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## CHAPTER 4

# High-Efficiency Silicon Solar Cells

Richard M. Swanson and Ronald A. Sinton

### 4.1 Introduction

In the last five years silicon solar cells have undergone significant evolution resulting in greatly improved efficiencies. As an illustration, Figure 4.1 plots the highest reported silicon concentrator cell efficiency versus year. Also shown for comparison are gallium-arsenide concentrator cell results. Silicon one-sun cells have undergone a similar, but less dramatic, improvement.

Besides the normal progress obtainable through continued design refinement, the major factors enabling this improvement are:

- incorporation of light trapping,
- reduction of recombination through improved material quality, cleaner processing, surface passivation and reduced contact coverage fraction, and
- improvements in understanding of the fundamental physical processes important in cell operation such as recombination and carrier transport in heavily doped regions.

Early workers tended to view solar cells as  $p$ - $n$  junctions which happen to have light-induced generation. This led to simple models of cell operation emphasizing diffusion of carriers in low-level injected doped regions (Hovel, 1975). Cell designs used thick, rather highly doped wafers. The importance of reducing recombination, such as by having high minority carrier lifetime, was recognized early; however, the physics of recombination was not sufficiently studied to know what was limiting the lifetime, and how high a lifetime could reasonably be attained in various parts of the cell.

An apt analogy to the importance of controlling and reducing recombination is provided by a leaky bucket being continually filled with a faucet (Schwartz, 1983). The level of water represents the density of electron-hole pairs and the incoming stream represents the incident photons. One wishes to attain the highest water level (highest carrier density and, hence, voltage) but it is found that every time a leak (source of recombination) is plugged the water rises only a little until another leak takes over. So it is in solar cells; in order to achieve significant increases in output voltage it is necessary to examine every part of the cell for potential recombination paths and take steps to block those paths. This requires that the internal flow of carriers must be well modeled and understood. Our ability to do this continues to improve. At this point it seems only fair to reveal that one can now state with

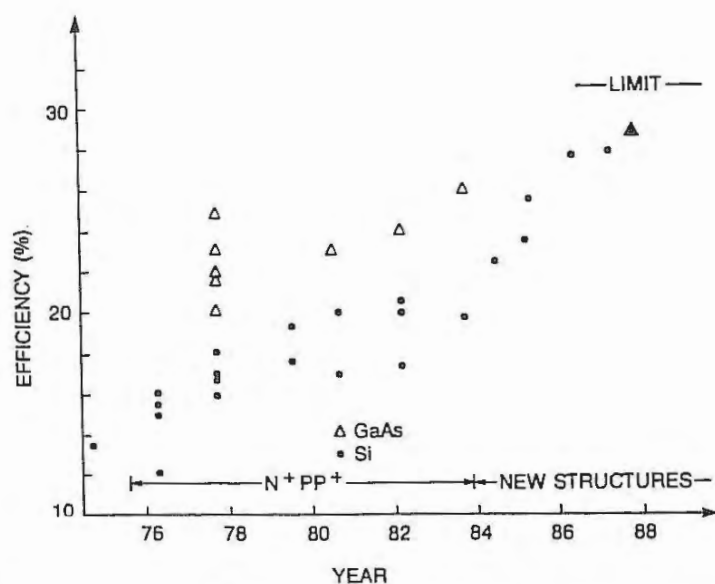


Figure 4.1: Highest reported silicon and gallium arsenide concentrator cell efficiencies versus date.

some certainty that the practical limit efficiency for one-sun silicon solar cells at room temperature is between 24 and 25 percent, and that for concentrator cells lies between 30 and 31 percent. An implementation of a concentrator system with a restricted acceptance angle for the incident light may extend these efficiencies somewhat towards the limit of 36–37% (Campbell, 1986). Thus, barring some unforeseen breakthrough, laboratory cell efficiencies are rapidly approaching their limits. Nevertheless, much work remains to consolidate these recent improvements into practical, production-worthy designs.

This article discusses these results. Particular emphasis is directed toward concentrator cells which operate in high-injection conditions, as this is where the bulk of the authors' experience lies. Most of the material presented in this chapter, however, is equally applicable to flat-plate cells. Concentrator cells have historically led the drive to higher efficiency because concentrator economics can tolerate the complex processing and high-quality materials that are necessary to achieve those high efficiencies. Many of the high-efficiency concepts which first appeared on concentrator cells, such as passivated emitters, have subsequently found their way into the entire range of solar cell applications including one-sun cells.

Section 2.3.4D presents a simplified view of basic cell operation while Section 4.3 contains the details of the relevant semiconductor device physics. Finally, Section 4.4 discusses the design of high-efficiency cells.

## 4.2 Basic Cell Operation

We assume that the reader is familiar with the fundamentals of both semiconductor device operation and solar cells. Excellent texts on the basics of solar cell operation can be found in references (Green, 1982), (Fahrenbruch and Bube, 1983), and more particularly Green, 1987). Rather than trying to re-do what has been done

in these texts, we present here a simplified viewpoint of device operation which has been central to our thinking.

The analysis of silicon solar cells is often couched in terms of the current density equations, drift plus diffusion, and the continuity equation. Such an approach obscures the physics of operation, however, because the operation of a well-designed solar cell is controlled by generation and recombination. The need for current transport is responsible only for certain second-order losses in the cell. This Section presents an analysis of cell operation in terms of an integral formulation of the continuity equation, which brings forth the balance between generation and recombination as determining the output of current, and quasi-Fermi potentials as determining the output of voltage.

#### 4.2.1 The Semiconductor Device Equations

The standard equations used to model steady-state carrier transport in silicon devices, when heavy doping effects can be neglected, are:

1. current transport equations

$$\vec{J}_n = -q\mu_n n \vec{\nabla} \psi_i + qD_n \vec{\nabla} n = -q\mu_n n \vec{\nabla} \phi_n \quad (4.1)$$

$$\vec{J}_p = -q\mu_p p \vec{\nabla} \psi_i - qD_p \vec{\nabla} p = -q\mu_p p \vec{\nabla} \phi_p \quad (4.2)$$

2. continuity equations

$$\vec{\nabla} \cdot \vec{J}_n = q(r - g_{ph}) \quad (4.3)$$

$$\vec{\nabla} \cdot \vec{J}_p = -q(r - g_{ph}) \quad (4.4)$$

3. Poisson's equation

$$\nabla^2 \psi_i = -\frac{q}{\epsilon}(p + N_D^+ - n - N_A^-) \quad (4.5)$$

4. carrier density equations

$$n = n_i e^{q(\psi_i - \phi_n)/kT} \quad (4.6)$$

$$p = n_i e^{q(\phi_p - \psi_i)/kT} \quad (4.7)$$

The symbols used have their standard meanings as given below:

|                       |                                                                                                                                       |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| $r = r_{th} - g_{th}$ | net thermal recombination rate per unit volume<br>(Here, $r_{th}$ is the recombination rate and $g_{th}$ is thermal generation rate.) |
| $g_{ph}$              | photogeneration rate per unit volume                                                                                                  |
| $\vec{J}_n$           | electron current density                                                                                                              |
| $\vec{J}_p$           | hole current density                                                                                                                  |
| $n$                   | electron concentration                                                                                                                |
| $p$                   | hole concentration                                                                                                                    |
| $\mu_n, \mu_p$        | electron and hole mobilities                                                                                                          |

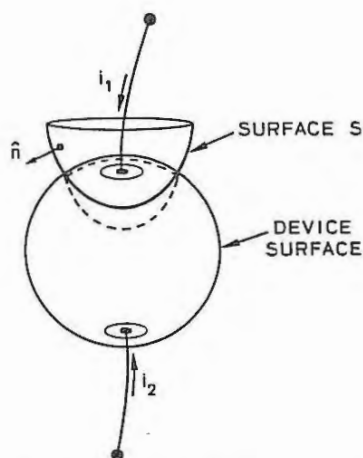


Figure 4.2: A general two terminal device.

|                  |                                             |
|------------------|---------------------------------------------|
| $D_n, D_p$       | electron and hole diffusivities             |
| $\phi_n, \phi_p$ | electron and hole quasi-Fermi potentials    |
| $\psi_i$         | potential referenced to the intrinsic level |
| $\epsilon$       | static dielectric permittivity              |
| $q$              | magnitude of electron charge                |
| $N_D^+, N_A^+$   | ionized doping density                      |

Using Equations (4.1) through (4.4), the electron and hole current densities can be eliminated. The resulting equations, along with Poisson's Equation (4.5), define three coupled non-linear differential equations in three unknowns,  $n$ ,  $p$ , and  $\psi_i$ . Equations (4.6) and (4.7) are superfluous but will prove useful in relating terminal voltage to carrier densities. Given appropriate boundary conditions these equations can be solved — in principle. The search for reasonable analytic solutions to these equations is hopeless, however; either some simplifications must be made or numerical techniques used. Several approximate analytic approaches will be presented below and in Section 4.4.

#### 4.2.2 An Integral Approach to the Terminal Current

Once a solution for  $n$ ,  $p$ , and  $\psi_i$  is found, either numerically or through judicious analytic approximation, the terminal current can be found in either one of two ways; by a differential or an integral method.

##### 4.2.2A Differential Method

Consider the general two terminal device, shown in Figure 4.2, with an imaginary surface  $S$  that surrounds terminal 1. The terminal currents are  $i_1$  and  $i_2 = -i_1$ . In the steady-state,  $i_1$  may be found by

$$i_1 = \int_S (\vec{J}_n + \vec{J}_p) \cdot \hat{n} dS \quad (4.8)$$

where  $\hat{n}$  is an outward unit vector normal to  $S$  and  $J_n$  and  $J_p$  are given by Equations (4.1) and (4.2). Any surface can be used to calculate  $i_1$  that surrounds contact 1, but if one doesn't use *exact* solutions for  $\vec{J}_n$  and  $\vec{J}_p$  (or equivalently, for  $n$ ,  $p$  and  $\psi_i$ ) then different surfaces may give different answers.

## 4.2.2B Integral Method

Using this method, one integrates the continuity Equations (4.3) and (4.4), over the device volume,

$$\int_V \bar{\nabla} \cdot \bar{J}_n dv = q \int_V (r - g_{ph}) dv \quad (4.9)$$

$$\int_V \bar{\nabla} \cdot \bar{J}_p dv = -q \int_V (r - g_{ph}) dv. \quad (4.10)$$

Next, Gauss' divergence theorem is used to convert the left-hand side to surface integrals over the device's surface,  $S_{tot}$ .

$$\int_{S_{tot}} \bar{J}_n \cdot \hat{n} dS = q \int_V (r - g_{ph}) dv \quad (4.11)$$

$$\int_{S_{tot}} \bar{J}_p \cdot \hat{n} dS = -q \int_V (r - g_{ph}) dv \quad (4.12)$$

The surface integration is divided into three regions;  $S_1$  (contact 1),  $S_2$  (contact 2), and  $S$  (remainder of device) giving

$$\int_{S_{tot}} \bar{J}_n \cdot \hat{n} dS = \int_{S_1} \bar{J}_n \cdot \hat{n} dS + \int_{S_2} \bar{J}_n \cdot \hat{n} dS + \int_S \bar{J}_n \cdot \hat{n} dS \quad (4.13)$$

$$\int_{S_{tot}} \bar{J}_p \cdot \hat{n} dS = \int_{S_1} \bar{J}_p \cdot \hat{n} dS + \int_{S_2} \bar{J}_p \cdot \hat{n} dS + \int_S \bar{J}_p \cdot \hat{n} dS. \quad (4.14)$$

At contact 1 the current is

$$i_1 = - \int_{S_1} \bar{J}_n \cdot \hat{n} dS - \int_{S_1} \bar{J}_p \cdot \hat{n} dS. \quad (4.15)$$

The minus sign results because the normal vector  $\hat{n}$  is outward while the current is referenced inward. Now, solving for  $-\int_{S_1} \bar{J}_p \cdot \hat{n} dS$  in Equation (4.14), inserting this into Equation (4.15), and using Equation (4.12) gives,

$$i_1 = \int_{S_2} \bar{J}_p \cdot \hat{n} dS - \int_{S_1} \bar{J}_n \cdot \hat{n} dS + \int_S \bar{J}_p \cdot \hat{n} + q \int_V r dv - q \int_V g_{ph} dV \quad (4.16)$$

Let us suppose that contact 1 is  $p$ -type and contact 2 is  $n$ -type so that  $J_p$  and  $J_n$  are minority carrier current densities in the integrations in Equation (4.16). Since, in a solar cell, positive current out of the  $p$ -type contact corresponds to positive output power it is convenient to define the terminal current  $I = -i_1 = i_2$ . Then Equation (4.16) can be written in the suggestive form

$$I = I_{ph} - I_{b,rec} - I_{s,rec} - I_{cont,rec} = I_{ph} - I_{rec} \quad (4.17)$$

where

$$I_{rec} = I_{b,rec} + I_{s,rec} + I_{cont,rec} \quad (4.18)$$

and

$$\begin{aligned}
 I_{ph} &= q \int_V g_{ph} dv && \text{photogeneration current} \\
 I_{b,rec} &= q \int_V r dv && \text{bulk recombination} \\
 I_{s,rec} &= \int_S \bar{J}_p \cdot \hat{n} dS && \text{surface recombination} \\
 I_{cont,rec} &= \int_{S_2} \bar{J}_p \cdot \hat{n} dS - \int_{S_1} \bar{J}_n \cdot \hat{n} dS && \text{contact recombination.}
 \end{aligned} \tag{4.19}$$

In other words, if one properly accounts for recombination, one can say that the output current equals the photogeneration current minus the total recombination current.\* It should be stressed that Equation (4.17) is an exact result of the continuity equation.

The position of the surface over which one integrates to get the contact recombination is completely arbitrary, as long as it surrounds the contact. If the integration surface is moved away from the metal-semiconductor contact, then the volume in the region between the integration surface and the metal must not be included in the recombination integral. This is a convenient maneuver when the region around the contact is heavily doped and low-level injected. Consider, for example, a metal contact to a heavily doped  $n$ -type region. If the integration surface is moved in from the surface to eliminate this region, the hole current at the new surface is then comprised of hole recombination in the doped layer plus the hole surface recombination. (This is of course what would have been calculated using by including the region in the original volume.) This current is then easily calculated, using conventional low-level-injection theory, as a function of the hole density at the edge of the integration region.

The integral approach has the advantage that any errors in  $n$  and  $p$  tend to be averaged out when performing the integrations. It also does not depend on knowing  $\bar{\nabla}n$  and  $\bar{\nabla}p$ . This is an advantage because most analytical approximations, or numerical calculation techniques, yield better results for  $n$  and  $p$  than for their gradients. For solar cells, using Equation (4.17) approaches the essence of what is desired more closely than the differential method which requires knowledge of the carrier fluxes throughout the device.

#### 4.2.3 The Terminal Voltage

A typical advanced solar cell has highly doped regions near the contacts (for ohmic contact and reduction of contact recombination), and a more lightly doped base. This is illustrated in the band diagram in Figure 4.3. The horizontal coordinate on this diagram, position, is not necessarily a spatially straight line from

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\* Sometimes one sees the terminal current written as the short-circuit current minus the "dark current." The short circuit current will be the photogeneration current minus whatever recombination occurs at short circuit. In this case the dark current is then any additional recombination obtaining when the device is not at short-circuit. In the simplest case of low-level injection, the equations defining the carrier density are linear and the dark current becomes independent of light intensity and equal to the recombination of the cell in the dark at the same junction potential. Such a cell is said to obey the "superposition principle." We will see below that narrow base cells also obey the superposition principle. In all other cases such a separation cannot be rigorously made. Equation (4.17) remains true, however.

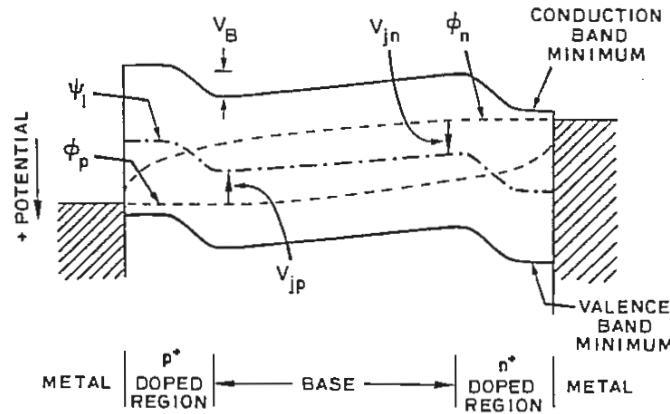


Figure 4.3: Solar cell band diagram.

front to back, but just represents a continuous physical path from the  $p^+$  to  $n^+$  contact areas. The terminal voltage (less any drop in the contacts and metal bus) is  $\phi_p$  at the  $p^+$  contact minus  $\phi_n$  at the  $n^+$  contact.

To a very good approximation  $\phi_n$  can be assumed constant through the  $n^+$  region, its space charge region, and into the edge of the quasi-neutral base near the  $n^+$  contact at position 2. The same applies to  $\phi_p$  in the  $p^+$  region up to position 1. This is because these regions are heavily doped and hence have an abundance of majority carriers. Referring to Figure 4.3 it is easily seen that the output voltage is

$$V = V_{jn} + V_{jp} + V_B + V_c + V_m \quad (4.20)$$

where

$$V_{jn} = \psi_i - \phi_n = kT/q \ln(n/n_i) \text{ [evaluated at point 2]} \quad (4.21)$$

$$V_{jp} = \phi_p - \psi_i = kT/q \ln(p/n_i) \text{ [evaluated at point 1]} \quad (4.22)$$

$$V_B = \psi_i(1) - \psi_i(2) = - \int_1^2 \bar{\nabla} \psi_i \cdot d\bar{l} = \int_1^2 \bar{E} \cdot d\bar{l} \quad (4.23)$$

$$V_c \text{ [contact voltage]} \quad (4.24)$$

$$V_m \text{ [metal grid voltage]}. \quad (4.25)$$

In normal operation,  $V_B$ ,  $V_c$ , and  $V_m$  are all negative and represent the base, contact and metal resistive loss respectively. Detailed methods of calculating  $V_c$  and  $V_m$  are available in the literature (Basore, 1984).

The importance of Equations (4.20) through (4.25) lies in the need to have solutions for  $n$ ,  $p$ , and  $\psi_i$  only in the base semiconductor region. The details of what happens in the  $n^+$  and  $p^+$  semiconductor regions are unimportant for determining voltage. This is fortunate for, as discussed below, what happens in these regions is difficult to model because Equations (4.1) through (4.7) do not apply in very highly doped regions. It should be kept in mind that the above voltage and current

equations are valid regardless of whether the base is high-level injected (i.e., has a minority carrier density greater than the doping density) or not.

Notice that if one neglects the base, contact and metal voltage drops, and assumes that  $n$  and  $p$  are constant throughout the base then Equations (4.21) through (4.25) imply that

$$V \approx \frac{kT}{q} \ln(pn/n_i^2). \quad (4.26)$$

In this case,  $\phi_n$  and  $\phi_p$  are constant throughout the base and

$$V = \phi_p - \phi_n. \quad (4.27)$$

These equations describe the essence of device voltage — the terminal voltage is just the separation of quasi-Fermi potentials.\* Equivalently, the  $pn$  product appears as the major determinant of voltage.

Transport losses, which are hopefully small in a high-efficiency cell, will decrease the voltage below this ideal as shown by Equation (4.20). If the cell can be well modeled as having a series resistance,  $R_s$ , so that  $V_B + V_c + V_m \approx -IR_s$ , then the above equations imply

$$V \approx \frac{kT}{q} \ln(pn/n_i^2) - IR_s. \quad (4.28)$$

In many cases this is a reasonable approximation; however, in cells operating in high-level injection, a more rigorous calculation of the base voltage is required. This will be covered in subsequent sections.

