxygen flow)
4. Polysilicon deposition ($6000 \text{ \AA}$) and first-step anneal (1050°C)*.
5. First-step anneal*.
6. Polysilicon finger definition.
7. Undoped glass deposition ($2000 \text{ \AA}$).
8. Metal-polysilicon and metal-substrate contact opening.
9. Doped glass deposition on both sides of the wafer*.
10. Drive-in; $900\text{-}1000^\circ\text{C}$ *.
11. Doped glass stripping and Al-1% Si alloy deposition.
12. Metal finger definition.

Note that the steps marked with “*” are the steps for J_o -measurement samples. In addition, the J_o -samples are divided into two sets; one set of samples had an additional 400°C -30 min forming gas anneal (FGA), the other did not. The growth of thin oxide was carried out with 200 sccm oxygen and 5 slm argon mixture. Typically, oxide thickness less than $20 \text{ \AA}$ was measured with ellipsometer. In step 2, a series of square contacts of size between 1 and $64 \mu\text{m}$ are opened for polysilicon-substrate contacts.

ρ_c Measurement

As shown in Fig. 1, the voltage difference, V_{ab} , between probe A and B is caused by several components of the series resistance along the current loop. They are the resistance imposed by the bulk of the polysilicon and the wafer, the metal-polysilicon contact resistance, and the polysilicon-substrate contact resistance. The potential drop across the polysilicon film is conceivably negligible because the film is heavily doped and very thin. The metal-polysilicon contact resistance is actually measured on the similar device (four-terminal resistor [11]) next to the device shown in the figure. Typi-

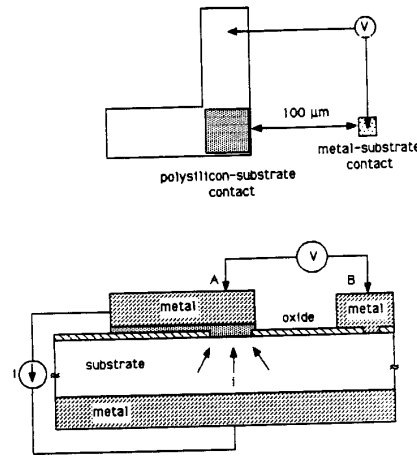


Figure 1: The device structure for the specific contact resistivity measurement.

cally, the ρ_c of the metal-polysilicon contact is less than $1 \times 10^{-6} \Omega\text{-cm}^2$. With such low ρ_c and large contact area between the metal and the polysilicon, the metal-polysilicon contact resistance can be ignored as well. As a result, the series resistance derived from V_{ab}/I is essentially determined by two terms; the bulk resistance of the silicon substrate and the polysilicon-substrate contact resistance. Such a series resistance can be expressed as a function of the size of the polysilicon-substrate square contact.

$$R = C \frac{\rho}{d} + \frac{\rho_c}{d^2}, \quad (1)$$

or

$$R_c = R \times d^2 = \rho_c + C \rho d; \quad (2)$$

where C is a constant that accounts for the contact geometry factor, ρ is the substrate resistivity, d is the width of the square contact, and ρ_c is the specific contact resistivity of the polysilicon-substrate contact. The contact size dependence of the last term in Eqn. (2) results from the crowding effect as the current flows toward the polysilicon-substrate contact. It is obvious that, from Eqn. (2), the ρ_c can be derived from the plot of R_c versus d which is obtained by measuring the series resistance of contacts of different sizes.

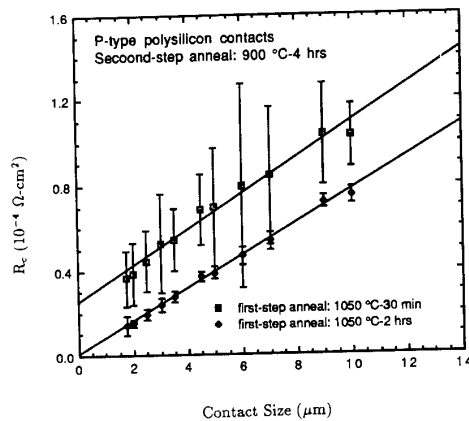


Figure 2: The R_c versus the contact size for p-type polysilicon contacts of different first-step anneals.

