

POINT-CONTACT SOLAR CELLS: MODELING AND EXPERIMENT

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Summary

A new type of silicon solar cell designed for high concentration applications, the point-contact solar cell (PCSC), is discussed. It is predicted that the PCSC is capable of an efficiency of 28% at the design point of 500X geometric concentration and 60 °C cell temperature. This paper discusses the modeling of this device and presents recent experimental results which have obtained 23% efficiency at 200X and 21% at 500X, both at a temperature of 24 °C.

1. Introduction

Silicon solar cells designed for high concentration present difficult design constraints. High base doping density is needed for low series resistance, yet high doping levels reduce minority carrier diffusion length and reduce the benefit of a back surface field. Similar problems appear in the emitter and grid. These constraints make it difficult to envision a conventional concentrator cell that has over 22% efficiency at high intensities [1].

Various approaches have been attempted to circumvent some of the problems with conventional cells [2]. In the etched vertical multi-junction cell (EVMJ), for example, deep grooves are etched in the front to allow the front surface grid to be much thicker, and hence of lower resistance [3]. In this manner the top junction is also brought closer to where electron-hole pairs are generated in the base, improving collection and decreasing series resistance. The EVMJ, however, suffers from a very large contacted emitter area and hence low output voltage. Another unconventional design is the interdigitated back-contact cell [4]. In this cell both the n- and p-type diffusions are interleaved on the back surface and contacted with two interdigitated comb-shaped metal bus systems. The cell is usually made of lightly doped silicon and operates in high injection. Following ref. 2 the advantages of this cell are as follows.

1. There is no shading of the front by the contact grid.

2. The metal contacts on the rear may cover nearly the entire cell and be quite thick, thus reducing series resistance.

3. The emitter diffusions may be optimized for low dark current because there is no need for lateral flow to the contact regions and there is very little generation in them because they are on the back.

4. The illuminated front surface does not contain any diffusions and as a result may have a very low surface recombination velocity. This yields good blue response.

5. The free carriers are generated in a lightly doped base and hence long diffusion lengths can be expected.

The IBC cell also has some drawbacks, the most serious of which is mounting difficulty; it is necessary to remove both types of carriers as well as the waste heat from the back side. Generally, these efforts have yielded disappointing results with efficiencies less than that currently achieved with highly refined conventional structures [5].

It has long been recognized that an important path to improved efficiency is through reducing carrier recombination. There have been attempts to reduce the emitter component of the dark current, and thus increase output voltage, by decreasing the contact coverage fraction both for the front and back contact [6]. Nevertheless, these cells also have had performance inferior to conventional concentrator cells. An apt analogy to controlling and reducing recombination is provided by a leaky bucket being continually filled with a faucet [7]. 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 is found. 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 flows of carriers must be well modeled and understood.

The point-contact solar cell has been proposed and has shown promising performance [8]. It represents one attempt to re-think cell design for higher performance. Much attention has been given to reducing recombination as well as maximizing photocurrent. In Section 2 the structure of the PCSC is presented and in Section 3 its operation is discussed to illustrate the design philosophy. Section 4 presents a model of PCSC operation that has been used to both design experimental devices and assess its mature potential. Finally, in Section 5 some experimental results are shown.

2. Structure of the point-contact solar cell

The structure of a point-contact solar cell is shown in Fig. 1. The top diffused junction that covers the entire surface of a conventional solar cell has been eliminated and the p and n diffusions are relegated to an array of

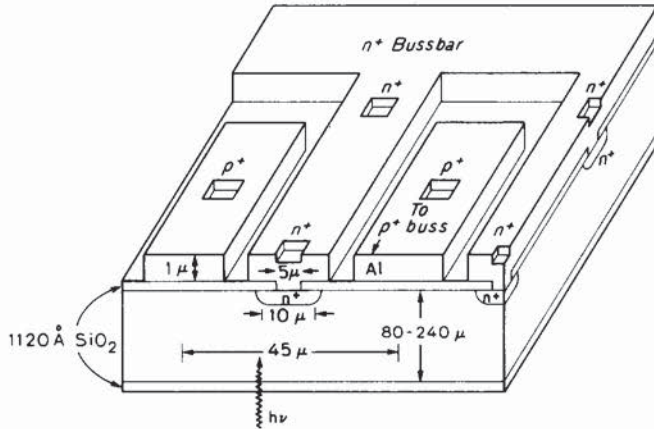


Fig. 1. Cross-sectional structure of the PCSC.