#### 4.2.4 Carrier Photogeneration

A solar cell's first function is to absorb light to produce electron-hole pairs. From Equation (4.17) it is immediately apparent that to maximize efficiency one must design the cell to produce as many electron-hole pairs as possible. The number of electron-hole pairs produced in the silicon by a given amount and spectrum of incident light is simply a function of:

- how many of the photons are transmitted through the cell front surface into the bulk, and
- the path length that these photons can travel once in the bulk silicon before leaving or being absorbed in a way which does not produce electron-hole pairs.

Silicon is weakly absorbing since it has an indirect bandgap. Thus, for practical solar cells, a substantial volume of silicon is usually devoted simply to absorbing light. In virtually all cells, this volume of silicon is the most lightly doped region. The amount of light absorbed depends upon the cell thickness and path that the light takes through the cell. The details of the optimization to maximize this photogeneration are discussed in Section 4.4, Cell Design Engineering. Current, state-of-the-art silicon cells incorporating light-trapping produce about 42 mA of current for each 100 mW of incident sunlight (AM 1.5 direct spectrum).

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\* Thermodynamically, this is equivalent to saying that the terminal voltage is the difference of the electron and hole electromotive force.

#### 4.2.5 Sources of Recombination

In this section we explore the impact of various types of recombination on the terminal characteristics. The phenomenological equations describing the common recombination processes are presented. Detailed discussion of the experimental determination of the various coefficients involved is delayed until Section 4.3, The Physical Details of Recombination and Transport.

To calculate terminal current the various recombination terms in Equation (4.17) need to be evaluated. Various regions of the cell require different approaches.

##### 4.2.5A Diffusion Region Recombination

Part of the integration in Equation (4.17) for the bulk recombination involves the  $n^+$  and  $p^+$  diffused regions where no solution, as yet, exists. The same applies to contact recombination. This problem can be side-stepped by defining the surface of the device to skirt the highly doped regions.\* The new surface of integration is then just inside the neutral base under the contact regions. It is easy to see in a physical manner why this is possible because the net hole current entering the  $n$ -type diffusion area, for example, either recombines within the diffusion region or at the contact. Thus the same result is obtained by either evaluating the hole current at the edge of the space charge region or calculating the net recombination in the diffused area plus contact. (The photogeneration in the diffused regions under the contacts is being neglected.)

It will be shown in Section 4.3 that the minority carrier hole injection current density into a highly doped  $n$ -type region can always be written, provided the doped region is everywhere low-level injected, as

$$J_p = J_{0n} \left( \frac{pn}{n_i^2} - 1 \right) \quad (4.29)$$

where  $J_{0n}$  is a temperature-dependent constant, to be called the diffusion saturation current, and  $p$  and  $n$  are evaluated at the internal edge of the neutral highly doped region (del Alamo, 1984). The  $pn$  product will be constant to within a very small error across the space charge region, so the  $pn$  product at the edge of the space charge region in the neutral base may be used instead. Equation (4.29) may still be used to calculate the injection current; however, any recombination in the space charge region will be thereby neglected if this region is also excluded from the volume recombination calculation. In high efficiency cells the space charge region recombination is normally very small.

$J_{0n}$  can be considered in two ways; it can be calculated using some particular model of transport in heavily doped regions or it can simply be measured for the diffusion employed and taken as an experimental parameter.

Similarly

$$J_n = J_{0p} \left( \frac{pn}{n_i^2} - 1 \right) \quad (4.30)$$

for the electron current density entering a  $p$ -type diffused region.

---

\* As mentioned above, the location of this surface is arbitrary.

#### 4.2.5B Recombination in the Base

Recombination in the base of silicon solar cells can occur through a variety of mechanisms. Radiative recombination is the inverse of the photogeneration process responsible for the operation of solar cells and hence must occur to some degree. Other, non-radiative mechanisms usually dominate in silicon. A wide variety of material defects, both intrinsic and extrinsic (or impurity related) can catalyze the recombination process. The three-particle process known as Auger recombination, which is discussed more fully in Section 4.3, becomes important at high carrier densities.

**Radiative recombination.** The simplest to model, if least important, form of recombination is radiative recombination. The process is proportional to the excess  $pn$  product:

$$r = B(pn - n_i^2) \quad (4.31)$$

where  $B$  is called the radiative rate coefficient.  $B$  has an experimental value of  $9.5 \times 10^{-15} \text{ cm}^3/\text{s}$  (Schlangenotto, 1974). Direct-gap semiconductors such as GaAs typically have radiative coefficients that are several thousand times larger. The weak, phonon-mediated radiative process in silicon means that other recombination paths usually dominate.

**Defect mediated recombination.** Any type of crystalline defect can potentially act as a catalyst for electron-hole recombination. The physical processes involved in this recombination are not well understood. The carriers must lose their energy through some mechanism. This could be radiative or non-radiative; the non-radiative process is usually thought to involve energy exchange with lattice distortions around the defect. Due to the lack of physical understanding, defect-mediated recombination is usually modeled using the phenomenological approach of Shockley, Read and Hall (Sze, 1981). Under low-level injection conditions, this gives a recombination rate proportional to the excess minority carrier density;

$$r = \frac{n - n_0}{\tau} \quad (4.32)$$

where  $n_0$  is the electron density in equilibrium and  $\tau$  is the low-level lifetime. More complicated expressions are obtained if one includes the effects of majority carrier capture.

Much of the early work on single crystal silicon cells was concerned with increasing the base lifetime,  $\tau$ , through reduction of crystalline defects. The use of high-quality, float-zone silicon combined with the incorporation of state-of-the-art semiconductor processing has reduced defect levels in laboratory cells to the point that bulk, defect-mediated recombination is no longer the dominant loss. Recombination in low-cost, commercial cells, particularly poly-crystalline cells, is still dominated by defect-mediated recombination, although progress continues. Recent results in hydrogen passivation (Schmidt, 1982) and phosphorus gettering (Narayanan, 1986) have allowed improved cell performance.

This work will concentrate on results achievable in high-quality silicon and, hence, defect mediated recombination will play a small role. One type of recombination that is intrinsic to semiconductors, and hence cannot be reduced through improved technology, is Auger recombination.

**Auger recombination.** In an Auger recombination event the excess energy of an electron-hole pair is given to a third free particle, either an electron or a hole. The recombination rate is then

$$r = C_n(n^2p - n_o^2p_o) + C_p(p^2n - p_o^2n_o). \quad (4.33)$$

$C_n$  is the  $n$ -type Auger coefficient and refers to the process where the excess energy is given to an electron. This process will dominate in  $n$ -type silicon.  $C_p$  is the corresponding  $p$ -type Auger coefficient. In material doped to over  $10^{18} \text{ cm}^{-3}$  experiments show that  $C_n = 2.8 \times 10^{-31} \text{ cm}^6/\text{s}$  and  $C_p = 0.99 \times 10^{-31} \text{ cm}^6/\text{s}$  (Dziewior and Schmid, 1977). When the doping, or carrier density, is less than  $10^{17} \text{ cm}^{-3}$ , the coefficients appear to be about four times larger (Sinton and Swanson, 1987a). These coefficients will be discussed more fully in Section 4.3.

#### 4.2.5C Surface Recombination

The only remaining portion of the cell where recombination can occur is at the free surfaces between contacted areas. Like bulk defect-mediated recombination, surface recombination is catalyzed through defects. These defects are usually thought to be mostly the dangling bonds of surface silicon atoms not bonded to four nearest neighbors. The net recombination rate per unit area is usually assumed to be proportional to the excess carrier density so that

$$J_{s,\text{rec}} = I_{s,\text{rec}}/A = qs(n - n_o) \quad (4.34)$$

on  $p$ -type surfaces and

$$J_{s,\text{rec}} = I_{s,\text{rec}}/A = qs(p - p_o) \quad (4.35)$$

on  $n$ -type surfaces.  $s$  is the phenomenological surface recombination velocity. It is very dependent on the surface preparation method. Clean, bare silicon surfaces have  $s$  in the range of  $10^3$  to  $10^5 \text{ cm/s}$ . Surfaces which are "passivated" through the growth of silicon dioxide can have  $s$  in the range of 1 to  $10^3 \text{ cm/s}$ . Improvements in surface passivation have been responsible for considerable improvement in cell performance. The details of surface recombination and passivation are discussed more fully in Section 4.3.

#### 4.2.6 Simplified Device Operation — The Narrow-Base Cell

In this section we use the previous concepts to analyze cell operation in a simplified manner. The main simplification is to assume constant electron and hole quasi-Fermi potentials, or equivalently, constant  $pn$  product. The voltage is then given by Equation (4.26).

This might be called the "narrow-base" approximation because, if the cell is sufficiently thick, gradients in  $\phi_n$  and  $\phi_p$  will necessarily become significant. We are thus ignoring any voltage drops in the base region, which will be small in the narrow-base approximation (i.e.,  $V_B = 0$  in Equation (4.20)). It is possible to make a first order improvement in this approximation by including resistance losses through a series resistance via Equation (4.28).

#### 4.2.6A Current-Voltage Characteristics

To calculate the current we use Equation (4.17) and evaluate all the sources of recombination.

**Diffused region recombination.** In this case the  $n$ -contact diffused region recombination current density is given by Equation (4.29)

$$J_{n\text{-cont,rec}} = J_{on} \left( e^{qV/kT} - 1 \right) \quad (4.36)$$

and the total current is just the area of the  $n$ -contact regions,  $A_{n\text{-cont}}$ , so that

$$I_{n\text{-cont,rec}} = A_{n\text{-cont}} J_{on} \left( e^{qV/kT} - 1 \right). \quad (4.37)$$

Note how these equations have the familiar form for the diffusion current in a diode. The current is actually composed of drift and diffusion components if the diffusions are non-uniformly doped.

Similarly

$$I_{p\text{-cont,rec}} = A_{p\text{-cont}} J_{op} \left( e^{qV/kT} - 1 \right) \quad (4.38)$$

for the recombination current in the  $p$ -type contact diffusion.

**Recombination in the base.** To perform the remainder of the bulk recombination integration the recombination in the base needs to be evaluated. If it is assumed that the base is  $p$ -type and low-level injected then

$$R_n = R_p = \frac{n - n_o}{\tau_n} \quad (4.39)$$

and

$$I_{\text{base,rec}} = q \int_V \frac{n - n_o}{\tau_n} dV. \quad (4.40)$$

Here,  $\tau_n$  includes the aggregate of all bulk recombination mechanisms: defect, Auger and radiative. Noting that, under low-level injection,

$$pn = n_i^2 e^{qV/kT} \approx N_A n \quad (4.41)$$

gives

$$I_{\text{base,rec}} = \frac{qAWn_i^2}{N_A\tau_n} \left( e^{qV/kT} - 1 \right) \quad (4.42)$$

so that base recombination has the same voltage dependence as diffused region recombination. Here  $A$  is the area of the device and  $W$  is the thickness of the base. We will find that anytime a region is in low-level injection and the recombination is linear in excess carrier density then the current will have this dependence on terminal voltage. That solar cells often have high-level injection and non-linear recombination effects is the main reason for introducing the above analysis.

If the base is high-level injected, then the electron and hole densities will be approximately equal by charge neutrality. This implies that

$$pn = n^2 = n_i^2 e^{qV/kT} \quad (4.43)$$

or

$$n = n_i e^{qV/2kT}. \quad (4.44)$$

Under high level injection, the defect-mediated recombination will be shown to be

$$R_p = \frac{n}{\tau_{hl}} \quad (4.45)$$

where  $\tau_{hl}$  is the high level lifetime (usually larger than the low level lifetime). Assuming constant quasi-Fermi potentials in this case gives

$$I_{\text{base,rec}} = \frac{qAWn_i}{\tau_{hl}} e^{qV/2kT}. \quad (4.46)$$

Note that this results in an "ideality factor" of two for the case of defect mediated bulk recombination in a high-level injected base. This should not be confused with the case of space-charge region recombination which often exhibits an ideality factor of near two.

Radiative recombination (the recombination of an electron-hole pair to produce a photon) is not particularly prevalent in silicon but is proportional, nevertheless, to the  $pn$  product and hence exhibits an "ideality factor" of one in both high-level and low-level injection. In Section 4.3.4 it will be shown that Auger recombination often dominates in highly injected bases. In high-level injection Equation (4.33) shows that the recombination will go as  $R_p = C_A n^3$  where  $C_A = C_n + C_p$ . This gives a recombination current of

$$I_{\text{base,rec}} = qAWC_A n_i^3 e^{3qV/2kT} \quad (4.47)$$

for an "ideality factor" of 2/3.\*

**Surface recombination.** The remaining portion of the device is the insulated surface between contact regions. Surface recombination, as we will see, proves to be a complicated function of excess carrier densities and is thus harder to model. If one assumes, however, that the surface region between contacts is low-level injected, and that the recombination is proportional to the excess minority carrier density, then

$$I_{\text{surf,rec}} = qs \int_S (n - n_o) dA \quad (4.48)$$

or, assuming constant quasi-Fermi potentials again,

$$I_{\text{surf,rec}} = \frac{qA_{\text{surf}} s n_i^2}{N_A} (e^{qV/kT} - 1) \quad (4.49)$$

where  $A_{\text{surf}}$  is the surface area of the device.

---

\* This gives an increase in voltage of 40 mV per decade of current, rather than the usual 60 mV per decade at room temperature.

If the surface is high-level injected, this becomes

$$I_{\text{surf,rec}} = q s A_{\text{surf}} n_i e^{qV/2kT}. \quad (4.50)$$

To obtain the overall recombination, the effects of all the above are added as appropriate. For example, if the cell is in low-level injection throughout, then, from Equation (4.17),

$$J = I/A = J_{ph} - \left( J_{on} + J_{op} + \frac{qWn_i^2}{N_A\tau_n} + \frac{qA_{\text{surf}}sn_i^2}{N_A} \right) \left( e^{qV/kT} - 1 \right). \quad (4.51)$$

Noting that the recombination current goes as  $e^{qV/\gamma kT}$  with  $\gamma = 1$ , we say that the cell has an "ideality-factor" of 1.

Alternatively, if the base is in high-level injection so that  $n = p$ , then

$$J = J_{ph} - \left( \frac{qsA_{\text{surf}}}{A} + \frac{qWn_i}{\tau_{hl}} \right) e^{qV/2kT} + (J_{on} + J_{op})e^{qV/kT} + (qWC_A n_i^3) e^{3qV/2kT}. \quad (4.52)$$

Note that, under high-level injection, the cell has an ideality factor which varies depending upon which recombination mechanism dominates.

Several observations are in order. Within the narrow-base approximation, the short circuit current ( $I$  when  $V = 0$ ) is just  $J_{ph}$ . This means that all photogenerated carriers are collected. One says that the internal quantum efficiency is then unity. If there is recombination of photogenerated carriers at short-circuit, then this must be due to gradients in  $\phi_n$  and  $\phi_p$  and is thus a type of transport loss. Also, within the narrow-base approximation, all cells obey the superposition principle; at any voltage the terminal current is the generation current minus the recombination current in the dark at the same voltage.

#### 4.2.6B Efficiency and the Maximum Power Point

The efficiency,  $\eta$ , is defined as the maximum output power divided by the solar power input,  $P_{\text{sun}}$ ,

$$\eta = \frac{I_{mp}V_{mp}}{P_{\text{sun}}} = \frac{J_{mp}V_{mp}}{P_{\text{sun}}/A}, \quad (4.53)$$

where  $V_{mp}$  and  $J_{mp}$  are the voltage and current evaluated at the point which gives maximum output power. This is often rearranged to give

$$\eta = \frac{J_{sc}}{P_{\text{sun}}/A} \frac{J_{mp}V_{mp}}{J_{sc}V_{oc}} V_{oc} = \mathcal{R} \cdot FF \cdot V_{oc} \quad (4.54)$$

where the subscript  $sc$  refers to short-circuit and  $oc$  refers to open-circuit.  $\mathcal{R} = J_{sc}/(P_{\text{sun}}/A)$  is called the responsivity, and  $FF = J_{mp}V_{mp}/J_{sc}V_{oc}$  is called the fill-factor.

In the narrow base approximation,  $J_{sc} = J_{ph}$ , so that the responsivity is 0.42 A/W when the one-sun photogeneration current is 42 mA per 100 mW. The responsivity in this approximation is independent of incident intensity because the

photogeneration current is linear in intensity. As seen in Section 4.4, actual cells may have a responsivity that is either sublinear or superlinear in intensity.

Closed-form solutions for the maximum power point in terms of the current-voltage characteristic do not exist; however, it is straight-forward to iteratively find the maximum power voltage and current for any given set of parameters.

For cases in which the ideality factor of the curve is well defined, an approximate equation for the fill factor in terms of the open circuit voltage has been proposed by Green (1983a). This is

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \quad (4.55)$$

where

$$v_{oc} = \frac{V_{oc}}{\gamma kT/q} \quad (4.56)$$

for an ideality factor  $\gamma$ .

Another approach that gives surprising accuracy is to estimate that the cell will be at the maximum power point when the terminal current is 95% of the short-circuit current. For a cell operating such that recombination in low-level injected regions dominates, so that the recombination is linear in excess carrier density, this indicates a reduction in  $n$  to 5% of its value at open circuit (cf. Equation (4.39)). Reducing the minority carrier density by 95% (a factor of 1/20) reduces the  $p$ - $n$  product by a factor of 1/20 as well (in low-level injection). The voltage corresponding to this new  $p$ - $n$  product is given by:

$$V_{mp} = \frac{kT}{q} \ln\left(\frac{1}{20}(pn/n_i^2)\right) = V_{oc} - \frac{kT}{q} \ln(20). \quad (4.57)$$

This amounts to a voltage reduction of 78 mV at the maximum power point for a temperature of 300K (27°C).

The effect of a series resistance,  $R_s$ , can be easily included in this approximation by noting that it will cause an additional voltage drop of  $I_{mp}R_s = J_{mp}\mathcal{R}_f$  where  $\mathcal{R}_f \equiv R_s A$ . The maximum power voltage is now

$$V_{mp} = V_{oc} - \frac{kT}{q} \ln(20) - 0.95J_{ph}\mathcal{R}_f \quad (4.58)$$

As an example, suppose that  $J_{sc} = 0.037$  A at 100 mW insolation and  $V_{oc} = 0.612$  V. Then the approximate efficiency is (neglecting series resistance)

$$\eta = \frac{(0.612 - 0.078) \times (0.037 \times 0.95)}{0.100} = 0.188. \quad (4.59)$$

If a specific series resistance of  $0.7 \Omega\text{cm}^2$  is present, then the efficiency is reduced to

$$\frac{(0.612 - 0.078 - 0.95 \times 0.7 \times 0.037) \times (0.037 \times 0.95)}{0.100} = 0.179. \quad (4.60)$$

Such a series resistance is seen to cause a 1% drop in absolute efficiency.

The preceding method of calculation efficiency is quite robust against the assumed terminal current. If a terminal current of 97% of the short-circuit current had been assumed, the calculated efficiency would be 18.7% for the case with no series resistance. Similarly, 93% yields 18.7%. The more exact Equation (4.55) gives 18.8% for this case.

All of the recombination mechanisms listed for the low-injection cell are linear in  $n$ . With this rule of thumb, the maximum-power-current is at 95% of the short-circuit-current, always gives a maximum-power-voltage 78 mV lower than the open circuit voltage. The corresponding results for the high-injection cells are that if base or surface recombination dominates, the maximum power point is 156 mV lower than the open-circuit voltage. If the diffused regions dominate it is 78 mV lower. If Auger recombination dominates, then the maximum power voltage is 52 mV lower. In each case, the assumption of 95% quantum efficiency introduces less than 0.3% error in absolute efficiency in comparison to the more exact methods over a wide range of the devices of interest (those with open circuit voltages greater than 600 mV).