RESULTS AND DISCUSSIONS

Fig. 2 shows two R_c -plots for the p-type polysilicon contacts. One has the first-step anneal at 1050 °C for 30 minutes, the other has 1050 °C for 2 hours. Each data point is the average of 16 measurements across the wafer and the error bar is drawn with 4 standard deviations. Since devices were made on the wafers of about the same resistivity, the slopes of the linear-fit lines are almost identical. Note that, the devices that received a 30-minute first-step anneal have higher intercepts than those that received a 2-hour first-step anneal. This indicates that more oxide breakup occurs when the anneal time increases. Another characteristic of the interfacial oxide breakup can also be seen from the spread in the data (the length of the error bar). The magnitude of the error bar is not due to the measurement uncertainty; instead, it results from the random distribution of the oxide breakup. When only a very small fraction of the interfacial oxide is broken, it is possible that the interfacial oxide on each contact may not be broken equally. Consequently, this gives rise to the fluctuation of the resistance measured. On the other hand, the fluctuation will be subdued when more oxide is broken. This explains the different appearance of error bars observed between these two sets of data.

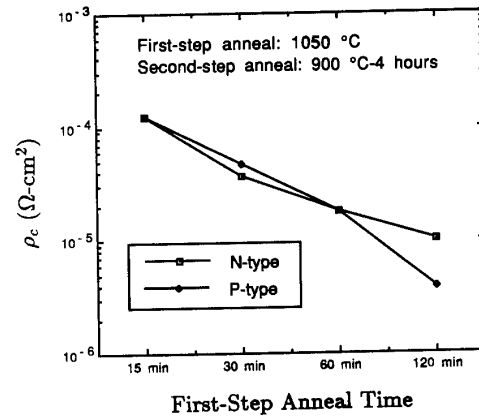


Figure 3: ρ_c of both n- and p- type polysilicon-substrate contacts is shown as a function of the time of the first-step anneal.

To see how the J_o and the ρ_c is affected by the first-step anneal, one set of samples (and device wafers) were first annealed at 1050 °C for various lengths of time (first-step anneal). After the doped-glass deposition, they were all annealed at 900 °C for 4 hours. The ρ_c measured from the device and the J_o measured from the photoconductivity decay are presented in the following figures.

In Fig. 3, ρ_c is plotted against the time of the first-step anneal for both types. Note that the ρ_c decreases as the anneal time increases. In addition, ρ_c measured from both n- and p- type devices are more or less the same, except those annealed with 120 minutes. The similarity of ρ_c between the n- and the p- type contact also indicates that the interaction between the dopant and the interfacial oxide is negligible; since such an interaction, if exists, would cause the ρ_c of the p-type to be lower [6].

The effects of the first-step anneal on J_o are presented in Fig. 4 and 5 for the n-type and the p-type polysilicon emitters respectively. In each figure, two sets of data are shown: the one with an FGA, and the one without. For the samples with an FGA, the J_o is significantly less than that without FGA for the same anneal condition. This indicates that the recombination

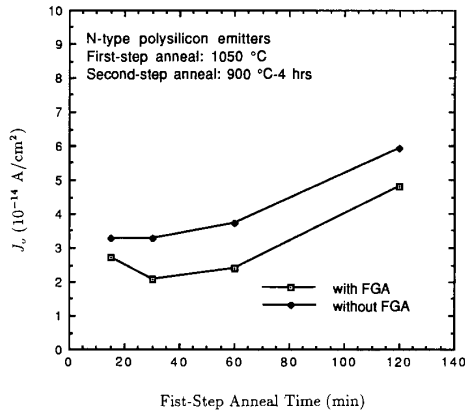


Figure 4: The J_o versus the first-step anneal time for n-type polysilicon emitters.

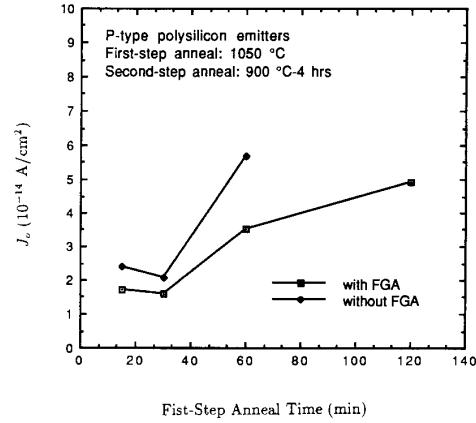


Figure 5: The J_o versus the first-step anneal time for p-type polysilicon emitters.

at the oxide interface is, at least, one of the dominant mechanisms for the emitter recombination. It is also important to note that the J_o of the p-type polysilicon emitter (Fig 5) appears to be much lower than what has been previously reported [1]. This may have to do to the use of thermal oxide as the interfacial layer in our samples. Either the thermal oxide is most robust during the high temperature anneal or the thermal oxide has lower interface defect state density (D_{it}) compared to the chemical oxide. Another interesting thing in these figures is that the J_o of the sample that received a 15-minute anneal is higher than the sample that received a 30-minute anneal. Moreover, such a behavior occurs in both the n- and the p- type samples. The possible explanation is that the interfacial oxide quality is improved by the high temperature anneal. This is not too surprising because the oxide was grown around 800 °C, in which higher D_{it} is expected [12,13]. Other than that, the J_o of both types appears to increase slowly with the anneal time. In addition, because the dominant recombination is likely at the oxide interface, it implies that the oxide must only be broken by very a small fraction, which is in consistent with what was observed in Fig. 2.