small points on the back surface. The back surface metalization is in the form of two interdigitated comb structures; one set of fingers contacting the n diffusions (becoming the negative contact) and the other contacting the p diffusions (becoming the positive contact). The structure is thus similar to the interdigitated back contact cell in that it has both electrical contacts on the back side [4]. In the PCSC, however, rather than having alternating n and p fingers, the contact metal touches the silicon only in an array of points on the back surface. The contact areas contain small diffused regions which alternate between n-type and p-type in a checkerboard fashion. The top surface and the regions between contacts on the bottom are covered with SiO_2 for surface passivation. The major advantage of restricting the contact coverage to small points is, as described in Section 3, that it increases the cell output voltage.

The base material is high resistivity float-zone silicon and is nominally $80 \mu\text{m}$ thick. As will be discussed, various thicknesses have been explored, both by modeling and by experiment, and it is found that the cells must be quite thin in order to maintain good quantum efficiency at high intensities.

In its fully-developed proposed form, the cell will be texturized on the top surface and an anti-reflection coating applied. Neither of these features has been incorporated into the current experimental cells discussed in Section 5. In addition, a mounting scheme has been proposed that allows the cell to be soldered down to a header, much as a conventional cell is, but also has not yet been incorporated in the devices reported here [9].

3. Operation

In order to obtain optimum performance, a solar cell must (a) absorb as much light as possible in electron-hole production, (b) transport the largest possible fraction of these electrons and holes to their respective

terminals and (c) do so at the highest possible terminal voltage. The way the PCSC optimizes each of these processes will be discussed in turn.

3.1. *Optimizing electron-hole production*

It is often felt that state-of-the-art silicon cells generate about as much current as theoretically possible. In fact, significant advances are still available through the use of light trapping and back surface reflectors [10]. Once a photon enters the cell it must produce an electron-hole pair to generate current. Silicon is only weakly absorbing at energies just above the bandgap so photons in this region have a significant chance of reaching the back of the cell. In cells with alloyed aluminum back contacts most of these photons will be parasitically absorbed there. By making the back reflective (preferably highly reflective) many of these photons will be reflected toward the front and have an additional chance to produce electron-hole pairs. It has been found that it is much easier to make the undoped, uncontacted regions reflective than the contact regions [11]. Thus the small contact coverage fraction of the PCSC is desired from this point of view. In addition, as shown in ref. 10, if one of the surfaces is slightly texturized, with tilt angles greater than 16° or so, most of the photons returned toward the top will be beyond the critical angle for escape and will once again head toward the back. In effect, the weakly absorbed photons are trapped within the cell.

In addition, because the point-contact cell has its metal on the back side there is no grid obscuration.

3.2. *Optimizing current collection*

Once electron-hole pairs are generated, electrons must end up at the n-type contact and holes at the p-type contact to appear as terminal current. The standard approach used here is to increase the minority carrier diffusion length by reducing impurities and defects as much as possible. When this length becomes much greater than the cell thickness the collection fraction approaches a maximum, but it is not necessarily unity. In a conventional cell electron-hole pairs created near the back have a large probability of being absorbed at the back contact. One can define a *local* collection efficiency which is the probability that an electron-hole pair produced at a particular point in the cell will be collected. Thus the local quantum efficiency is small near the back of a conventional cell. Even the presence of a back surface field does little if the cell has sufficient base doping to provide adequately low resistance for 500X operation (*i.e.* around $0.2 \Omega \text{ cm}$) [12]. If the cell base is lightly doped (or undoped) a built-in field at the back can trap the carriers, resulting in near unity collection efficiency. This is especially true if the contacts are shrunk to points, as in the PCSC, provided that the surface between contacts has sufficiently low recombination velocity (less than about 20 cm s^{-1}). Unfortunately, lightly doped bases are not very suitable for conventional high concentration cells because of high series resistance. More correctly, the problem is actually one of loss of conductivity modulation near the back of the cell [13]. A significant advantage can thus accrue

for the PCSC, but to realize this advantage, the modeling in Section 4 shows that the minority carrier diffusion length must be quite large (greater than about $800\text{ }\mu\text{m}$), the surface recombination velocity must be very low (less than about 10 cm s^{-1}), and the cell must be thin (less than $100\text{ }\mu\text{m}$).