For cases of well defined ideality factor the connection between this method and that of Equation (4.55) is seen if one realizes that then

$$J = J_{ph} - J_0 e^{qV/\gamma kT} \quad (4.61)$$

so that

$$V_{mp} = \frac{\gamma kT}{q} \ln(0.05 J_{ph}/J_0) = V_{oc} - \frac{\gamma kT}{q} \ln(20) \quad (4.62)$$

The fill factor is then

$$FF = (1 - 1/20) \frac{v_{oc} - \ln(20)}{v_{oc}} \approx \frac{v_{oc} - \ln(20)}{v_{oc} + v_{oc}/20} \quad (4.63)$$

in the above approximation. This almost exactly equals Equation (4.55) when  $v_{oc} = 20$ , a typical value. The equation is very insensitive to the exact value for the current at maximum power because that affects only the argument of the logarithmic term and the small term in the denominator. An advantage of analyzing cells in this manner, however, is that the assumption of constant ideality factor is not needed — one simply evaluates the efficiency at 95% of  $J_{ph}$ .

It is interesting to analyze what this means physically. In low-injection silicon solar cells, the excess minority carrier density in the bulk at the maximum power point is about 5% of what it is under open circuit voltage conditions. In a high-injection cell dominated by bulk or surface recombination, it is also 5%. But in a high-level injected cell dominated by emitter recombination, it operates with a base carrier density 22% of its open circuit value. If it is high-level injected and Auger recombination dominates, it operates at 37% of its open circuit carrier density.\* These figures provide some interesting insight into solar cell operation under these

\* Emitter recombination is quadratic in base carrier density in high-level injected cells so that a reduction of  $n$  to 22% reduces recombination to  $0.22^2 = 0.05$ . When Auger recombination dominates, recombination is cubic in  $n$  resulting in  $0.37^3 = 0.05$ .

various conditions. This type of solar cell modeling, in which the voltage and current are calculated explicitly in terms of carrier density, is more intuitive than some other modeling methods. It is easily generalized to more complex solar cells, such as the backside point-contact design, and helps remind the designer that it is the carrier density at the maximum power point that is important in determining the dominant sources of recombination and efficiency.

Of course all of these approximate calculations assume that the device designer has implemented a design with negligible series resistance, both laterally through the diffused regions and in the metal grid.

This analysis fails if the condition of uniform carrier density in the bulk is not met. For uniform carrier density, several conditions must be satisfied. These are given below.

$$L \geq W \quad (4.64)$$

$$D/W \geq (s \text{ or } \frac{J_o N_A}{qn_i^2}) \quad (4.65)$$

The first condition is that the diffusion length be much greater than the wafer thickness. The second condition states that the diffusion velocity must exceed either the surface recombination velocity, or the effective surface recombination velocity in the case of a diffused surface.

Cases where the carrier density is not uniform include conventional thick solar cells with low base diffusion length, or devices requiring transport of carriers over large distances, as in backside point-contact cells. The existence of very large local current densities also causes deviations from uniformity, again as in backside point-contact cells near the point-contacts. In these cases, this analysis is still useful as an initial approximation, indicating the mechanisms which dominate the behavior. In any case, once the design field is narrowed, a more precise model should be used to evaluate and "fine tune" the design. Often, the baseline gained with the approximate model helps guide the user through a more complex, complete numerical analysis by providing a case from which to judge the numerical result.

#### 4.2.7 Limit Efficiencies

It is interesting to calculate the efficiency limits for silicon solar cells as a predictive guide to possible improvements. We first present approximate limit efficiencies calculated in the context of the narrow-base solar cells discussed here. Consider a 100  $\mu\text{m}$  thick one-sun cell. The limit imposed by the amount of light absorbed is about 42  $\text{mA}/\text{cm}^2$  of current density. The other limit generally considered fundamental is the bulk Auger recombination. Most of the other recombination parameters are often considered to be technologically surmountable. For a case under high-level-injection conditions, the I-V curve will be defined by

$$J = J_{ph} - C_A n^3 W q. \quad (4.66)$$

This gives an open-circuit voltage of 744 mV, and an efficiency of 27.9% at 25 °C. This value is about one absolute percentage point lower than the efficiency calculated in the same way by Green (1984) because an ambipolar Auger coefficient

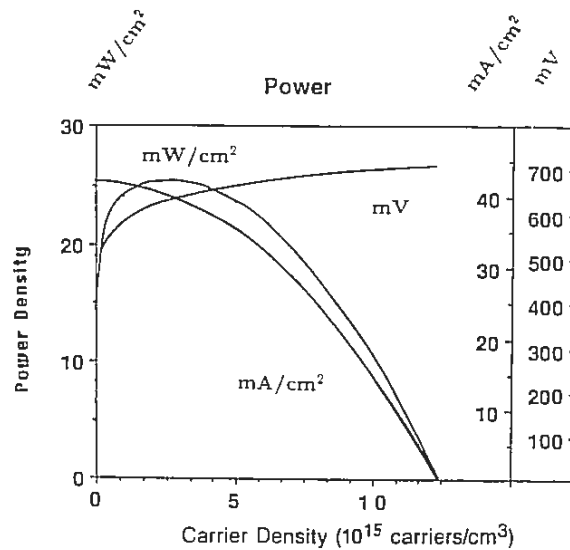


Figure 4.4: An example of the modeling of a cell operating near the Auger limit to the efficiency, but with  $n$ - and  $p$ -type emitter saturation current densities of  $2.5 \times 10^{-14}$  A/cm<sup>2</sup>. The voltage and current density as a function of the parametric variable  $n$ , the carrier density. The power density, the product of  $J$  and  $V$ , is also shown.

of  $1.66 \times 10^{-30}$  was used here that is 4 times higher than Green assumed. This will be discussed more fully in Section 4.3.

Another relevant limit would be to abandon the rather optimistic assumption that all of the technologically-related parameters are surmountable and insert best estimates for these instead. When this is done, the most significant additional recombination is from the diffused areas. For example, assume that both  $J_{on}$  and  $J_{op}$  can be reduced to  $2.5 \times 10^{-14}$  A/cm<sup>2</sup>, a relatively optimistic scenario. Then

$$J = J_{ph} - C_A n^3 W q - (J_{on} + J_{op}) \left( \frac{n}{n_i} \right)^2. \quad (4.67)$$

The terminal current density, voltage, and power density determined by this equation are shown in Figure 4.4 as an example of the modeling techniques of the last section. The parametric variable, the carrier density, is given by the horizontal axis. Since there are two recombination terms with differing dependencies on the carrier density, the ideality factor for this cell is ill defined. So the approximate methods are inaccurate and the maximum-power-point is best determined directly from Equation (4.67) and the associated voltage for each carrier density. Evaluation of this I-V curve yields a significantly lower open-circuit voltage of 713mV, and an efficiency of 25.5%.

The similar calculations for a 50  $\mu$ m-thick concentrator cell operating at 300 suns with a responsivity of 43.2 mA/100mW indicate that in the Auger limit, an efficiency of 33% is to be expected. When the effects of emitter saturation current are considered, this is reduced to 32.2%. The effects of this emitter recombination are smaller in this case because the carrier density is much higher under concentration and the base Auger recombination truly dominates under these conditions. The assumption of a photogenerated current density of 43.2 mA/cm<sup>2</sup> assumes that the

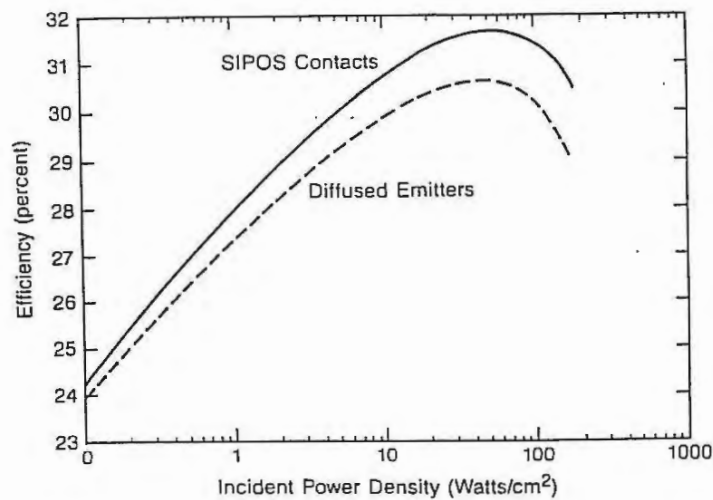


Figure 4.5: The predicted efficiency for a 50  $\mu\text{m}$ -thick point-contact solar cell. The emitter size and shape has been independently optimized for the two cases, with SIPOS contacts and with diffused emitters.

directionality of the light is taken advantage of in the ways available for concentrating systems as described in a later section on light-trapping. In principle, current densities up to 46  $\text{mA}/\text{cm}^2$  are possible for 100  $\text{mW}/\text{cm}^2$  of AM 1.5D (air-mass 1.5 direct-normal sunlight).

For concentrator cells, other factors also reduce the expected efficiencies. The high current densities cause voltage drops within the base region, making many of the assumptions in the simplified analysis less valid. A modeled result for a point-contact cell, in which the effects of all of the recombination mechanisms are included as well as the base voltage drops and three-dimensional effects is shown in Figure 4.5. This indicates the sensitivity to the emitter saturation current by showing the attainable efficiencies for two choices of emitter technology within the constraints of the backside point-contact solar cell design (Sinton and Swanson, 1987a). In this case an efficiency of 30.5% is predicted with diffused emitters and 31.5% with SIPOS emitters.

More detailed accounts of the limit efficiencies for silicon solar cells are available. Reference (Tiedje, Yablonovitch, Cody, and Brooks, 1984) carefully details the limit efficiency for a one-sun cell with only bulk Auger and radiative losses, finding a value of 29.8%. In Green (1987), an examination of the photogeneration enhancements available from the use of concentrated light are discussed. When the maximum theoretical concentration of sunlight is assumed, efficiencies as high as 36% are possible.

## 4.3 The Physical Details of Recombination and Transport

### 4.3.1 Introduction

In order to model cell operation properly one must not only have useful methods of solving the semiconductor equations but, perhaps more importantly, accurate

physical parameters such as recombination coefficients and mobilities are needed as well, all as a function of doping density. Solar cell performance depends heavily on recombination, as opposed to most other semiconductor devices where recombination is rather secondary to their operation. Therefore much of the device literature is of insufficient detail on recombination parameters which has necessitated new measurements. Band-gap shrinkage, and other heavy doping effects, are also of determining performance for diffused regions and so the solar cell community has been active in researching these effects also. This section presents some of the recent results in this area.

### 4.3.2 Transport and Recombination in Doped Regions

We have seen that it is only necessary to calculate the motion of minority carriers to determine the recombination in doped regions. In order to do this, one must know certain physical parameters such as mobility and lifetime which are often not well known. The problem is complicated by the fact that at higher doping densities the density of states is modified by so-called "heavy doping effects."

As mentioned in Section 4.1, the semiconductor equations presented there do not incorporate effects occurring at high doping densities. As discussed more fully in del Alamo (1984), this can be easily corrected for the case of minority carrier transport in low-level injected regions. Thermodynamically, the driving force for carrier transport is the gradient in electromotive force, or quasi-Fermi level. To first order, the current will be proportional to that gradient. In addition, since the minority carriers are dilute and don't interact with each other, the current should be proportional to the minority carrier density. For the case of  $n$ -type material, the second version of Equation (4.2) expresses this fact, where the factor  $q\mu_p$  can be thought of as the proportionality constant. We thus have

$$\vec{J}_p = -q\mu_p p \vec{\nabla} \phi_p \quad (4.68)$$

being valid in heavily doped semiconductors. Of course, one must know  $\mu_p$  in order to perform calculations. Often the mobility of holes when they are majority carriers is used here, but we shall see that this is not exactly correct.

In addition, the minority carrier density in heavily doped material can be written

$$p = p_0 e^{q(\phi_p - \phi_n)/kT}. \quad (4.69)$$

This is valid regardless of the density of states of the valence band because the hole quasi-Fermi level is sufficiently far from the valence band that the non-degenerate form for the Fermi factor is appropriate. Of course, heavy doping effects mean that the equilibrium minority carrier density is no longer given by the low-density mass-action law; specifically

$$p_0 \neq n_i^2/N_D. \quad (4.70)$$

Often we will use an "effective bandgap shrinkage" defined through

$$p_0 = \frac{n_i^2}{N_D} e^{\Delta E_g/kT}. \quad (4.71)$$

This is not directly a true shrinkage in bandgap, but incorporates effects from changes in shape of the bands as well (del Alamo and Swanson, 1984).

Finally, we have the continuity equation

$$\frac{\partial J_p}{\partial x} = -qR_p = -q\frac{p - p_o}{\tau_p}. \quad (4.72)$$

A normalized excess carrier density is defined through

$$u = \frac{p}{p_o} - 1 = e^{q(\phi_p - \phi_n)/kT} - 1 \approx e^{qV/kT}. \quad (4.73)$$

Note that  $u$  is a measured external parameter through the terminal voltage.

The above equations can be written

$$J_p = -qp_o D_p \frac{du}{dx} \quad (4.74)$$

$$\frac{dJ_p}{dx} = -\frac{qp_o D_p}{L_p^2} u \quad (4.75)$$

where

$$D_p \equiv \frac{kT}{q} \mu_p \quad (4.76)$$

and

$$L_p \equiv \sqrt{D_p \tau_p}. \quad (4.77)$$

Examination of the above equations shows that there are actually only two independent parameters which control minority carrier motion in the steady-state,  $p_o D_p$  and  $L_p$ . In particular, the lifetime cannot be determined using steady-state measurements without assuming a value for  $D_p$  or  $\mu_p$ . This has caused considerable discrepancy to appear in quoted literature values for these variables (Swanson, del Alamo, and Swirhun, 1984).

We have made measurements of  $L_p$  using transistor structures and  $\tau_p$  using photoluminescence decay. This has allowed a determination of  $\mu_p$ . Similar measurements have also been performed on  $p$ -type material to determine  $L_n$  and  $\tau_n$ . The results are shown in Figures 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11 (del Alamo and Swanson, 1987 and Swirhun, Kwark, and Swanson, 1986).

At higher doping densities the lifetime decreases, probably due to Auger recombination. We have found that the lifetime is rather independent of sample preparation and doping technique, suggesting that traps are not playing a significant role at high doping. The measurements tend to be in rather good agreement with those of Dziawior and Schmid (1977). An Auger coefficient of  $C_n = 2.8 \times 10^{-31} \text{ cm}^6/\text{s}$  for  $n$ -type material, Figure 4.6, and  $C_p = 1 \times 10^{-31} \text{ cm}^6/\text{s}$  for  $p$ -type material, Figure 4.9, represents the results well. In this case the lifetimes can be modeled as

$$\tau_p = \frac{1}{C_n N_D^2} \quad (4.78)$$

(4.71)

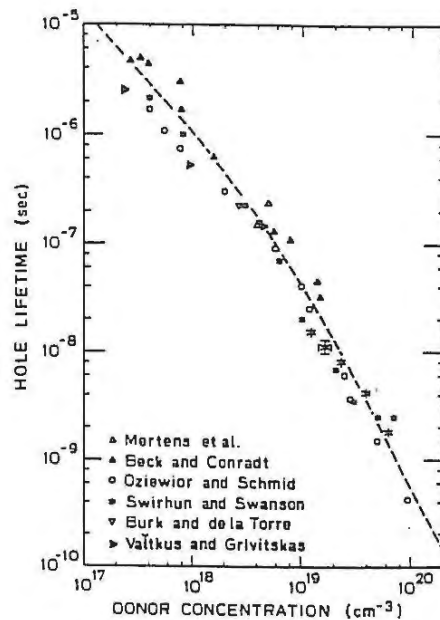


Figure 4.6: Minority carrier lifetime versus doping in *n*-type material (del Alamo, 1985).

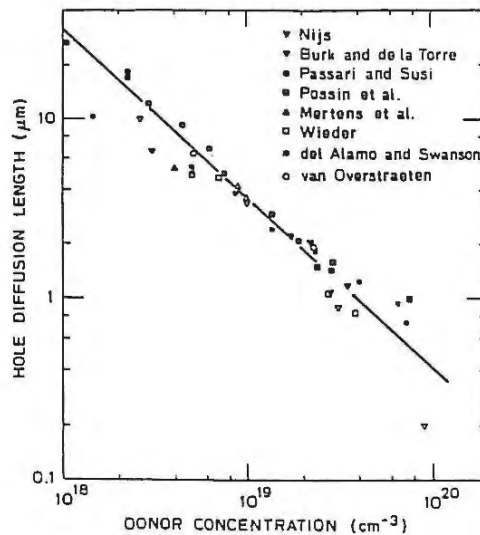


Figure 4.7: Minority carrier diffusion length versus doping in *n*-type material (del Alamo, 1985).

and

$$\tau_n = \frac{1}{C_p N_A^2} \quad (4.79)$$

The measured minority carrier mobilities, shown in Figures 4.8 and 4.11, deviate substantially from values of the same carriers when they are majority carriers, the majority carrier values, being more than a factor of two higher at the highest doping densities. This effect has been predicted theoretically by Bennett (1983) and has

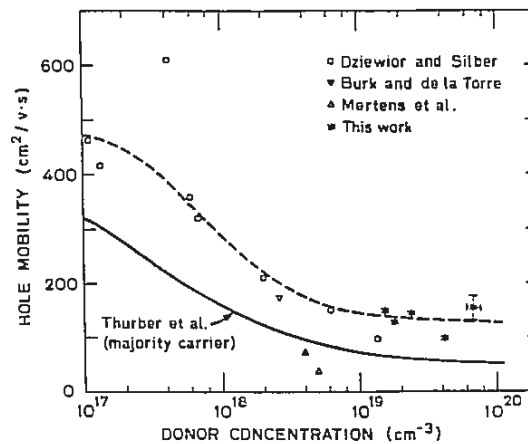


Figure 4.8: Minority carrier mobility versus doping in  $n$ -type material (del Alamo, 1985).

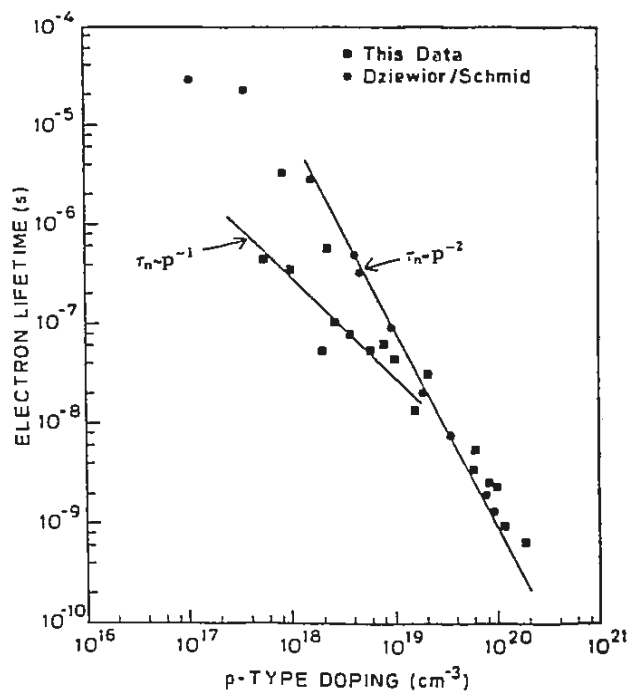


Figure 4.9: Minority carrier lifetime versus doping in  $p$ -type material (Swirhun, 1987).

also been experimentally reported by Dzierwior and Silber (1979). Note that there is no evidence for a “mobility edge” as one sees in amorphous silicon, because this would result in lower minority carrier mobility.