The effect of the second-step anneal (dopant drive-in) on both the J_o and the ρ_c were also investigated. All samples (and devices) received a first-step anneal at 1050 °C for one hour, followed with various treatments in the second-step anneal. The results are summarized in Table 1. The label on the right most column represents the second-step anneal condition of that sample. As shown in the table, the J_o increases with the temperature and time of the second-step anneal. In the meantime, the ρ_c decreases as the drive-in temperature increases. Considering the significant increase of J_o caused by increasing the drive-in temperature from 900 to 1000 °C, it is beneficial to use the two-step anneal to optimize J_o .

In Fig. 3, the decrease of ρ_c with the anneal time is what would be expected from the gradual breakup of the interfacial oxide. This is in consistent with the increase of J_o shown in Fig. 4 and Fig. 5, since J_o depends on the oxide integrity in the opposite way. This is especially clear when both ρ_c and J_o are plotted together. Fig. 6 is the ρ_c versus J_o plot for all the results obtained in this experiment. The inset is the list of the label

Table 1: The effect of the second-step anneal on J_o and ρ_c .

	N-type		P-type	
	$J_{o,e}$ ($\times 10^{-14}$ A/cm ²)	ρ_c ($\mu\Omega\text{-cm}^2$)	$J_{o,e}$ ($\times 10^{-14}$ A/cm ²)	ρ_c ($\mu\Omega\text{-cm}^2$)
900 °C-4 hour	2.4	18	3.5	18
1000 °C-30 min	4.5	~ 6	8.2	3.8
1000 °C-60 min	7.9		10.5	

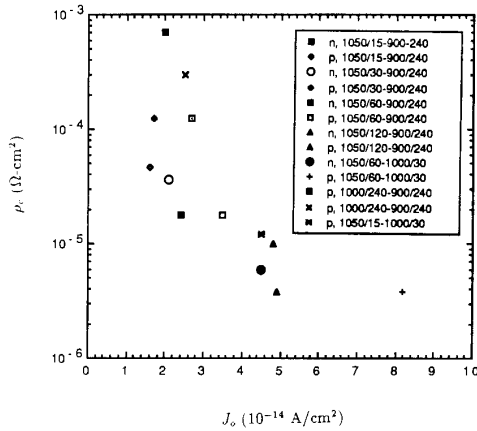


Figure 6: ρ_c - J_o of this work.

for each point. It specifies the type of polysilicon emitter, the first-step anneal (temperature/minute), and the second-step anneal (temperature/minute). As shown in the figure, the data runs from the upper-left corner to the lower-right corner which is similar to that reported by Crabbé [6] and is the typical trend when both ρ_c and J_o are regulated by the extent of oxide breakup. Nevertheless, from left to right, two distinct regimes are shown in the figure. In one regime, J_o is almost constant while ρ_c drops drastically. In the other regime, ρ_c decreases very slowly and J_o increases in much faster pace. In the first regime, that the J_o is inert to the oxide breakup is because the extent of the oxide breakup is very small such that the J_o is still dominated by the recombinations at the oxide interface and in the single-crystal outdiffusion. On the other hand, the drastic change of the ρ_c can be attributed to the transition of the majority carrier transport from the tunneling to the channel resistance. When the interfacial oxide is intact, tunneling is the only process available for the majority carriers to pass through the interfacial oxide. This usually results in a high contact resistance because of low tunneling probability. As the oxide starts to break up, additional highly conductive channels are created due to the intimate contacts formed between the polysilicon and the substrate in the broken regions [3,4,5]. A drastic change of ρ_c is observed when more currents flow through those channels. In the other regime, J_o starts to increase because the recombination in the polysilicon becomes comparable to the recombination mentioned

previously. On the other hand, the slow decrease of the ρ_c in this regime is because the majority carrier transport is completely dominated by the channel resistance. The increase of the oxide breakup can be thought as more parallel resistors added together; consequently, a significant change of ρ_c will not be observed.