Obviously the so-called dead layer loss sometimes experienced in conventional cells when light is absorbed in the highly doped diffused regions is eliminated in the PCSC.

In order to quantify these effects, a ray tracing program was written that incorporates the statistical optics theory of Yablonoich and Cody [10]. This program was then used to explore the effect of various cell parameters on the photocurrent. The results of this exercise are shown in Tables 1 and 2. The first line of Table 1 gives a baseline case, that of a typical cell $350\text{ }\mu\text{m}$ thick and doped to 10^{17} cm^{-3} with boron. This cell, as do all the rest, has a two layer anti-reflection coating consisting of $540\text{ }\text{\AA}$ of TiO_2 and $1020\text{ }\text{\AA}$ of MgF_2 . The current loss due to reflection is about 3% with this coating. Reading across the first row of Table 1 it is seen that this cell has no texturizing, a minority carrier diffusion length of $200\text{ }\mu\text{m}$, a back surface recombination

TABLE 1

Computed short-circuit currents for conventional cells with a thickness of $350\text{ }\mu\text{m}$ and base doping of 10^{17} cm^{-3}

<i>Texturized</i>	$L_{\text{diff}}\text{ (}\mu\text{m)}$	$s\text{ (cm s}^{-1}\text{)}$	R	$J_{\text{sc}}\text{ (mA cm}^{-2}\text{)}$		
				<i>Active</i>	<i>Total</i>	<i>% Inc.</i>
No	200	10^6	0	36.56	33.64	0
No	1000	10^6	0	37.34	34.35	2.1
No	200	10^6	0.95	37.00	34.04	1.2
Yes	200	10^6	0	38.94	35.82	6.5
Yes	200	10^6	0.95	39.72	36.54	8.6

TABLE 2

Computed short circuit currents for a thin cell (thickness, $100\text{ }\mu\text{m}$) with a lightly doped base

<i>Texturized</i>	$L_{\text{diff}}\text{ (}\mu\text{m)}$	$s\text{ (cm s}^{-1}\text{)}$	R	$J_{\text{sc}}\text{ (mA cm}^{-2}\text{)}$		
				<i>Active</i>	<i>Total</i>	<i>% Inc.</i>
No	1000	10^6	0	34.47	31.71	-5.7
No	1000	10^6	0.95	35.00	32.20	-4.3
No	1000	10	0	37.26	34.28	1.9
No	1000	10	0.95	38.41	35.34	5.0
Yes	1000	10^6	0	37.00	34.04	1.2
Yes	1000	10^6	0.95	38.66	35.57	5.7
Yes	1000	10	0	39.30	36.16	7.5
Yes	1000	10	0.95	42.78	39.36	17.0
Yes	1000	10	0.95	42.78	42.78	27.2

velocity of 10^6 cm s^{-1} , and a back surface reflectance of zero. The predicted active area photocurrent is 36.56 mA cm^{-2} at 100 mW cm^{-2} AM 1.5 illumination. Assuming an 8% grid coverage fraction the cell short circuit current will be 33.64 mA cm^{-2} . The last column gives the percent improvement over this base case. In the next row it is seen that increasing the diffusion length to an improbable $1000 \mu\text{m}$ gives only a 2.1% improvement. Including a back surface reflector (third row) yields 1.2%. These meager improvements might make one pessimistic about the possibility for significant gains. The reason that there is so little benefit is that the back region of the cell, as discussed previously, has a very low local collection efficiency. Light reflected from the back will most probably generate electron-hole pairs near the back where the collection efficiency is low. Texturizing the cell produces some improvement; mainly because the reflection loss is reduced and the light travels a longer path through the cell. The predicted 36 mA cm^{-2} for a texturized cell is in line with the best observed current for conventional concentrator cells.