Using transport measurements across the base region of transistors the apparent bandgap shrinkage was measured. These devices have epitaxial bases so that the doping profiles are uniform, simplifying the data interpretation. The results are shown in Figures 4.12 and 4.13.

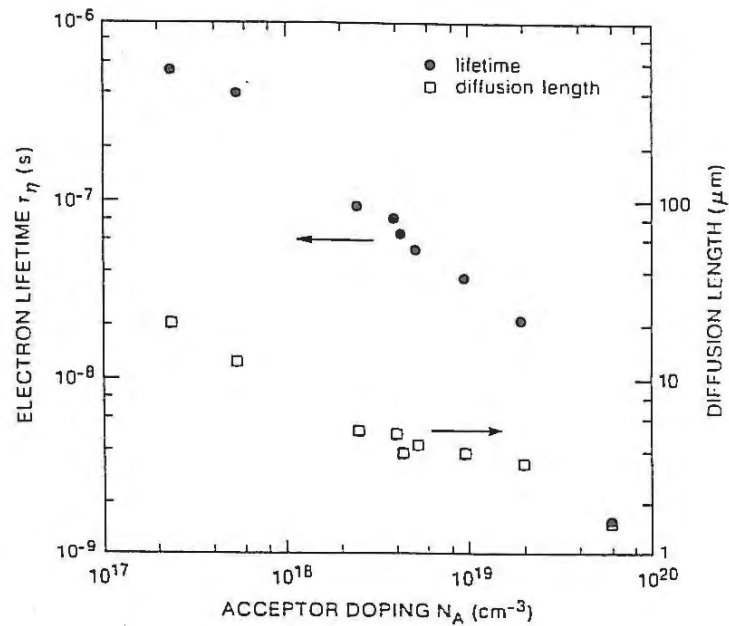


Figure 4.10: Minority carrier diffusion length versus doping in *p*-type material (Swirhun, 1987).

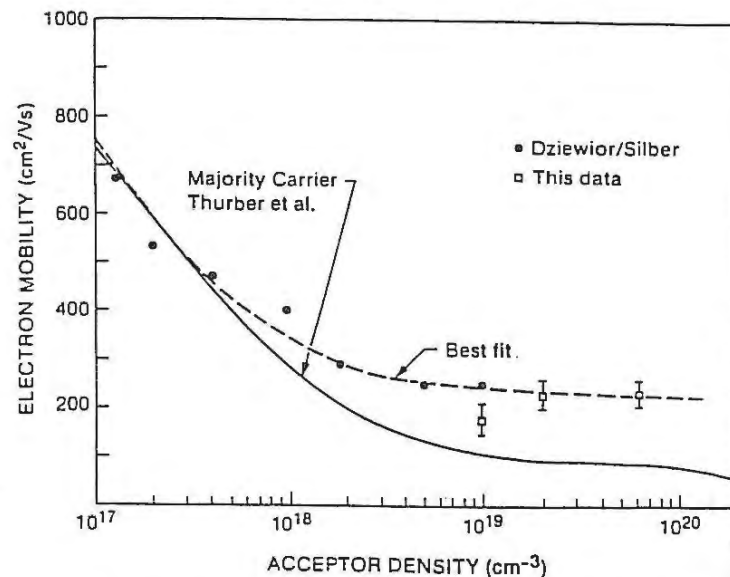


Figure 4.11: Minority carrier mobility versus doping in *p*-type material (Swirhun, 1987).

The apparent bandgap shrinkage for *p*-type material agrees well with the measurements of Slotboom and deGraaf (1977); however, the *n*-type data falls considerably below most of the other reported literature values. When the original data is used to correct literature values to that which would be computed using the new, higher minority carrier mobility, the agreement is nearly perfect (Figure 4.12) in this case as well.

Using the above physical parameters, it is possible to calculate the saturation current for diffusions of arbitrary profile (del Alamo, 1985). For example, Figure 4.14

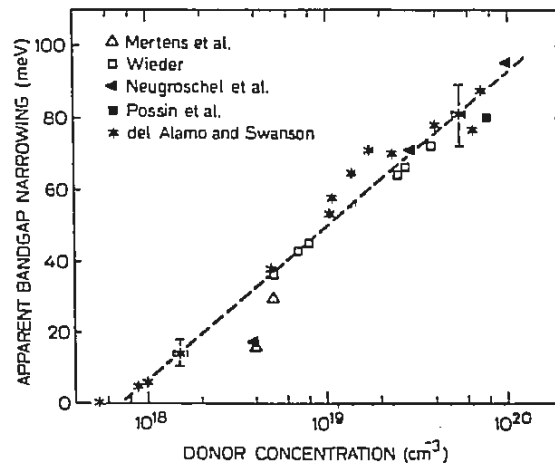


Figure 4.12: Apparent band gap shrinkage versus doping for  $n$ -type material (del Alamo, 1985).

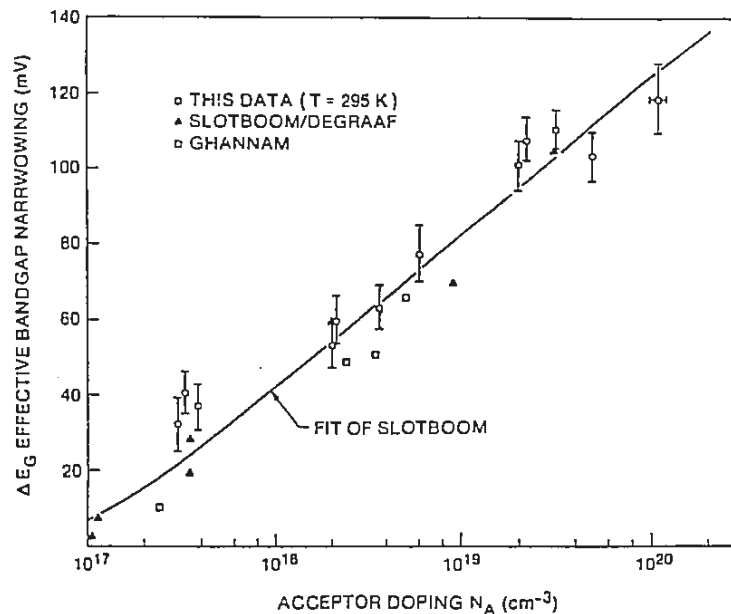


Figure 4.13: Apparent band gap shrinkage versus doping for  $p$ -type material (Swirhun, 1987).

shows the calculated saturation current for  $n$ -type emitters with Gaussian profiles when the surface recombination velocity is large, as it would be under metal contacts. Note that the most important factor in obtaining low saturation current is to have a large junction depth. If, however, one has passivated surfaces with a surface recombination velocity of  $10^3$  cm/s then the best emitters have a low surface recombination velocity and are shallow to limit bulk recombination in the heavily doped portion. Such a calculation is shown in Figure 4.15.

#### 4.3.3 Surface Recombination

Surfaces contribute significantly to recombination because they tend to have a relatively large density of recombination centers. Both the density and capture

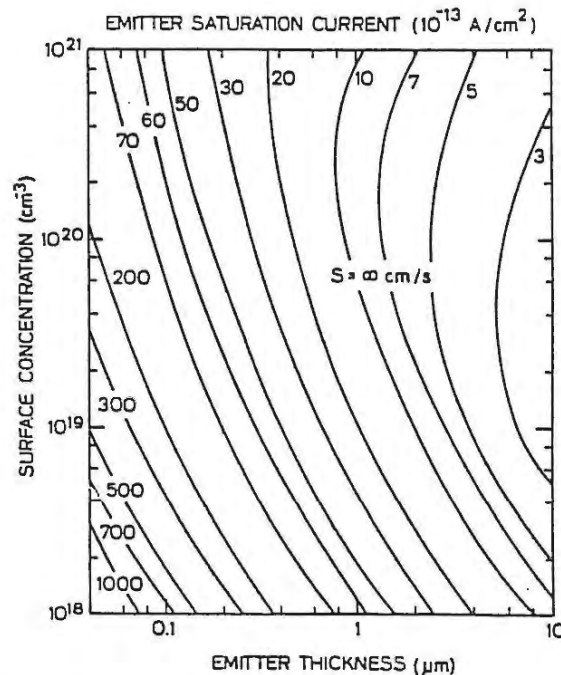


Figure 4.14: Calculated emitter saturation current for  $n$ -type emitters versus junction depth and surface concentration assuming a Gaussian profile. The surface recombination velocity is infinite (del Alamo, 1985).

cross-sections of these centers are very process dependent. In addition, the surface can be charged, affecting the surface potential and carrier densities. This makes modeling surface recombination problematic. Some measurements and calculations are presented below which indicate that surface recombination velocities can be significantly less than previously thought.

Assuming simple Shockley-Read-Hall type recombination the total recombination through the continuum of possible states at the interface between silicon and silicon-dioxide, the total surface recombination velocity for an oxide passivated surface can be calculated (Eades and Swanson, 1985). This requires knowledge of both the density and cross-section dependence on energy as well as the surface potential. Capture cross section measurements were performed using DLTS on oxidized and annealed silicon surfaces. The results are shown in Figure 4.16, Figure 4.17, and Figure 4.18. Very little band bending would be expected for these samples which have fixed charge densities less than  $10^9 \text{ cm}^{-2}$ .

Using the above densities and cross sections the surface recombination velocity can be calculated. Figures 4.19 and 4.20 present the results for low-level injection.

Note that  $n$ -type surfaces have significantly lower recombination velocities than  $p$ -type. This is a direct result of the much smaller capture cross section for holes than electrons.

Because of the large capture cross section energy dependence the recombination velocity is very injection level dependent. This is illustrated in Figures 4.21 and 4.22.

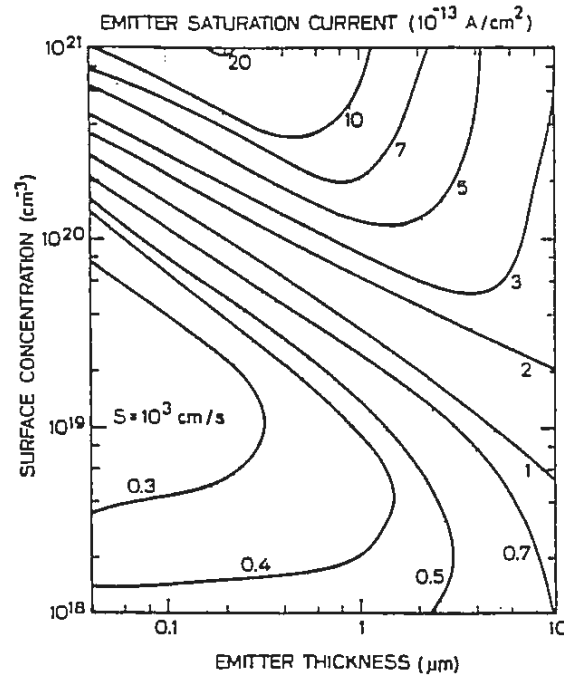


**Figure 4.15:** Calculated emitter saturation current for  $n$ -type emitters versus junction depth and surface concentration assuming a Gaussian profile. The surface recombination velocity is  $10^3$  cm/s (del Alamo, 1985).

Since solar cells usually run at significant injection levels the relevant recombination velocity is usually much less than that encountered at very low injection levels. Measurements based on low injection levels should thus be used with caution. In addition, it is interesting to note that recombination velocities less than 10 cm/s are attainable on high quality surfaces.

#### 4.3.4 Auger Recombination in High Level Injection

At high levels of injection the electron and hole densities are equal and so the Auger recombination rate becomes

$$R_n = R_p = C_n n^3 + C_p n^3 = (C_n + C_p) n^3 = C_A n^3 \quad (4.80)$$

where  $C_A = C_n + C_p$  is called the ambipolar Auger coefficient. In attempting to model the performance of point-contact silicon solar cells running in high-level injection we have been forced to adjust the typical ambipolar Auger coefficient used in device modeling (Sinton and Swanson, 1987a). Accordingly, we adapted the point-contact cell design into a test structure ideally suited for measuring this parameter.

Figure 4.23 shows the structure of a point-contact silicon solar cell. Electron-hole pairs are generated at the bottom and must diffuse to the  $n$  and  $p$  diffused regions at the top to be collected. The cell depends on obtaining very high carrier recombination lifetime to achieve high current collection and voltage. Accordingly, procedures were developed that yield trap assisted lifetimes over one millisecond in finished devices. Surface recombination was reduced by passivating the surface

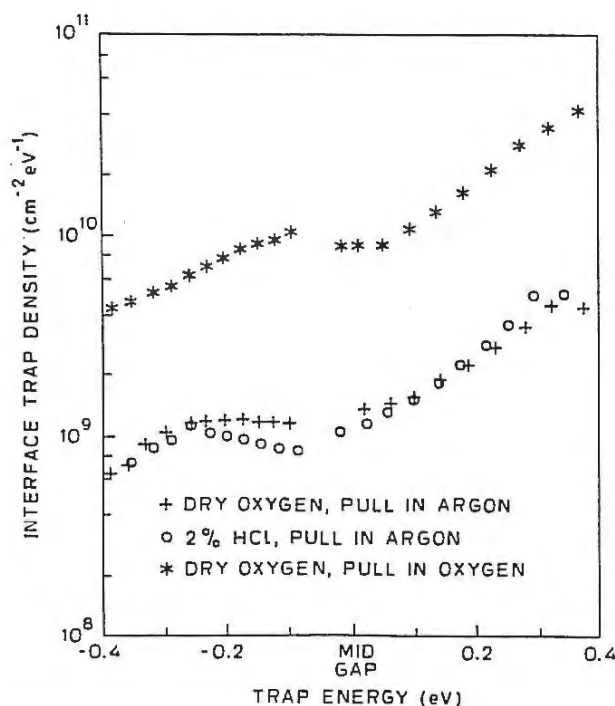


Figure 4.16: Interface trap density for the oxides studied. All samples were post-metallization annealed at 450°C in forming gas. The values in the lower half of the gap come from measurement of a *p*-type substrate and the upper gap values from an *n*-type sample (Eades and Swanson, 1985).

with silicon dioxide except in the metal contact areas. When this is done one finds that recombination in the diffused regions, or at the metal-semiconductor contact, dominates. To reduce this component the size of the diffused regions is reduced to a polka dot array of small regions — hence the name “point-contact cell.”

Cells with varying sizes and spacings of contact diffusions were fabricated. The resulting diffused region recombination components were extracted with the results shown in Figure 4.24. As expected, this recombination is proportional to the contact coverage fraction. Measurements indicated that the lifetime in the bulk was decreasing with carrier density, and at a rate faster than that predicted using the “standard” ambipolar Auger coefficient of  $4 \times 10^{-31} \text{ cm}^6/\text{s}$ . Thus a device with very small contact coverage was fabricated — the “Auger test structure.” This was to force bulk Auger to be as dominant as possible.

Figure 4.25 shows a secondary effect of having small, widely spaced contacts for this purpose — the base region carrier density, as calculated from our device model, is nearly uniform from front to back. This is a result of the reduced contact recombination and therefore the reduced diffusion of carriers to the contacts. This causes the modeled results to be quite independent of assumed transport parameters.

In order to assure that the test device is dominated by Auger recombination, the modeling code was exercised to identify the sources of recombination as a function of incident power. As seen in Figure 4.26, at all power densities over 1 watt/cm<sup>2</sup>, Auger recombination dominates. This lends support to the accuracy with which

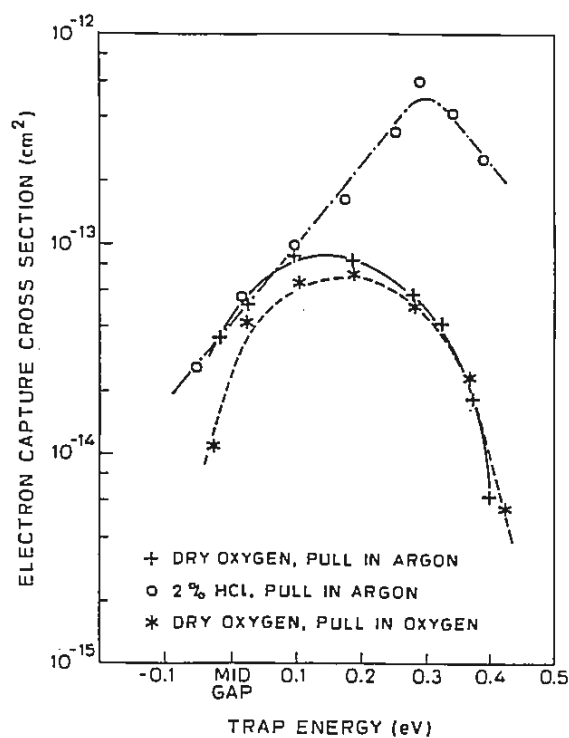


Figure 4.17: Electron capture cross section in the upper half of the gap (Eades and Swanson, 1985).

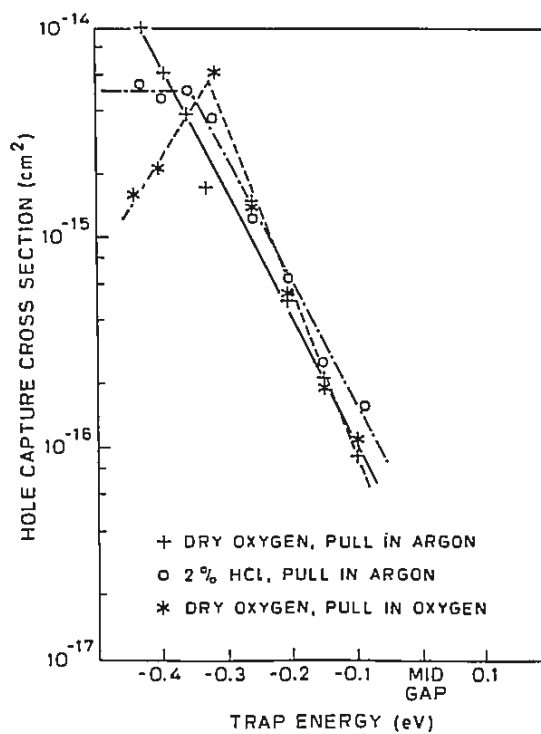


Figure 4.18: Hole capture cross section in the lower half of the gap (Eades and Swanson, 1985).

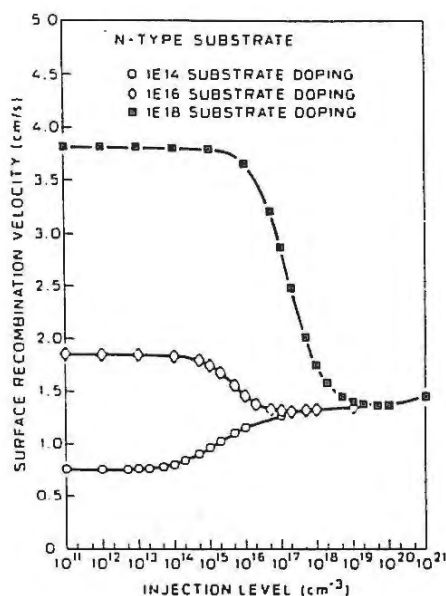


Figure 4.19: Surface recombination velocity in low-level injection for an  $n$ -type substrate at flat-band (Eades and Swanson, 1985).