The data shown in Fig. 6 are quite useful for silicon solar cells. First, most of J_o are below 5×10^{-14} A/cm² which is about one order magnitude lower than that of diffused-emitters. Second, most of ρ_c are also lower than 5×10^{-5} Ω·cm². This means that the potential drop across the contact is negligible as long as the current density is less than 100 A/cm². It is interesting to see how much of the cell efficiency can be improved with polysilicon emitters of characteristics given here. With the cell modeling, which is similar to the one reported by Sinton [8], more than one absolute percent of the cell efficiency is obtained for a backside contact solar cell with polysilicon emitters with characteristics shown here ($J_o=2 \times 10^{-14}$ A/cm² for the n-type, $J_o=3.5 \times 10^{-14}$ A/cm² for the p-type, and $\rho_c=1 \times 10^{-5}$ Ω·cm² for both types).

CONCLUSIONS

To conclude, we showed that polysilicon emitters with low J_o and ρ_c can be obtained with a very small fraction of interfacial oxide breakup. Typically, $\rho_c \sim 1 \times 10^{-5}$ Ω·cm² and $J_o \leq 5 \times 10^{-14}$ A/cm² are obtained for both n- and p- type polysilicon emitters. From the cell modeling, polysilicon emitters with these qualities can be quite useful for silicon concentrator solar cells. Because only small fraction of interfacial oxide is broken, the J_o is primarily dominated by the recombination at the oxide interface and in the single-crystal diffusion region. Consequently, an interfacial oxide of good quality is important to obtain low J_o . Our results also indicates that ρ_c drops drastically when the oxide starts to breakup. This is explained by the transition of the dominant majority-carrier transport from the tunneling to the channel resistance.

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References

- [1] Y. Kwark, R. A. Sinton, and R. M. Swanson, "Low J_0 Contact Structures Using SIPOS and Polysilicon Films," In *18th IEEE Photovoltaic Specialists Conference*, page 787, 1985.
- [2] H. C. de Graaff and J. G. de Groot, "The SIS Tunnel Emitter: A Theory Emitters with Thin Interface Layers," *IEEE Trans. Electron Devices*, ED-26(11):1771, November 1979.
- [3] G. L. Patton, J. C. Bravman, and J. D. Plummer, "Impact of Processing Parameters on Base Current in Polysilicon Contacted Bipolar Transistors," In *IEDM Tech. Dig.*, page 30, 1985.
- [4] J. C. Bravman, G. L. Patton, and J. D. Plummer, "Structure and Morphology of Polycrystalline Silicon-Single Crystal Silicon Interfaces," *J. Appl. Phys.*, 57(8):2279, April 1987.
- [5] G. R. Wolstenholme, N. Jorgensen, P. Ashburn, and G. R. Booker, "An Investigation of the Thermal Stability of the Interfacial Oxide in Polycrystalline Silicon Emitter Bipolar Transistors by Comparing Device Results with High Resolution Electron Microscopy Observation," *J. Appl. Phys.*, 61(1):225, January 1987.
- [6] Emmanuel F. Crabbé, "*Carrier Transport in Polysilicon Emitter Contacts for Scaled Bipolar Transistors*," PhD thesis, Stanford University, 1988.
- [7] P. Ashburn and B. Soerowirdjo, "Comparison of Experimental and Theoretical Results on Polysilicon Emitter Bipolar Transistors," *IEEE Trans. Electron Devices*, ED-31(7):853, July 1984.
- [8] R. A. Sinton and R. M. Swanson, "An Optimization Study of Si Point-Contact Concentrator Solar Cells," In *19th IEEE Photovoltaic Specialists Conference*, page 1201, 1987.
- [9] R. R. King R. A. Sinton and R. M. Swanson, "Studies of Diffused Phosphorus Emitters: Saturation Current, Surface Recombination Velocity, and Quantum Efficiency," *IEEE Trans. Electron Devices*, 37(2):365, February 1990.
- [10] D. E. Kane and R. M. Swanson, "Measurement of the Emitter Saturation Current by a Contactless Photoconductivity Decay Method," In *18th IEEE Photovoltaic Specialists Conference*, page 578, 1985.
- [11] Simon S. Cohen and Gennady SH. Gildenblat, editors. "*Metal-Semiconductor Contacts and Devices*," Volume 13 of *VLSI Electronics Microstructure Science*, Academic Press, 1986.
- [12] Reda R. Razouk and Bruce E. Deal, "Dependence of Interface State Density on Silicon Thermal Oxidation Process Variables," *J. Electrochem. Soc.*, 126(9):1573, September 1979.
- [13] M. Revitz, S. J. Raider, and R. A. Gdula, *J. Vac. Sci. Technol.*, 16(2):345, 1979.

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