Table 2 considers the case of a lightly doped, thin ($100 \mu\text{m}$) cell. It will be shown in Section 4, that lightly doped cells must be thin to prevent loss of conductivity modulation. In the lightly doped cells it is possible to achieve very long diffusion lengths, as will be discussed in Section 5. As the first two lines show, significant current is lost due to the reduced cell thickness. In a lightly doped cell, however, back surface fields have the effect of reducing the apparent recombination velocity at the back face. It is seen that by combining a back surface reflector with a back surface field one can obtain performance comparable to that of a conventional thick cell. Truly impressive gains are realized by also adding texturizing. In fact, by examining the last rows of Table 2 it is clear that there is a synergistic effect among texturizing, back surface reflectors, and back surface fields (*i.e.* low effective surface recombination velocity). The effect of incorporating all of them is greater than the sum of their separate contributions. This is simply because light trapping caused by texturizing and back surface reflectors requires high local collection efficiency at all points in the cell (not just at the front) to be maximally effective.

Finally, by putting the contacts on the back, as in the point-contact cell, grid obscuration is eliminated. The resulting current, shown in the last row of Table 2 at 42.78 mA cm^{-2} , is 27% greater than that of the baseline cell. This accounts for the major portion of the increased performance of the point-contact cell.

The carrier density in the back surface contact devices that are made on undoped material decreases in going from front to back because the carriers must diffuse to the contact areas. This will be discussed fully in Section 4. In order to maintain sufficient conductivity modulation at the back it is necessary to make the cell rather thin, around $100 \mu\text{m}$ as in Table 2. The point-contact cell, therefore, relies rather heavily on light trapping to produce increased absorption. There is concern, however, whether the standard texturizing procedure, which produces regular pyramidal facets, has sufficient randomization to promote light trapping.

To address this issue the following experiment was performed to compare the measured and calculated optical absorption *versus* photon energy in two wafers. The first wafer was polished on both sides and the second received a standard texturizing treatment on both sides. Both wafers had approximately 1000 Å of SiO₂ on each face. The total absorptance of the wafers was found by measuring the reflectance and transmittance *versus* energy and subtracting their sum from unity. By referring to Fig. 2 it can be seen from the symmetry of the problem that the absorptance in this case is equivalent to that of a wafer half as thick with a perfect reflector on the back. The measured results are shown in Fig. 3 along with the calculated absorption. Calculating the absorption in the polished wafer is, of course, straightforward. For the texturized case, the theory of Yablonoich and Cody [10] was used. The agreement is quite satisfactory indicating that the currents calculated using this theory should be obtained in practice. (Texturizing has not been implemented in complete cells to date.) Note that the absorption edge of the texturized wafer is shifted around 0.1 eV lower than that of the polished wafer. There is even significant optical absorption apparent below the band gap energy. This is because light trapping has enhanced the absorption sufficiently to see the weak photon-absorption-with-phonon-absorption process.

3.3. Optimizing output voltage

Finding ways of increasing the output voltage is difficult due to many complex interacting factors. As a rough estimate, the output voltage V is

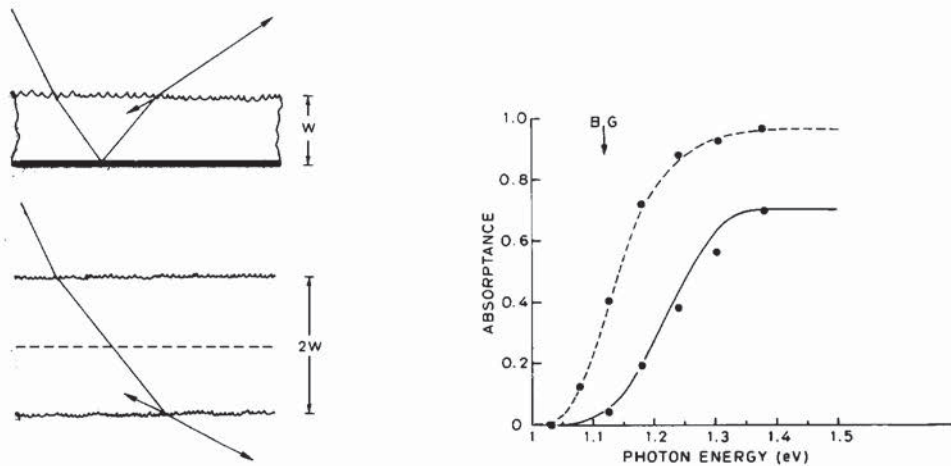


Fig. 2. Illustration that the absorption path length in a texturized cell with a perfect reflector on the back is equivalent to that of a cell twice as thick and texturized on both sides.