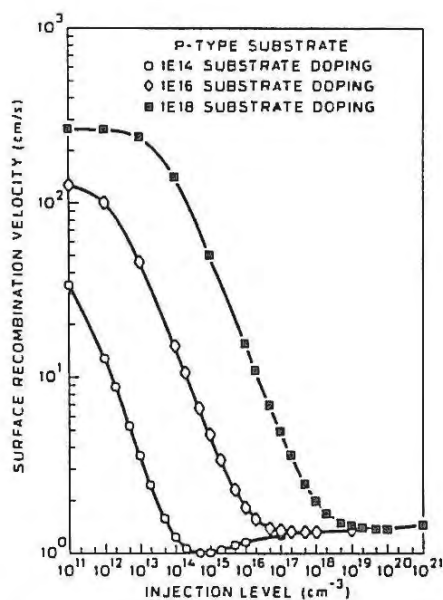


Figure 4.20: Surface recombination velocity in low-level injection for a  $p$ -type substrate at flat-band (Eades and Swanson, 1985).

the Auger coefficient can be extracted by fitting the measured characteristics to the model.

In Figure 4.27 the measured open circuit voltage of the Auger test structure is shown as a function of incident power. In order to fit this result to the model it is necessary to use an Auger coefficient of  $1.66 \times 10^{-30} \text{ cm}^6/\text{s}$ , a factor of over four times the standard value. Also shown is the result of using the standard value.

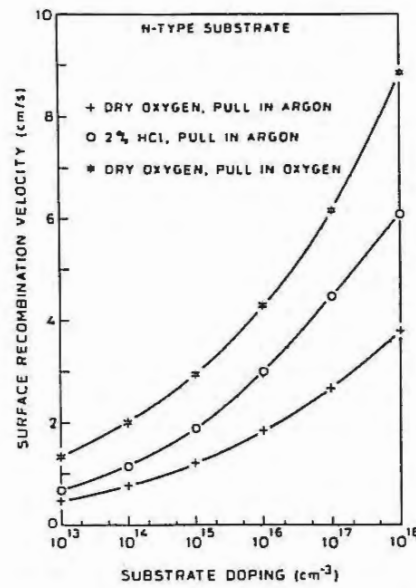


Figure 4.21: Surface recombination velocity versus injection for an *n*-type substrate at flat-band (Eades and Swanson, 1985).

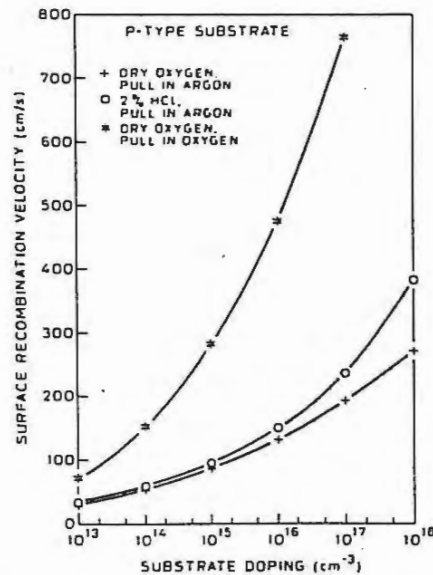


Figure 4.22: Surface recombination velocity versus injection for a *p*-type substrate at flat-band (Eades and Swanson, 1985).

Altering the Auger coefficient alters more than the open-circuit voltage. For example the open-circuit voltage decay after interrupting a forward current is controlled by recombination of carriers in the base. Figure 4.28 shows the decay rate of the voltage as a function of carrier density in the open-circuit configuration. The carrier density is determined from the terminal voltage. A constant base lifetime would result in a constant  $dV/dt$  whereas a lifetime that is inversely proportional to

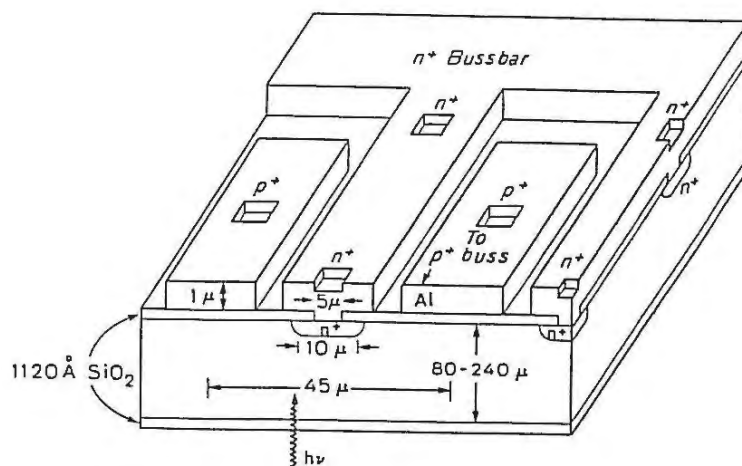


Figure 4.23: Structure of the point-contact solar cell.

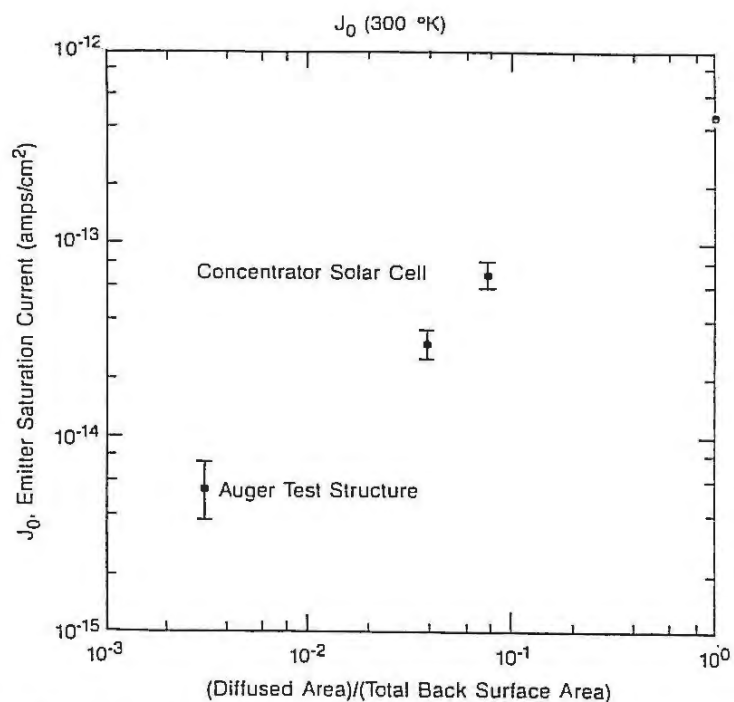


Figure 4.24: Measured saturation current of point-contact cells versus contact coverage fraction. The concentrator solar cell shown is the optimized 27.5% cell reported in Sinton et al. (1986).

carrier density squared, as in Auger recombination, yields a parabolic dependence. To best fit the data requires an Auger coefficient of  $1.66 \times 10^{-30} \text{ cm}^6/\text{s}$  once again.

Finally, as the incident intensity increases, the carrier density at the front of the cell increases causing a loss of carriers by Auger recombination, even at the short-circuit condition. This causes the short circuit current to be sublinear in incident

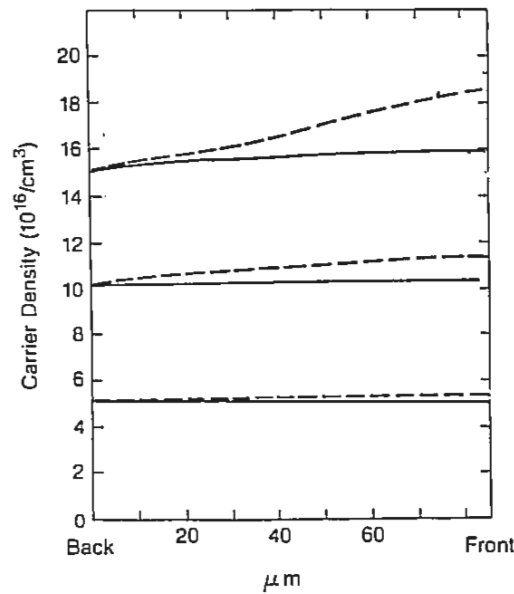


**Figure 4.25:** Calculated carrier density from front to back for the standard device, labeled “concentrator solar cell” in the previous figure, (dashed line) and Auger test structure (solid line) under open-circuit-voltage conditions. The profiles shown are those that would result in three particular backside carrier densities (hence voltages). The Auger test structure can attain high voltages at lower concentrations of incident light, and with less of a gradient in carrier density across the wafer.

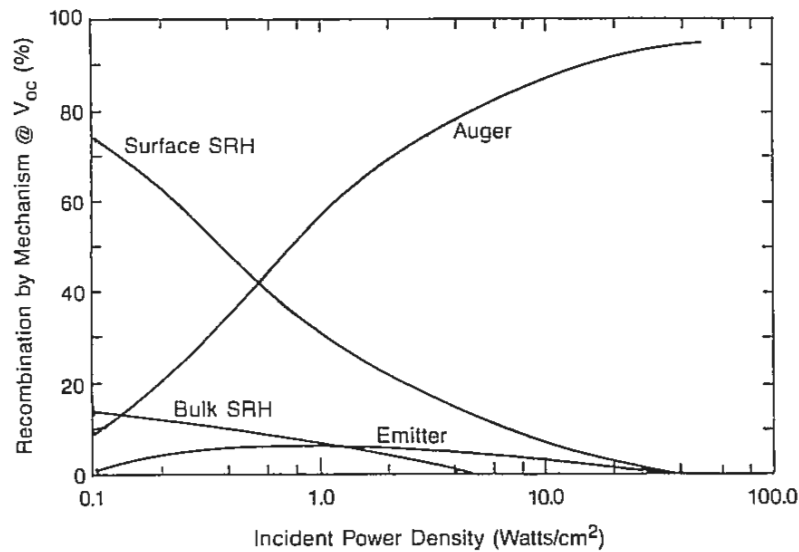


**Figure 4.26:** Calculated recombination by source versus incident solar power level for the Auger test structure. SRH refers to Shockley-Read-Hall, defect mediated recombination.

power. Although this is a less accurately modeled second order effect, as shown in Figure 4.29, it is necessary to use an increased Auger coefficient to predict the measured result using the modeling code.

In Figure 4.30 the lifetime versus carrier density, as measured with the Auger test structure, is presented as the dashed line. The solid line is from measurements

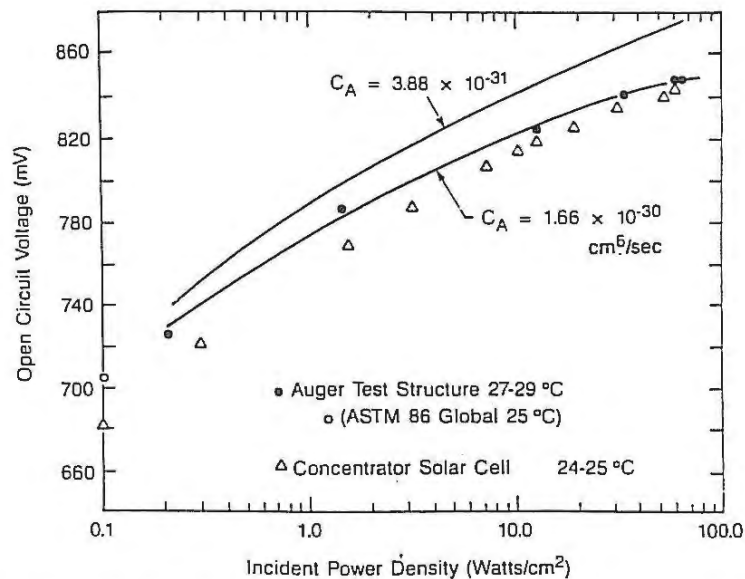


Figure 4.27: Measured open-circuit voltage of the Auger test structure versus incident power density.

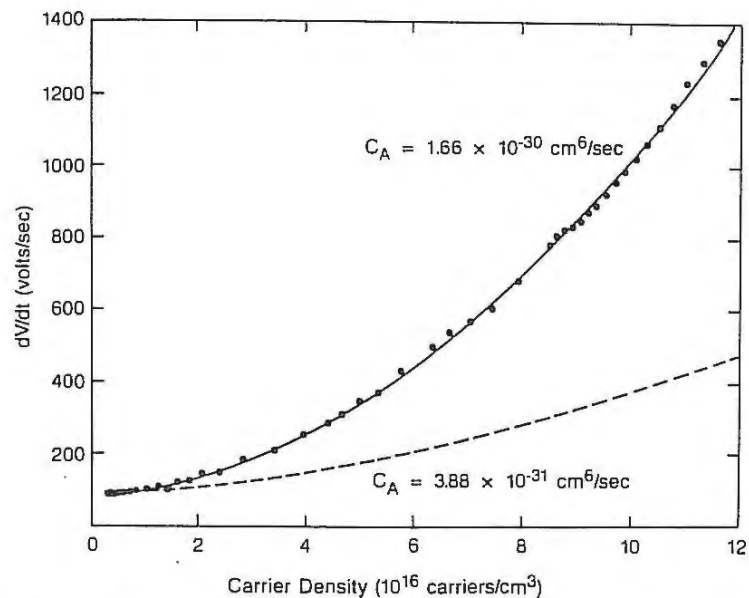


Figure 4.28: Rate of change of open circuit voltage versus time following a current pulse.

on high lifetime, high resistivity, highly injected material using a photoconductivity decay technique (Yablonovitch and Gmitter, 1986). It is in agreement with our results. The measured ambipolar Auger coefficient is once again  $1.66 \times 10^{-30}$  cm<sup>6</sup>/s. This is four times that which one would obtain by summing the *n*- and *p*-type Auger coefficients determined from material doped over  $1 \times 10^{19}$  cm<sup>-3</sup>. Also shown are various results on low level injection in material where the carrier density is achieved by doping rather than injection. The lifetime on doped material is in

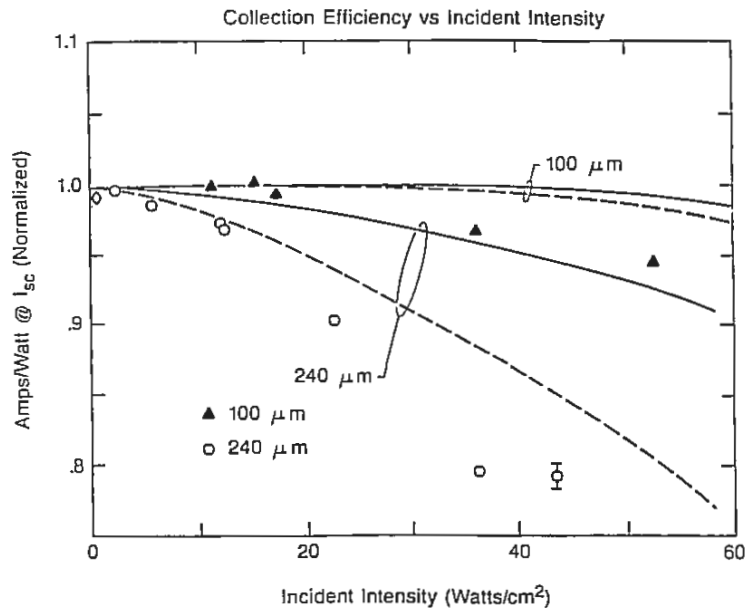


**Figure 4.29:** Measured and calculated responsivity normalized to its value at low intensity versus incident intensity. The solid lines are calculated for an Auger coefficient of  $3.88 \times 10^{-31} \text{ cm}^6/\text{s}$  and the solid lines for the value developed here,  $1.66 \times 10^{-31} \text{ cm}^6/\text{s}$ .

substantial agreement with that on highly-injected material. This implies that the Auger coefficient must be higher for doping, as well as injected, densities in the range of  $1 \times 10^{17} \text{ cm}^{-3}$ . In the past this has been explained by postulating that an additional recombination mechanism is operative in doped material, probably due to a doping related defect. This explanation seems highly suspect because of the agreement of results on doped material with those on injected material — the presence of the free carriers is sufficient to yield lifetimes in the observed range so that no additional recombination mechanism need be postulated. The only way of reconciling these results is to postulate that the Auger coefficient is slightly carrier density dependent. In fact, other authors have predicted very similar results in a much ignored 1981 paper (Vaitkus and Grivtkas, 1981). They see a sort of jog in the Auger coefficient in the  $10^{18} \text{ cm}^3$  range which they attribute to degeneracy effects. Whatever the cause, it is necessary to use the higher value of ambipolar Auger coefficient to correctly model electron-hole plasmas in this carrier density range.

## 4.4 Cell Design Engineering

### 4.4.1 Maximizing Photogeneration

The major improvement which has pushed the efficiency of concentrator cells from about 20% to 28% over the last 8 years has been light-trapping. A major problem with silicon is that it doesn't absorb light very well. Even a wafer 1 mm thick only absorbs about 95% of the light available for producing electron-hole pairs. One way to absorb more of the light in a thin layer is to utilize light-trapping. Because of the difference in index of refraction between silicon and air, light which

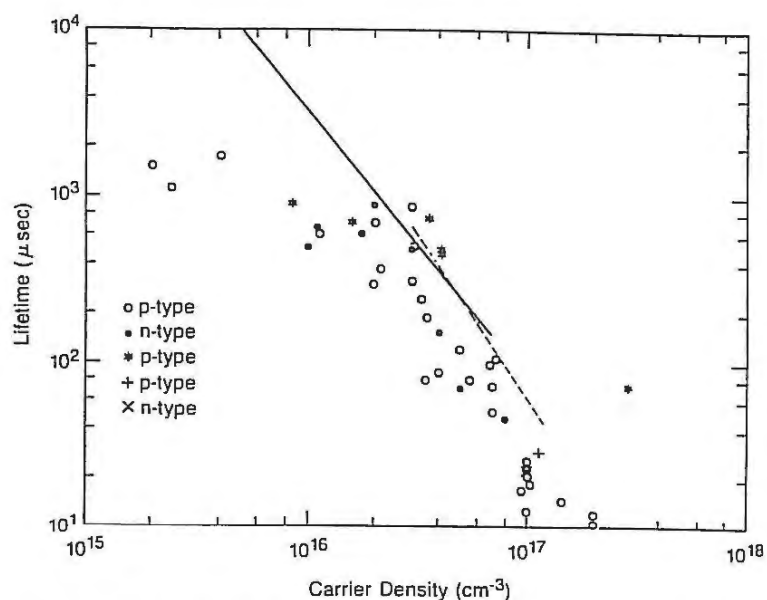


**Figure 4.30:** Measured lifetime on high-level injected electron-hole plasmas versus injected carrier density. A comparison is shown between the results from measurements on specialized solar cells (dashed line)(Sinton and Swanson, 1987a), and photoconductivity decay measurements (solid line)(Yablonovitch and Gmitter, 1986). Also included are data where the carrier density is from doping. This data is (from top to bottom in the legend): (Huber, Bachmeier, Wahlich, and Herzer, 1986), both *p*- and *n*-type; (Ciszek, 1987) for *p*-type, and (Dziewior and Schmid, 1977) for *p*- and *n*-type.