Fig. 3. Measured and calculated total absorptance *vs.* photon energy: continuous curve, untexturized, 120 μm; dashed curve, texturized, 80 μm; solid circles, theory.

$$V = \frac{kT}{q} \ln\left(\frac{pn}{n_i^2}\right) - V_{\text{res}} \quad (1)$$

where kT/q is the thermal voltage, p is the hole density and n the electron density in the base, n_i is the intrinsic carrier concentration and V_{res} is the total resistive loss, including base region drop. A high pn product is needed to obtain high junction voltage. In the lightly doped (or intrinsic) base cell, a high pn product is also needed for another reason. Here one relies on maintaining sufficient conductivity modulation to limit the base's resistive voltage drop. Unfortunately, however, a high pn product results in a large recombination (or dark) current. Recombination current subtracts from the collected photocurrent and thus reduces the terminal current. At the maximum power point the balance between loss of current due to recombination and operating at a high voltage is optimized.

Carrier recombination can occur in four regions of the PCSC: (1) the bulk silicon (which is largely mediated through defects and impurities), (2) the surfaces of the silicon on the front and between the contact diffusions on the back (passivation with SiO_2 reduces this component), (3) the diffused junction regions and (4) the metal-silicon contacts. Research into improving the recombination related parameters of solar cells [11] has resulted in cells where the recombination is dominated entirely by the diffused junction regions. This is the major impetus for reducing the coverage fraction of the diffused regions. In fact, however, modeling has shown that sufficient carrier density in the base to produce low series resistance can be achieved *only* by reducing this coverage fraction, as in the PCSC structure [1].

In actuality, the situation is complicated by the fact that in the PCSC carriers must diffuse into the contact regions. This causes a drop in carrier density and junction voltage at the contact. Also, as the current converges into the contact regions, a sort of spreading resistance loss results. Clearly, the contacts cannot be arbitrarily small because of these effects. For a given contact size there will be an optimum contact spacing. These issues are discussed in the next section.

4. Modeling point-contact solar cells

In order to properly design the point-contact cell, as well as to assess the potential of the concept, a three-dimensional cell model is needed. Exact numerical solution of the semiconductor transport equations in the complex, three-dimensional geometry of the point-contact cell would, at best, be expensive. On the other hand, a simplified one-dimensional analytic solution would not address the essential three-dimensional aspect of the problem and could not tackle the issues of optimum contact size and spacing. The difficulty is compounded by the fact that the cell operates in high level injection so that the superposition principle is not applicable. A compromise method of modeling this cell is presented here which has proven tractable and

accurate. The approach is based on emphasizing the accurate determination of the total recombination current, rather than carrier densities and fluxes, and proceeds as follows. The model solves the semiconductor transport using a variational approach to obtain the base carrier density. Knowing this, the terminal voltage is calculated by assuming constant quasi-Fermi levels across the n-i and p-i space charge regions. Finally, the terminal current is found by subtracting the total recombination current from the photo-production current. In this section the model is presented and exercised to determine the optimum point-contact cell design. The potential efficiency of mature point-contact cells is then calculated. The details of this model are described in more detail in ref. 1.

4.1. Semiconductor device equations

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

1. Current transport equations:

$$\vec{J}_n = -q\mu_n n \vec{\nabla}\psi_i + qD_n \vec{\nabla}n \quad (2)$$

$$\vec{J}_p = -q\mu_p p \vec{\nabla}\psi_i - qD_p \vec{\nabla}p \quad (3)$$

2. Continuity equations:

$$\vec{\nabla} \cdot \vec{J}_n = q(r - g_{ph}) \quad (4)$$

$$\vec{\nabla} \cdot \vec{J}_p = -q(r - g_{ph}) \quad (5)$$

3. Poisson's equation:

$$\nabla^2 \psi_i = -\frac{q}{\epsilon} (p + N_D^+ - n - N_A^-) \quad (6)$$

4. Carrier density equations:

$$n = n_i e^{q(\psi_i - \phi_n)/kT} \quad (7)$$

$$p = n_i e^{q(\phi_p - \psi_i)/kT} \quad (8)$$

The symbols used have their standard meanings, defined as follows: r , net recombination rate per unit volume; 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; μ_n , μ_p , electron and hole mobilities; D_n , D_p , electron and hole diffusivities; ϕ_n , ϕ_p , electron and hole quasi-Fermi levels; ψ_i , potential at the intrinsic level; ϵ , dielectric constant; q , electron charge.

Using eqns. (2)-(5) the electron and hole current densities can be eliminated. The resulting equations, along with Poisson's eqn. (6), define three coupled non-linear differential equations in three unknowns, n , p and ψ_i . Equations (7) and (8) are superfluous but will prove useful in relating terminal voltage to carrier densities. Given appropriate boundary conditions these equations can, in principle, be solved. The search for reasonable analytic solutions to these equations is hopeless and some simplifications

must be made. An approach that has proven tractable and accurate for the point-contact cell is presented below.

4.2. Integral approach to the terminal current

Once a solution for n , p and ψ_i is found, the terminal current can be found in either of two ways — by a differential or an integral method.

4.2.1. Differential method

Consider the general two-terminal device shown in Fig. 4 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

$$i_1 = \int_S (\vec{J}_n + \vec{J}_p) \cdot \hat{n} dS \quad (9)$$

where $\hat{n}$ is an outward unit vector normal to S , and J_n and J_p are given by eqns. (2) and (3). Any surface can be used to calculate i_1 that surrounds contact 1, but if *exact* solutions for $\vec{J}_n$ and $\vec{J}_p$ (or equivalently, for n , p and ψ_i) are not used then different surfaces may give different answers.

4.2.2. Integral method

Using this method, one integrates the continuity eqns. (4) and (5), over the device volume

$$\int_V \vec{\nabla} \cdot \vec{J}_n dv = q \int_V (r - g_{ph}) dv \quad (10)$$

$$\int_V \vec{\nabla} \cdot \vec{J}_p dv = -q \int_V (r - g_{ph}) dv \quad (11)$$

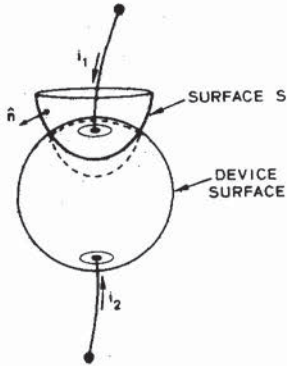


Fig. 4. General two-terminal semiconductor device.

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

$$\int_{S_{\text{tot}}} \vec{J}_n \cdot \hat{n} dS = q \int_V (r - g_{\text{ph}}) dv \quad (12)$$

$$\int_{S_{\text{tot}}} \vec{J}_p \cdot \hat{n} dS = -q \int_V (r - g_{\text{ph}}) dv \quad (13)$$

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

$$\int_{S_{\text{tot}}} \vec{J}_n \cdot \hat{n} dS = \int_{S_1} \vec{J}_n \cdot \hat{n} dS + \int_{S_2} \vec{J}_n \cdot \hat{n} dS + \int_S \vec{J}_n \cdot \hat{n} dS \quad (14)$$

$$\int_{S_{\text{tot}}} \vec{J}_p \cdot \hat{n} dS = \int_{S_1} \vec{J}_p \cdot \hat{n} dS + \int_{S_2} \vec{J}_p \cdot \hat{n} dS + \int_S \vec{J}_p \cdot \hat{n} dS \quad (15)$$

At contact 1 the current is

$$i_1 = - \int_{S_1} \vec{J}_n \cdot \hat{n} dS - \int_{S_1} \vec{J}_p \cdot \hat{n} dS \quad (16)$$

The minus sign results because the normal vector $\hat{n}$ is outward while the current is referenced inward. Now, solving for $-\int_{S_1} \vec{J}_n \cdot \hat{n} dS$ in eqn. (15), inserting this into eqn. (16), and using eqn. (13) gives

$$i_1 = \int_{S_2} \vec{J}_p \cdot \hat{n} dS - \int_{S_1} \vec{J}_n \cdot \hat{n} dS + \int_S \vec{J}_p \cdot \hat{n} + q \int_V r dv - q \int_V g_{\text{ph}} dV \quad (17)$$