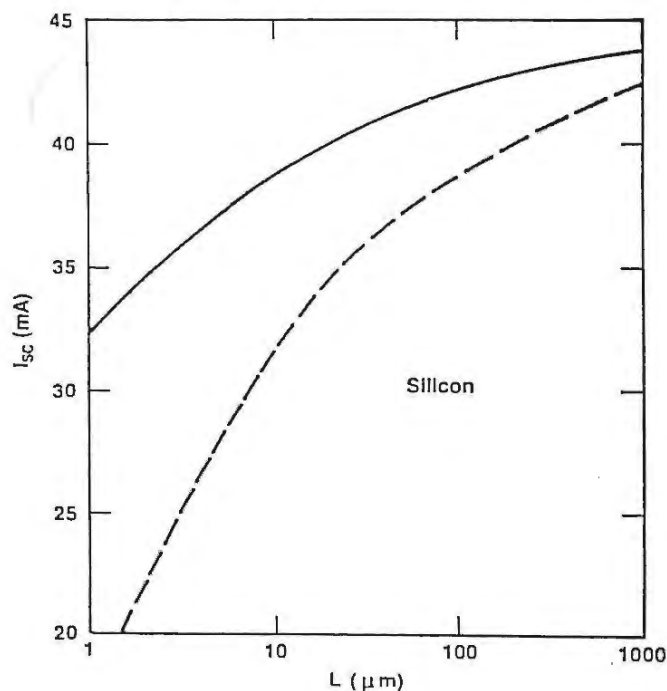


**Figure 4.31:** The short-circuit current as a function of cell thickness with textured Lambertian surfaces (solid) and polished surfaces (dashed)(Tiedje, Yablonovitch, Cody, and Brooks, 1984).

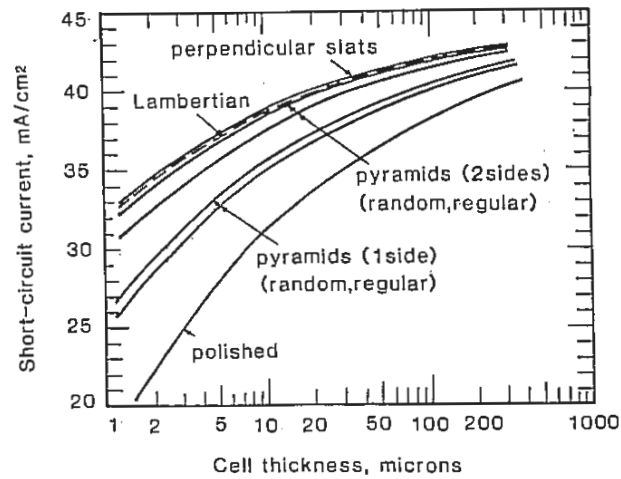


Figure 4.32: The calculated short circuit density as a function of the silicon cell thickness for various light-trapping schemes (Green and Campbell, 1987). AM 1.5 Global,  $97\text{mW}/\text{cm}^2$ .

is inside the silicon must be within  $16^\circ$  of normal to the surface in order to escape. Otherwise, it will reflect off of the interface and traverse the wafer again. Essentially, it is trapped. This enhancement is shown in Figure 4.31 indicating the short-circuit currents possible for silicon cells of different thicknesses with and without light-trapping (Tiedje, Yablonovitch, Cody, and Brooks, 1984). This silicon is assumed to have unity front surface transmission and a perfect backside mirror.

One way to achieve light trapping is to texturize the front surface of the wafer. This leads to a somewhat randomized scatter of the light as it enters the wafer. If this light is assumed to scatter around until it is isotropic then the formulation of the enhancement caused by the light trapping is straightforward. If an ideal backside mirror is in place then this enhancement is found to be equivalent to increasing the wafer thickness by a factor  $4n^2$ , about 50 (Yablonovitch and Cody, 1982). Alternative methods of calculation utilize ray tracing to evaluate specific structures.

The most common engineering solution to incorporate light-trapping is to use anisotropic etching to form pyramids or V-grooves on the surface of a (100) oriented wafer. The slopes on these features are well defined as the (111) planes, which have an angle of  $54.7^\circ$  to the wafer surface. This makes the problem very amenable to ray-tracing, especially for the case of normally-incident light.

The results from one such study are shown in Figure 4.32 (Green and Campbell, 1987). This figure indicates that the limit of Lambertian scattering, also shown in Figure 4.31, is closely approached by the case of pyramidal texturization on both sides of a wafer. A slightly better scheme, superior to both Lambertian and double-sided texturization, is the use of V-grooves on both sides of the wafer. Those on the rear are oriented perpendicularly to the front-side grooves. Pyramids on the front-side only, a popular implementation, are significantly less effective. For example, they would produce almost 3 mA less current on a  $50\text{ }\mu\text{m}$ -thick cell.

Much of the difference between the six texturization schemes shown in the figure would be diminished in the case of non-normal incidence for the light, a non-specular backside reflector, or a distribution of angles on the texturized surfaces.

An implementation of texturization onto solar cells must take account of many technological details of the texturized surface. Four texturized surfaces are shown in Figure 4.33. These were formed by different amounts of isotropic etching after creating the features with an anisotropic etch. Notice that these examples span the range from regular pyramidal texturization towards a more Lambertian surface.

Each of these wafers was measured to have a different light absorption characteristic and surface recombination velocity. Additionally, the surface recombination velocities were found to be a sensitive function not only of the texturization details, but the anneal schedule as well. These results are summarized in Figure 4.34.

The absorption of incident light in these wafers is controlled by two effects:

1. The degree of light-trapping. The light-trapping of weakly absorbed light will diminish as the wafer is isotropically etched and becomes more planar.
2. The double-bounce incidence that the pyramidal surface provides will also cease to function as the topography flattens.

Both of these effects are clearly seen in the reflectance data shown in Figure 4.35. A loss in the double-bounce incidence shows up as an increase in the reflectance for short wavelengths. The loss of light-trapping is indicated by increased reflection at long wavelengths near the bandgap for silicon (1,110 nm).

An even more direct demonstration of the effects of light-trapping is shown in Figure 4.36. This comparison of the spectral responsivity of a texturized and an untexturized solar cell clearly indicates the enhancements of both the double-bounce incidence and the light-trapping.

The photogeneration increases arising from light-trapping occur rather uniformly within the cell. In order that this increased current can appear as terminal current, the solar cell must have a very high internal quantum efficiency. The line shown in Figure 4.36 is the theoretical limit if there were no reflection or recombination losses. An actual measurement of the cell reflection indicated that this cell does have internal collection efficiency greater than 98% between 350 nm and 950 nm wavelengths.

A new and important wrinkle was introduced in a paper by Campbell and Green where it was pointed out that more effective light-trapping than that discussed above was possible (Campbell and Green, 1986). An enhancement of  $(4n^2)/(\sin^2\theta)$  is available where  $\theta$  is the acceptance angle of the light. The essence of this idea is that if you know the angle of incidence of the light, then you can engineer where it goes in order to utilize it most effectively. Above, it was argued that light-trapping from a texturized surface works because only light within 16–17° of normal will escape. Consider the case shown in Figure 4.37. This shows (for illustration purposes) an extreme case of engineering where the light will go. In the two cells, the same number of photons is incident per  $\text{cm}^2$  of cell area. However, in the second case, (b), the path length presented to the photons is 20,000  $\mu\text{m}$ , to be compared with top case, (a), in which the photons traverse only 100  $\mu\text{m}$  of silicon. This difference amounts to an increase in short-circuit current density of about 15%. The penalty paid is in achieving the 100X concentration necessary for case (b). Considerations related to

obtaining the necessary light concentration introduce factors of  $\sin\theta$  into the analysis. For solar energy, the half angle of the sun defines a maximum concentration ratio. This in turn limits the enhancement factor to  $4n^2\sin^{-2}(0.27^\circ)$ . Of course, absorption leading to electron-hole production is not the only absorption which is enhanced. Parasitic, free-carrier absorption and non-ideal mirrors limit the practicality of this enhancement technique to values much less than the theoretical limit.

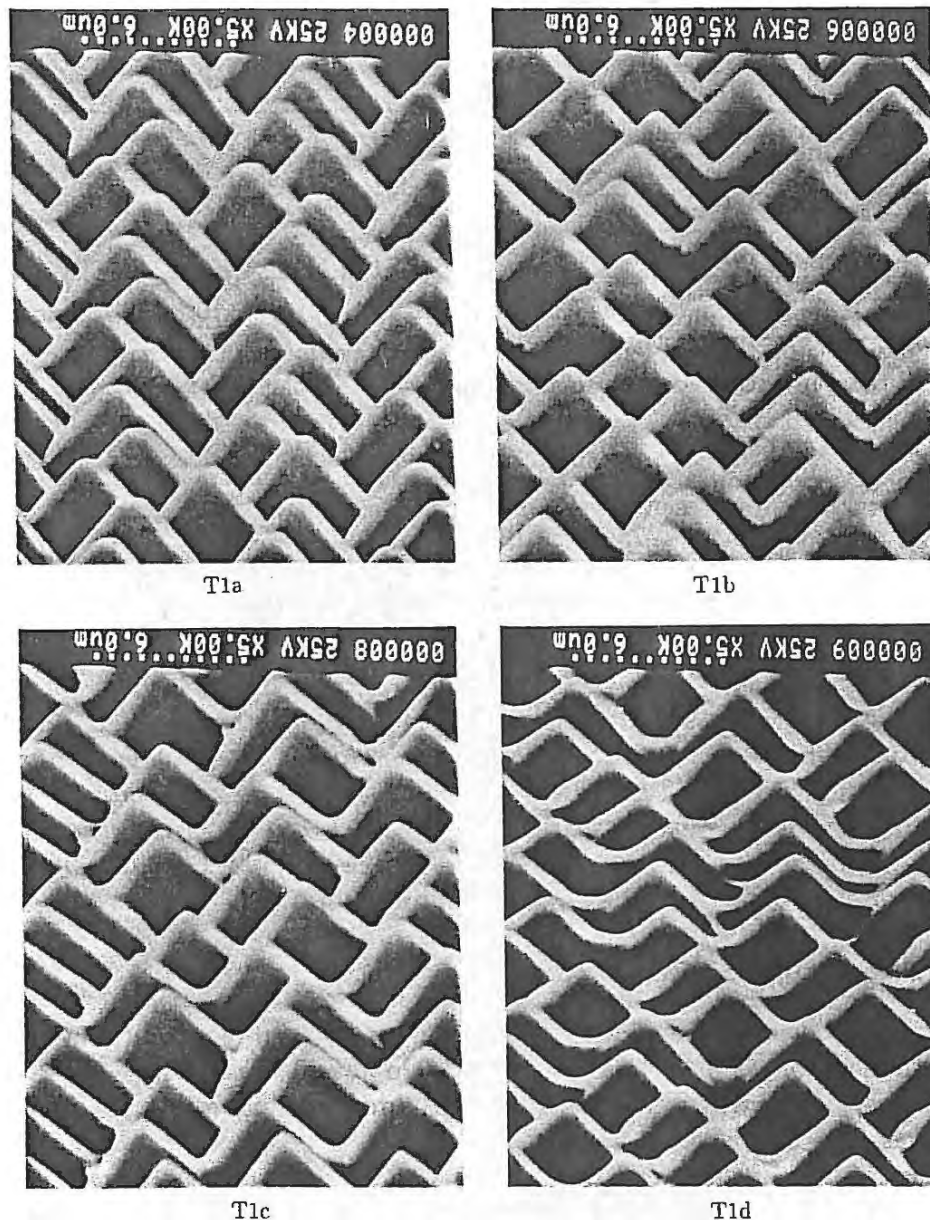


**Figure 4.33:** Texturized surfaces formed by anisotropic etching of (100) silicon followed by various times of isotropic etching (King and Swanson, 1988).

| Dependence of Surface Recombination Velocity (SRV)<br>of Texturized Surfaces<br>on Pyramid Rounding in $\text{HNO}_3 : \text{NH}_4\text{F}$ Solution |                                                      |                                                         |                                                       |                                                         |                                                       |
|------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|---------------------------------------------------------|-------------------------------------------------------|---------------------------------------------------------|-------------------------------------------------------|
| Sample<br>ID                                                                                                                                         | Pyramid<br>Rounding<br>Process                       | Forming Gas Anneal Only                                 |                                                       | After Aluminum Anneal                                   |                                                       |
|                                                                                                                                                      |                                                      | Untexturized<br>SRV<br>( $\frac{\text{cm}}{\text{s}}$ ) | Texturized<br>SRV<br>( $\frac{\text{cm}}{\text{s}}$ ) | Untexturized<br>SRV<br>( $\frac{\text{cm}}{\text{s}}$ ) | Texturized<br>SRV<br>( $\frac{\text{cm}}{\text{s}}$ ) |
| T1a ( $w = 280\mu\text{m}$ ),<br>V2a ( $w = 81\mu\text{m}$ )                                                                                         | 20 sec in<br>50:1 $\text{HNO}_3:\text{NH}_4\text{F}$ | 12.9                                                    | 65.4                                                  | 9.31                                                    | 15.3                                                  |
| T1b ( $w = 277\mu\text{m}$ ),<br>V2b ( $w = 81\mu\text{m}$ )                                                                                         | 2 min in<br>20:1 $\text{HNO}_3:\text{NH}_4\text{F}$  | 19.2                                                    | 51.7                                                  | 10.65                                                   | 38.9                                                  |
| T1c ( $w = 271\mu\text{m}$ )<br>V2c ( $w = 72\mu\text{m}$ )                                                                                          | 4 min in<br>same 20:1 solution                       | 12.7                                                    | 36.0                                                  | 25.9                                                    | 29.1                                                  |
| T1d ( $w = 265\mu\text{m}$ )<br>V2d ( $w = 70\mu\text{m}$ )                                                                                          | 8 min in<br>same 20:1 solution                       | 13.6                                                    | 38.9                                                  | 2.91                                                    | 1.90                                                  |

**Figure 4.34:** The measured surface recombination velocity for the various texturization profiles indicated on the last figure. Texturized surfaces have higher surface recombination velocities than untexturized prior to aluminum anneals (King and Swanson, 1988).

Two practical implementations of this idea are shown in Figure 4.38 and Figure 4.39. The first is the prismatic cell cover, which refracts the light from over the metal front-surface grid lines into the cell (O'Neill, 1985), shown in Figure 4.38. A similar structure using reflective optics was suggested in the original paper (Campbell and Green, 1986). Another idea with the same result is to put the solar cell in a reflective box with an input aperture for light which is smaller than the cell area, Figure 4.39. This increases the probability that the light will be absorbed rather than escape (Sinton and Swanson, 1987a). The enhancement possible is shown in Figure 4.40. In fact, these ideas for decreasing the acceptance angle for light could be used instead of texturizing in cases when texturizing is difficult to achieve. A method which reduced this acceptance angle to  $17^\circ$  can give a planar cell absorption equivalent to Lambertian texturization.

#### 4.4.2 Effects on Cell Performance

There are several advantages to using light-trapping on relatively thin solar cells rather than making 1 mm thick cells in order to absorb the available light.

The first, a practical concern, is that you can make more thin solar cells than thick ones from a given amount of silicon.

Second, many of the parasitic recombination mechanisms are related to the cell volume. These can be virtually eliminated by thinning the cells. This causes gains in efficiency right down to the thickness where the cell is too thin to absorb the majority of the light, even with light-trapping techniques. This principle is essentially that

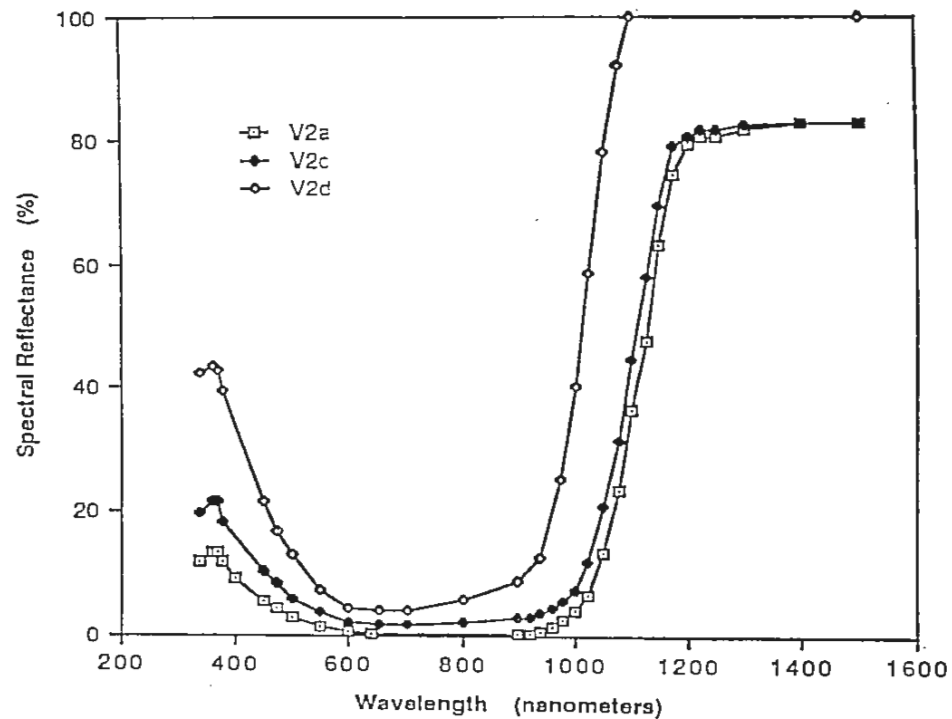


Figure 4.35: Reflectance data from several wafers between 70 and 80  $\mu\text{m}$  thick. V2d is untexturized. V2c had a longer isotropic etch after texturization than V2a (King and Swanson, 1988).

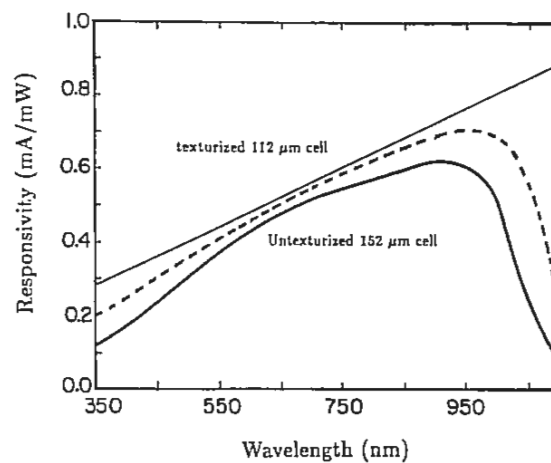


Figure 4.36: The spectral responsivity for two cells processed at the same time. The texturized cell shows a lower reflectance loss, since the light gets a double bounce. Also the texturized cell has a vastly improved response to light near the bandgap energy (Sinton et al., 1986).

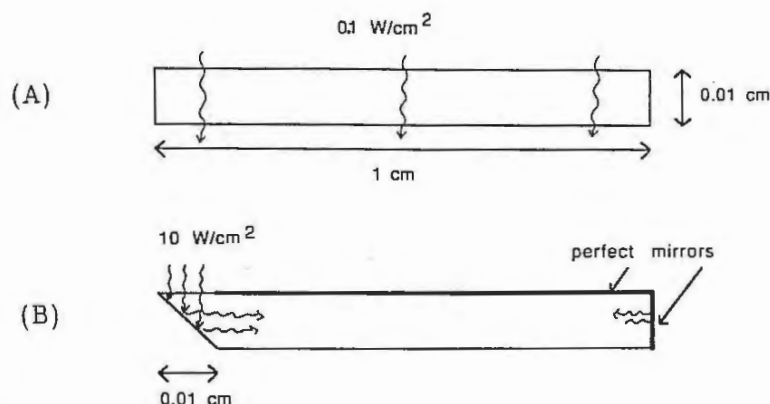


Figure 4.37: An extreme case of engineering a solar cell to maximize the photogeneration per unit input power. The same number of photons are incident on both of these cells. In case (B), the path length traversed by these photons is greater by a factor of 200 than in case (A); this increases the short-circuit current density by about 15%. Unfortunately, case (B) requires that the light be concentrated by a factor of 100.

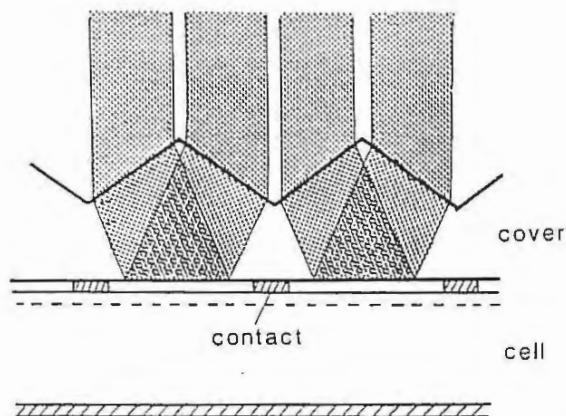


Figure 4.38: A prismatic secondary concentrator, in which the light is refracted onto the non-metallized areas. Since the metallized areas can act as nearly perfect mirrors to photons already within the cell, this scheme enhances the near-bandgap response (Green, 1987).

if you have starting material for which the diffusion length is less than the cell thickness, and you can't change the diffusion length, then use a thinner cell.

The third reason for using thin cells when possible is that in order to collect the photogenerated minority carriers and produce power, a gradient in carrier density must exist to drive the carrier diffusion. Over long distances, this gradient represents a loss in terminal voltage. The closer the collecting junction to the photogeneration, the better.

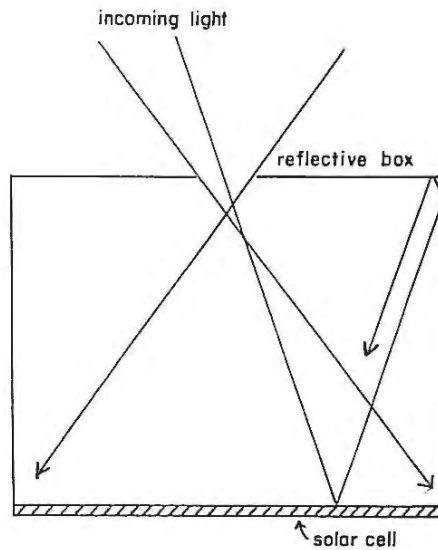


**Figure 4.39:** A reflective box which reduces the effects of cell reflectance and improves the near bandgap response by not letting photons escape until they are incident upon the cell several times on average (Sinton and Swanson, 1987b).

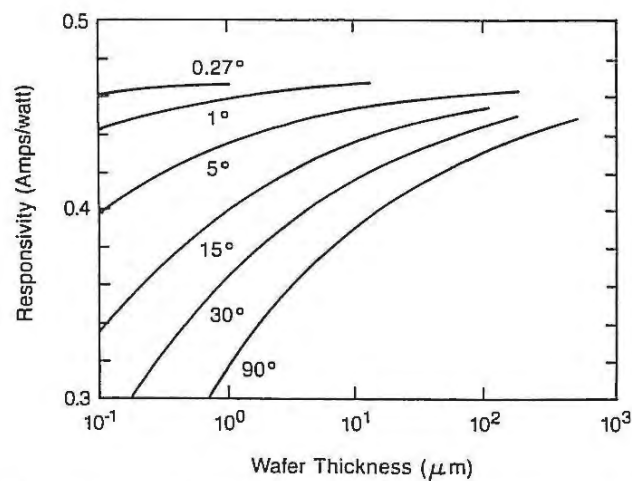


**Figure 4.40:** The responsivity vs. cell thickness for textured cells as a function of the cell thickness (adapted from Campbell and Green, 1986). The curves refer to cells with varying acceptance angles.

These effects are clearly seen in a modeling study on backside point-contact solar cells. For lower lifetime substrates, a  $200\text{ }\mu\text{m}$  thick textured cell which is 18% efficient would compare to an equivalent 28% efficient cell at  $50\text{ }\mu\text{m}$ . In a system which imposed an acceptance angle of  $15^\circ$ , the efficiency would increase to nearly 30%. These results are given in Figure 4.41.

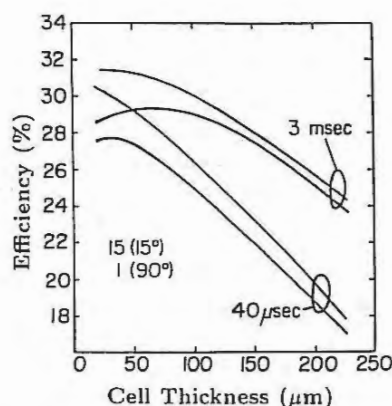


**Figure 4.41:** The efficiency vs. thickness for cells with two different values of bulk lifetime. Cells fabricated on low-lifetime material show improvement as the base is thinned. This improvement is even more dramatic if the light-trapping is enhanced by reduced acceptance angles (Sinton and Swanson, 1987b). The upper curve for each pair is for a  $15^\circ$  acceptance angle and the lower curve for a  $90^\circ$  acceptance angle. These acceptance angles correspond to 15:1 and 1:1 cell:aperture area ratios in the scheme of Fig 4.39.

Another effect of a common light-trapping implementation, front-side silicon patterning, is the fore-shortening of the photogeneration profile. In cells operating in the "thin-base" limit, this is a second order effect in that if the cell already has a unity quantum efficiency, the exact position of photogeneration only changes the terminal voltage slightly. However, in the case of a cell with a low internal base quantum efficiency, generating the electron-hole pairs very close to the front-side junctions can have a significant beneficial effect.

#### 4.4.3 Emitters: Optimizing the Diffused Regions in the Cell

Most high-efficiency silicon solar cells are dominated by the recombination in the diffused regions, or at the metal contacts to these diffused regions. This fact can be demonstrated by modeling of the type described earlier.

The front emitter in a conventional solar cell presents the most difficult optimization problem in the design. A proper treatment requires, at the very minimum, a detailed knowledge of the doping dependence of two quantities, the product of the equilibrium minority carrier density with the minority carrier mobility, and the diffusion length (del Alamo, 1985). Once these parameters are known, then an emitter model which solves the transport equations developed in Section 4.3 can predict the minority carrier characteristics of a particular diffusion. The important quantities for solar cell design are internal quantum efficiency for illuminated emitters and emitter saturation current,  $J_0$ , for all emitters. Additional parameters from the point of view of designing practical solar cells are the metal-silicon contact resistance and the sheet resistance.

Once all of these facts are in, it is clear that there is no single superior solar cell emitter design. A different design is necessary for each application. A good illustration of this is the diversity of emitters in use today. Clearly, this is a very significant design detail for which no clear consensus exists.

#### 4.4.4 Minimizing Emitter Recombination

It is widely recognized that recombination in the diffused regions, especially at the metal-silicon interface, is the dominant parasitic loss mechanism in most silicon solar cells. A review of the literature indicates that there are three methods for specifically addressing this issue.

- In the point-contact solar cell, this recombination is reduced by minimizing the emitter area, both of dopants and metal-silicon contacts.
- A more common method is illustrated in the PESC solar cell by Green et al. Here, a passivated planar diffused region is used, with an absolute minimum of metal-silicon contact area. An example is shown in Figure 4.49.
- The last method is to use a fundamentally different type of emitters such as polysilicon, SIPOS (Semi-Insulating Polysilicon, or charge-induced emitters).

A discussion of the optimization of diffused  $n$ -type emitters can be based upon the modeling of del Alamo (del Alamo, 1985). In this work, the fundamental transport parameters were determined using test devices fabricated on uniformly doped epitaxial layers. These parameters were then compared to previous work, and a consensus was found based upon a careful comparison of the assumptions made in interpreting and reporting the previous data. The minimum number of directly measured parameters was then applied via an emitter model to predict the performance of several common emitter profiles. This section draws heavily upon the experimental and modeling results of del Alamo.

Figure 4.42 indicates the internal quantum efficiency for an emitter illuminated with sunlight with an AM 1 spectrum. A silicon-silicon dioxide surface recombination velocity of 1000 cm/sec was assumed. The internal quantum efficiency plotted here is the fraction of the electron-hole pairs generated in the emitter that are collected rather than recombining. A more directly useful quantity would be the absolute current that is absorbed and recombined in the emitter. This could have been calculated directly, but can also be found by multiplying the internal quantum efficiency of the emitter by the amount of current generated there. This is shown in Figure 4.43. This plot shows contours of potential short-circuit-current that is lost to absorption and recombination in the front emitter. The contour of  $0.5 \text{ mA/cm}^2$  indicates a loss of about 1.2% of the potential cell current. It is interesting to note that this contour is along a line of nearly constant sheet resistance,  $71 \pm 5 \text{ } \Omega/\square$  in the  $10^{19} \text{ cm}^{-3}$  decade of surface concentration.

Figure 4.14 shows the emitter saturation current as a function of the surface dopant concentration and the junction depth. This is for a surface recombination velocity of infinity, and is appropriate for metal-contacted diffusions. Figure 4.15 gives these same contours of emitter saturation current but for an assumed surface recombination velocity of 1000 cm/sec, a good assumption for oxide passivated diffusions in many cases. Note, however, that the values in the lower left hand corner are very sensitive to this assumption.

Consider the design of an optimized front-surface emitter. The first criteria is that the emitter does not absorb and recombine many carriers. This is insured by staying to the left of the  $0.5 \text{ mA/cm}^2$  contour in Figure 4.43. This implies sheet resistances greater than  $70 \text{ } \Omega/\square$ .

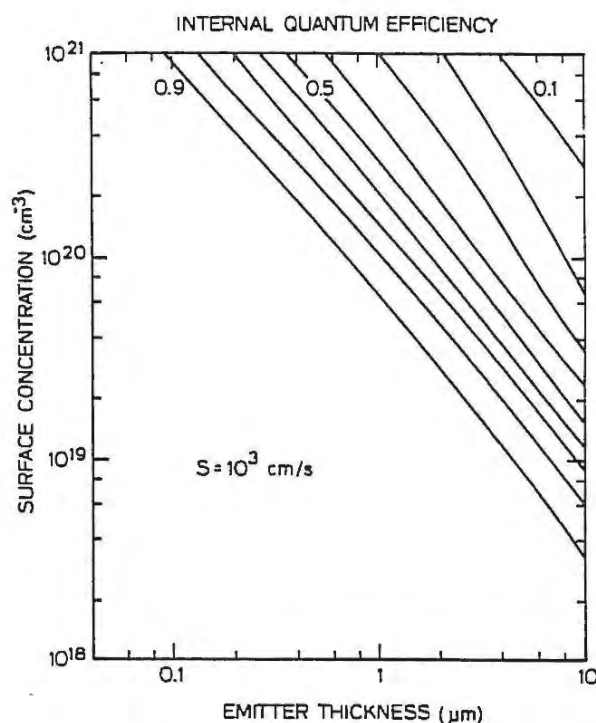


**Figure 4.42:** The quantum efficiency for gaussian, phosphorus doped emitters under an AM 1 spectrum. The passivated surface is assumed to have an  $S=1000 \text{ cm/sec}$  (del Alamo, 1985). The base doping is  $10^{16} \text{ cm}^{-3}$ .

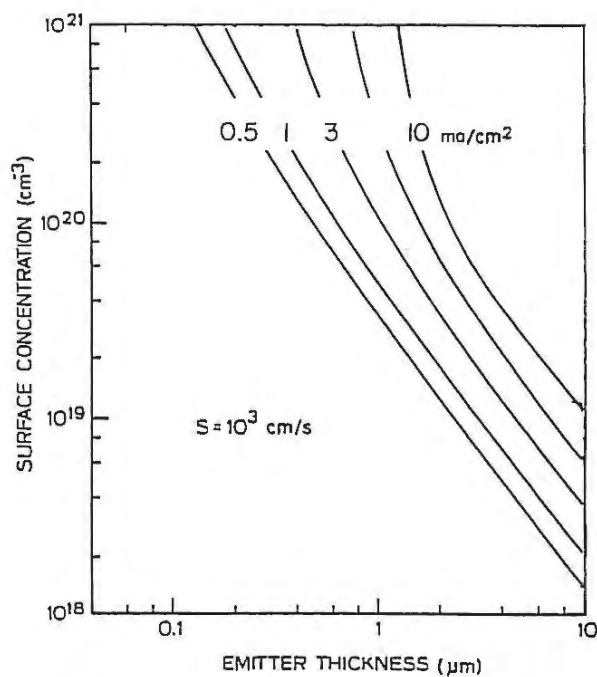


**Figure 4.43:** Contours of absolute current density lost in the emitter to photon absorption and subsequent recombination.

Low sheet resistance is another asset to a good emitter. For one-sun cells, a low sheet resistance allows a coarse grid pattern. In concentrator cells, a low sheet resistance and a fine grid pattern may both be necessary. Assume for example that you would like a sheet resistance less than  $200 \Omega/\square$ . This leaves a rather narrow, well defined portion of the curve from which to choose an emitter; those that lie between 70 and  $200 \Omega/\square$ . Three more criteria enter. The emitter saturation current should be as low as possible for the passivated emitter regions. This drives the optimum towards the lower portion of the plot. Additionally, the top grid needs to contact this emitter. This actual contact area may vary greatly, but must minimize the spreading resistance effects in the diffused region and be adequately large that the contact resistance is negligible. The lowest values of  $J_0$  for  $s = \infty$  (metal contacted emitters) are in the mid to lower-right-hand region.

All of these criteria favor rather lightly doped, very deep emitters. This result is in contrast to some of the conventional wisdom of solar cell front emitters, but is coming into a wider acceptance rather recently (Cuevas and Balbuena, 1988). The one point which may favor keeping a surface concentration above the  $10^{19}$  range is the contact resistance. In one-sun cells, the metal-silicon area can be quite small, with high current densities. In concentrator cells, the area must be larger, and will certainly have high current densities. A plot of the contact resistance of Ti and PtSi contacts as a function of the surface concentration of phosphorus is shown in Figure 4.44. The contact resistance is a very strong function of this surface concentration. For perspective, consider a concentrator cell with 1% metal-silicon contact area, designed for operation at  $36 \text{ W/cm}^2$  of incident power (360 suns). The current density in this case would be  $14 \text{ A/cm}^2$ , or  $1400 \text{ A/cm}^2$  at the contacts. For Ti contacts, this would give a 0.7 mV drop for a surface concentration of  $10^{20}/\text{cm}^3$ , 3 mV at  $4 \times 10^{19}$ , but 84 mV at  $2 \times 10^{19}$ ! This simple example illustrates that contact resistance can be a real problem if ignored during the design phase.

In short, the criteria outlined above for an optimized single-diffusion front-side phosphorus emitter are:

- $\Omega/\square \geq 70$  to avoid current loss.
- $\Omega/\square \leq 200$  to minimize series resistance.
- Surface dopant concentration  $\leq 10^{20} \text{ cm}^{-3}$  to obtain low emitter saturation currents for the passivated emitter regions.
- Surface dopant concentration  $\geq 10^{19} \text{ cm}^{-3}$  to insure good contact resistance.
- Junction depth  $\geq 0.1 \mu\text{m}$  for process control of the metal-silicon interface.

The region of emitters that meet these requirements are in the shaded region of Figure 4.45. Within this shaded area, minimization of the emitter saturation current for the metal-contacted areas, as shown in Figure 4.14, drives the choice towards the lower right-hand corner. This emitter,  $2 \mu\text{m}$  deep and doped around  $10^{19} \text{ cm}^{-3}$  is quite deep and lightly doped.

Several recent papers highlight this trend towards thicker front-side emitters. In work by Tobin et al., deep front emitters of varying thickness were investigated as a way to produce high-temperature stable cells (Tobin, Spitzer, Bajgar, Geoffroy, and Keavney, 1987). Recognizing that metalization spiking through the junction during contact sintering was a major constraint, emitters with surface concentrations between 1 and  $2 \times 10^{19}/\text{cm}^3$  were compared on a standard solar cell. Cells with

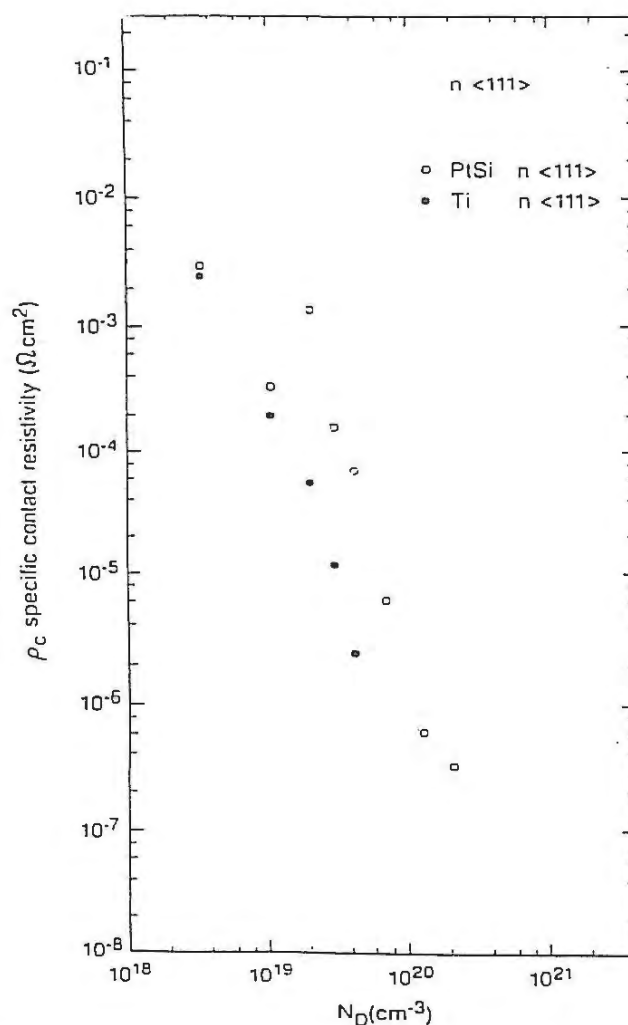


Figure 4.44: The contact resistivity for PtSi and Ti contacts to  $\langle 111 \rangle$  Si (Swirhun, 1987).

0.94  $\mu\text{m}$  thick emitters were shown to be stable with respect to 15 minute anneals in  $\text{N}_2$  at 600 °C. This is a significant result, indicating the process insensitivity and robust qualities of deep emitters. No significant change in short circuit current was noted in increasing the junction depth from 0.26–0.94  $\mu\text{m}$ . This is in good agreement with the modeled results of del Alamo. However, since the total solar cell saturation current for these cells was about  $6.6 \times 10^{-13} \text{ A/cm}^2$  and independent of the junction depth, it seems that the cells were base dominated so that no conclusions can be made about trends in the emitter  $J_0$ .

Another study in which special care was taken to determine the emitter component has been reported by Cuevas and Balbuena (1988). For example, a 1  $\mu\text{m}$  thick emitter with a surface concentration of  $10^{19} \text{ cm}^{-3}$  was found to have a  $J_0$  less than  $1.6 \times 10^{-13} \text{ A/cm}^2$ . The same emitter, unpassivated, had  $20 \times 10^{-13}$ . These values are in good agreement with the modeling shown above. These relatively deep emitters were put to use in demonstrating a simple process yielding 19%, 4  $\text{cm}^2$  cells.

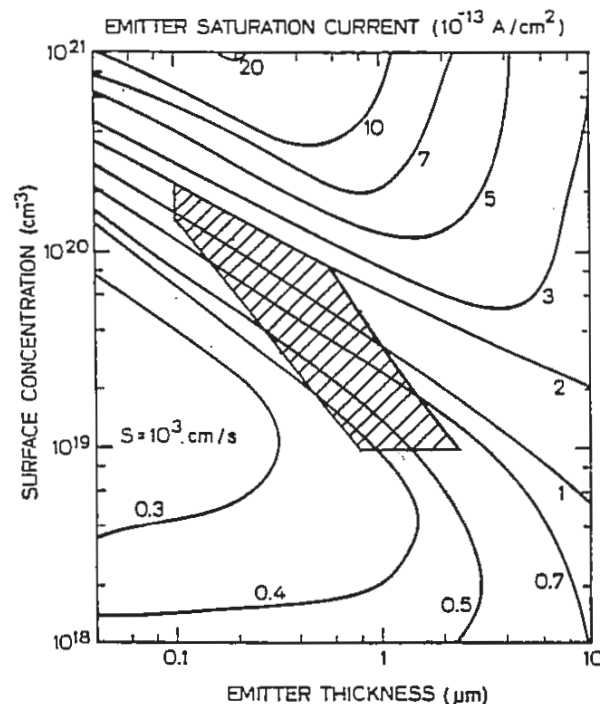


**Figure 4.45:** The region of interest for a single-diffusion optimized  $n^+$  emitter on the front of a solar cell. The criteria taken into account which bound this area are the passivated region emitter saturation current (top), contact resistance (bottom), emitter quantum efficiency (right), and metal-contact process control (left). The optimization of the metal-contacted areas makes the right lower corner of the shaded region preferred.

This discussion above was based almost entirely upon the modeling of del Alamo. A prudent alternative would be to measure the emitters of interest experimentally. A collection of measured values is shown in Table 4.1, for several phosphorus and boron diffusions (Kane and Swanson, 1985). In the case of boron emitters, it was found necessary to deposit a thin aluminum layer on the surface in order to attain a large enough surface recombination velocity that the emitter is transport limited. This result is called  $J_{o,AI}$  in Table 4.1. A comparison of these experimental values with those shown in the modeling indicates good agreement.

#### 4.4.5 Specific Design Examples

First, consider the backside point-contact solar cell design shown in Figure 4.23. The effective emitter saturation current in this design is reduced by minimizing the total diffused area to that covered by metal contacts. This is shown with experimental data in Figure 4.24. Additionally, notice that these emitters are on the back of the cell, where little photogeneration occurs. Therefore the emitter quantum efficiency constraint does not exist. From the modeling on metal contacted emitters, the choice appears to be for very deep emitters 4–10 microns deep, with surface concentrations between  $10^{19}$  and  $10^{20} \text{ cm}^{-3}$ . The same emitters can be used to advantage on the front of the solar cell, if they are in the shadow of gridlines (Sinton,

**Table 4.1:** Measured emitter saturation currents for several diffusions. (Kane and Swanson, 1985).  $J_{o,pass}$  is the emitter saturation current for diffusion which have received high-quality thermal oxidations to passivate the surface.  $J_{o,bare}$  is the result after etching off the passivation oxide in HF. This simulates a case with large surface recombination velocity.

Boron emitters  
Substrate:  $N \approx 10^{13} \text{ cm}^{-3}$

| $R_{sh}(\frac{\Omega}{\square})$ | $x_j(\mu\text{m})$ | $N_{surf}(\text{cm}^{-3})$ | $J_{o,pass}(\frac{\text{pA}}{\text{cm}^2})$ | $J_{o,bare}(\frac{\text{pA}}{\text{cm}^2})$ |
|----------------------------------|--------------------|----------------------------|---------------------------------------------|---------------------------------------------|
| 5.3                              | 4.8                | $7.0 \times 10^{19}$       | 0.35                                        | 0.42                                        |
| 37                               | 2.1                | $3.6 \times 10^{19}$       | 0.07                                        | 0.57                                        |
| 63                               | 3.0                | $1.3 \times 10^{19}$       | 0.09                                        | 1.10                                        |
| 240                              | 1.1                | $5.4 \times 10^{18}$       | 0.13                                        | 1.00                                        |
| 463                              | 1.2                | $1.3 \times 10^{18}$       | 0.06                                        | 1.10                                        |

Phosphorus emitters  
Substrate:  $N \approx 10^{13} \text{ cm}^{-3}$

| $R_{sh}(\frac{\Omega}{\square})$ | $x_j(\mu\text{m})$ | $N_{surf}(\text{cm}^{-3})$ | $J_{o,pass}(\frac{\text{pA}}{\text{cm}^2})$ | $J_{o,bare}(\frac{\text{pA}}{\text{cm}^2})$ |
|----------------------------------|--------------------|----------------------------|---------------------------------------------|---------------------------------------------|
| 9.0                              | 5.8                | $5.0 \times 10^{19}$       | 0.45                                        | 0.50                                        |
| 57.2                             | 3.6                | $1.2 \times 10^{19}$       | 0.10                                        | 1.10                                        |
| 75.3                             | 1.8                | $2.0 \times 10^{19}$       | 0.13                                        | 1.70                                        |
| 370                              | 1.2                | $2.5 \times 10^{18}$       | 0.08                                        | 1.70                                        |
| 890                              | 1.3                | $1.0 \times 10^{18}$       | 0.01                                        | 7.00                                        |

Kane, and Midkiff, 1988). From the modeling on passivated emitters, it is clear that these deep, heavily-doped emitters would not be appropriate in an illuminated region. Additional advantages to the dark performance for these emitters are that being deep and heavily doped, contact resistance can be very low, and the effects of the various problems which can occur at the metal-silicon interface are minimized in deep emitters (such as junction spiking). Criteria associated with three-dimensional behavior in the base need to be addressed, and puts limits on the size and spacing of the diffused regions. An optimized design for a point-contact cell has about 10% of the backside area covered by  $n$ -type emitter and 10% covered by  $p$ -type emitter. Such a cell has an effective emitter saturation current of about  $0.9 \times 10^{-13} \text{ A/cm}^2$ , relative to the total cell area. Measurements indicate that the  $p$  and  $n$ -type emitters have comparable effective contributions of  $0.45 \times 10^{-13} \text{ A/cm}^2$  each.

This design is a good candidate for a demonstration of the limits of the approximate modeling described in Section 4.2. This solar cell design is one of the few cases in the literature where all of the parameters have been well characterized independently of the solar cell itself.

For the design described above and shown in Figure 4.23, the simple modeling is easily applied. For the low concentration range, the device is dominated by surface emitter recombination. In this range, operating under high-level-injection, one has

$$J_{ph} - J = \frac{J_o}{n_i^2} n^2 + 1.8 S q n. \quad (4.81)$$

The value for  $J_o$  to be plugged in here is the area-weighted value discussed above,  $9 \times 10^{-14} \text{ A/cm}^2$ . The front surface of a point contact solar cell and 80% of the back is base-oxide interface, hence the  $1.8 \text{ cm}^2$  per  $\text{cm}^2$  of cell area giving rise to the "1.8" in the surface recombination. Assume that the surface recombination velocity

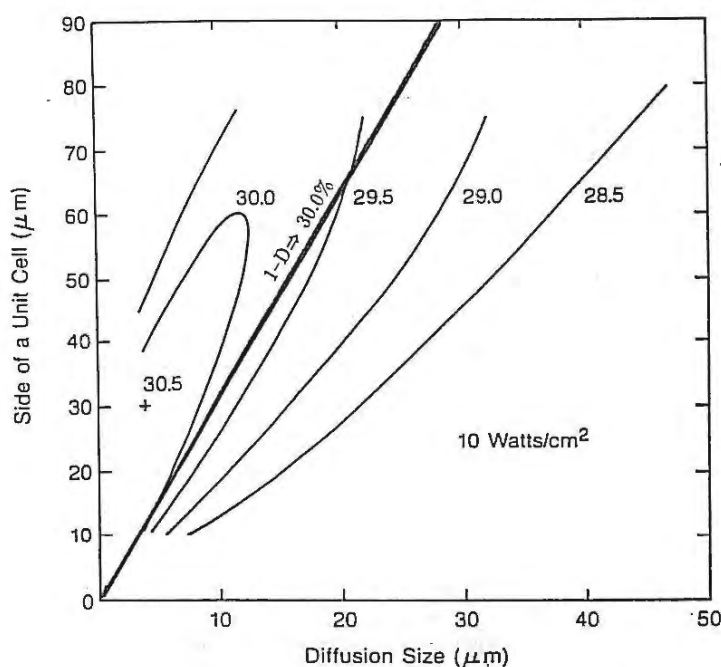


**Figure 4.46:** The contours for efficiency for a point-contact cell as a function of the emitter size and spacing. The results for an approximate, one-dimensional model are also shown, as 30% efficiency for a line of constant emitter coverage fraction (Sinton and Swanson, 1987a).

is 7.5 cm/sec (a value typically measured for oxidized and texturized surfaces), the photogeneration,  $J_{ph}$ , is 0.432 A/W times the incident power,  $P_{sun}$ , and the maximum power point is at a quantum efficiency of 95%. Then the left side of the above equation is equal to  $0.05 \times J_{ph}$ . Luckily, the equation is a quadratic equation, easily solved for  $n$ , hence  $V_{mp}$ . Then

$$\eta = \frac{0.95 \times J_{ph} \times V_{mp}}{P_{sun}} \quad (4.82)$$

At 100 suns ( $10 \text{ Watts/cm}^2$ ), these assumptions lead to an efficiency of 30%. This is shown superimposed upon the results from a complete 3-dimensional simulation for a  $50 \mu\text{m}$  thick cell in Figure 4.46. This turns out to be a very good approximation. But it is also clear what the limitations are. From this one-dimensional analysis, it might seem wise to reduce the emitter coverage fraction further, for example to the 0.3% of the total area indicated for the "Auger test structure" in Figure 4.24. This would be predicted to yield higher voltages and efficiencies due to the reduction in diffused region recombination. The experimental result is shown for this structure in Figures 4.47 and 4.48. This emitter area is too small to efficiently draw current from the cell. The structure becomes completely dominated by the ignored, three-dimensional effects causing a loss of current at high power densities. This effect would be completely missed by the one-dimensional model. However, a complete three-dimensional model is able to explain these effects fairly accurately as indicated in Figure 4.48.

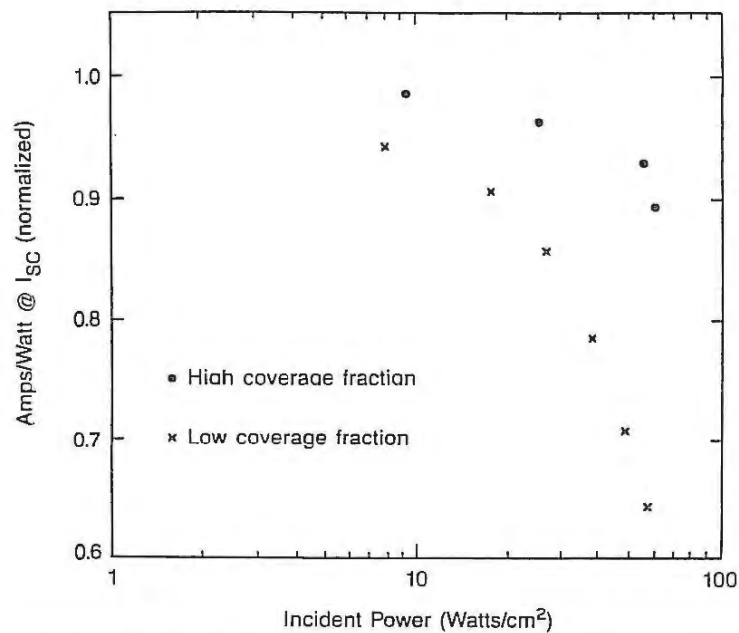


Figure 4.47: For a solar cell with too small contacts which are too widely spaced, the quantum efficiency under high illumination quickly drops off. A one-dimensional analysis which simply reduced the emitter saturation current by the coverage fraction of the diffusion would miss this important point.

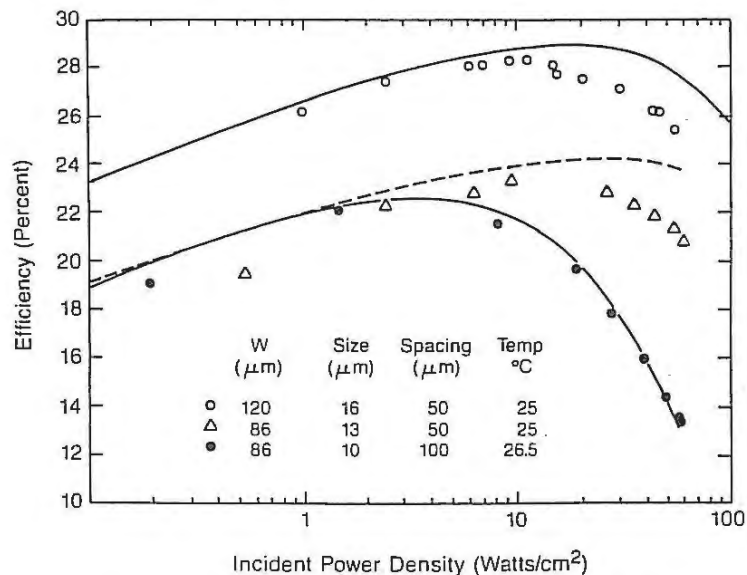


Figure 4.48: Here, three dimensional modeling is shown which does a pretty good job of predicting the effects of having less than optimum emitter area (Sinton and Swanson, 1987a).

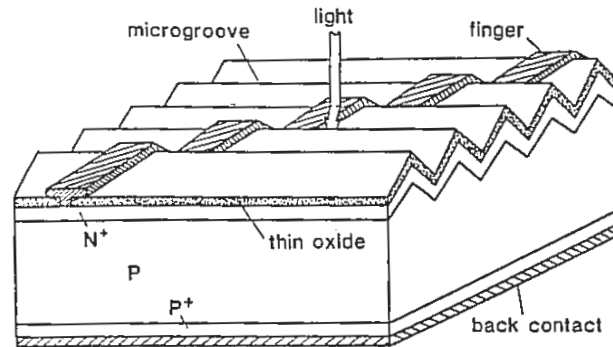


Figure 4.49: A low-resistivity concentrator solar cell with 25% efficiencies at  $10 \text{ W/cm}^2$  (Green et al., 1987).

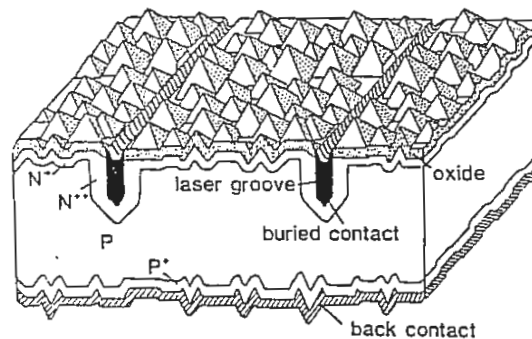


Figure 4.50: A schematic diagram of a laser grooved cell (Green, 1987).

The point-contact cell, being highly three-dimensional, is a worst-case challenge for a simple modeling scheme. However, even in this case, it is clear that the range of efficient operation is the same range where the simplifying assumption, namely uniform carrier density, works best. It is interesting to note that a one-dimensional model works well on optimized three-dimensional structures. Essentially, the three-dimensional effects work against higher efficiency, hence in an optimized design are minimized. A simple model can be a good guide but must be used judiciously.

In the 25% efficient PESC (for Passivated Emitter Solar Cell) concentrator design by Green et al., a planar junction is used in the front of the solar cell, Figure 4.49 (Green, Zhao, Blakers, Taouk, and Narayanan 1987). This junction is characterized by a sheet resistance of  $50 \Omega/\square$ . From the curves on quantum efficiency, it can be seen that this is a good choice for a concentrator cell, since it has a low sheet resistance, but not so low as to suffer diminishing quantum efficiencies. An emitter with this sheet resistance may cause a loss of  $1\text{--}2 \text{ mA/cm}^2$ . The exact process schedule and resulting geometry for the emitter is not given, but for the sake of discussion presume that it is  $4000 \text{ \AA}$  thick, gaussian, and has a surface dopant density of  $10^{20} \text{ cm}^{-3}$ . Then we would predict an emitter saturation current of  $2 \times 10^{-12} \text{ A/cm}^2$  for the 2% of metal-contacted area and  $2 \times 10^{-13} \text{ A/cm}^2$  for the 98% of the area which is oxide-passivated. This yields an effective emitter saturation current of about  $2.4 \times 10^{-13} \text{ A/cm}^2$  for the cell front-side. Presuming that the Al back surface field has a performance similar to the optimum for deep  $p^+$  diffusions,

$4 \times 10^{-13}$  A/cm<sup>2</sup>, then this cell design would have an effective emitter saturation current density of  $6.4 \times 10^{-13}$  A/cm<sup>2</sup>, if fabricated on a long lifetime substrate (perhaps a weak assumption here). This is consistent with the approximate value calculated from the one-sun open-circuit voltage, namely  $4.5 \times 10^{-13}$  A/cm<sup>2</sup>. Note that a one-sun solar cell could have less metal-silicon area and lower doping in the front-side  $n^+$  emitter since the series resistance effects are less important. Hence, much better values for the emitter  $J_0$  can be (and have been) demonstrated under those conditions (Blakers and Green, 1985).

A truly optimized design might use deep, heavily-doped diffusions under the metal lines, minimizing the  $J_0$  and contact resistance there, but have deep lightly doped emitters elsewhere, in the region of photogeneration. This design has been implemented by several groups, perhaps most cleverly in the laser-grooved cell (Green, 1987). This cell is fabricated without lithography, and has very thick metal gridlines defined by the laser grooves (Figure 4.50).

These examples discussed above all utilized rather conventional integrated circuits emitter diffusion technology. One very encouraging recent development has been the fabrication of very efficient cells without subjecting the bulk of the wafer to high temperatures and, hence, potential lifetime-reducing contamination. In work reported by Wood et al., a wafer was implanted with a boron junction using a non-analyzed glow-discharge apparatus utilizing BF<sub>3</sub> (Wood, Westbrook, and Jellison, Jr., 1987a and Wood, Westbrook, and Jellison, Jr., 1987b). This diffusion was then annealed by an excimer laser, which melts a thin surface layer. Subsequent solar cell open-circuit voltages indicate that the total solar cell  $J_0$  is about  $6 \times 10^{-13}$  A/cm<sup>2</sup>. This is for a  $p^+$  emitter with a sheet resistance of 34  $\Omega/\square$ . Significantly, these solar cells have 97% of the short circuit current of cells fabricated with a passivated emitter having a factor of 6 higher in sheet resistance. Most likely, this indicates a quantum efficiency for the heavily doped emitters approaching unity. Some of these cells have measured efficiencies of 18.9%. These do not have any of the light-trapping features described earlier. There is every indication that the technology demonstrated is capable of efficiencies of about 21–22% if applied to a texturized, high lifetime wafer. This would be very interesting for a fabrication sequence in which the highest temperature that the wafer is subjected to is 500 C and no patterning of the passivating oxide prior to metalization is necessary. The same authors have demonstrated 19.6% efficient cells by following the above procedure with a thermal oxidation at 850 C.

Another process by which solar cells can be fabricated at low temperature has been demonstrated by Jaeger and Hezel (1987). In this cell, no diffused emitter or back-surface-field exist. Instead, a front  $n^+$  region is formed by an inversion layer which results from a high fixed charge density introduced as cesium contamination prior to a deposition of an overlying silicon nitride layer. Contact to the emitter is made by an MIS structure, Al-thin SiO<sub>2</sub>-Si. The back surface is directly contacted by a metal grid, but is passivated between gridlines by another silicon-nitride layer. This solar cell has achieved voltages at one-sun of 590 mV. It is extremely difficult to separate the recombination components in this cell because it is not clearly dominated by the boundary condition at any single surface. The authors concluded that the front and back of the solar cell had comparable amounts of recombination. This analysis assigns an emitter saturation current of  $3 \times 10^{-12}$  to the front emitter.