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 currents in the integrations in eqn. (17). 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 eqn. (17) can be written in the suggestive form

$$I = I_{\text{ph}} - I_{\text{b,rec}} - I_{\text{s,rec}} - I_{\text{cont,rec}} \quad (18)$$

where

$$I_{\text{ph}} = q \int_V g_{\text{ph}} dv \quad \text{photoproduction current}$$

$$I_{b, \text{rec}} = q \int_V r \, dv \quad \text{bulk recombination}$$

$$I_{s, \text{rec}} = \int_S \vec{J}_p \cdot \hat{n} \, dS \quad \text{surface recombination}$$

$$I_{\text{cont, rec}} = \int_{S_2} \vec{J}_p \cdot \hat{n} \, dS - \int_{S_1} \vec{J}_n \cdot \hat{n} \, dS \quad \text{contact recombination} \quad (19)$$

In other words, if one properly accounts for recombination, one can say that the output current equals the photoproduction current minus the total recombination current. It should be stressed that eqn. (18) is an exact result of the continuity equation.

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 $\vec{\nabla}n$ and $\vec{\nabla}p$. For solar cells, using eqn. (18) approaches the essence of what is desired more closely than the differential method which requires knowledge of the carrier fluxes throughout the device. This is the approach used here.

4.3. Terminal voltage

The point-contact cell has highly doped regions near the contacts and a lightly doped base. Its band diagram is shown in Fig. 5. The horizontal coordinate position on this diagram is not a spatially straight line from 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 ϕ_p at the p^+ contact minus ϕ_n at the n^+ contact.

To a very good approximation ϕ_n can be assumed constant through the n^+ region, its space charge region, and into the edge of the neutral base near

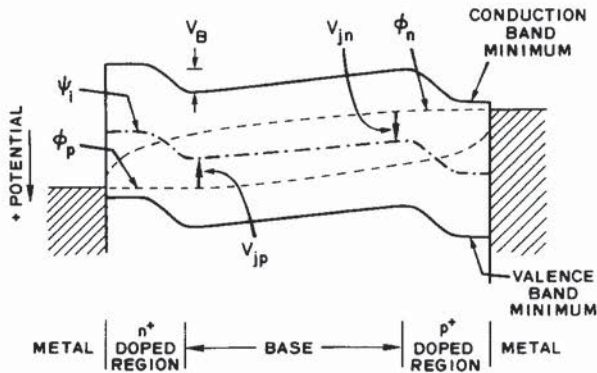


Fig. 5. Point-contact solar cell band diagram.

the n^+ contact at position 2. The same applies to ϕ_p in the p^+ region up to position 1. Referring to Fig. 5 it is easily seen that the output voltage is

$$V = V_{jn} + V_{jp} + V_B + V_c + V_m \quad (20)$$

where

$$V_{jn} = \psi_i - \phi_n = kT/q \ln(n/n_i) \quad (\text{evaluated at point 2}) \quad (21)$$

$$V_{jp} = \phi_p - \psi_i = kT/q \ln(p/n_i) \quad (\text{evaluated at point 1}) \quad (22)$$

$$V_B = \psi_i(1) - \psi_i(2) = - \int_1^2 \vec{\nabla} \psi_i \cdot d\vec{l} = \int_1^2 \vec{E} \cdot d\vec{l} \quad (23)$$

$$V_c \quad (\text{contact voltage}) \quad (24)$$

$$V_m \quad (\text{metal grid voltage}) \quad (25)$$

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 [14].

The importance of eqns. (20)–(25) lies in the need to have solutions for n , p and ψ_i only in the base semiconductor region. The details of what happens in the n^+ and p^+ semiconductor regions is unimportant. This is fortunate for, as discussed below, what happens in these regions is difficult to model because eqns. (2)–(8) do not apply in very highly doped regions.

Notice that if one neglects the base voltage drop and contact drop and assumes that n and p are constant throughout the base then eqns. (21)–(25) imply that

$$V \approx \frac{kT}{q} \ln(pn/n_i^2) - V_{res} \quad (26)$$

as posited by eqn. (1).

4.4. High level transport equations in the base

As seen in the previous section, solutions for n , p and ψ_i are needed in the base. For high concentration cells with base doping less than 10^{16} cm^{-3} the carrier density in the base will be greater than the doping, *i.e.* the base is high level injected. It has been shown, however, that the base will be quasi-neutral to a very good approximation [15]. This implies

$$n + N_A^- = p + N_D^+$$

where N_A^- and N_D^+ are the ionized acceptor and donor densities. In high level injection one can further neglect the charge on donors and acceptors giving

$$n = p \quad (27)$$

From eqns. (2) and (3), and using the Einstein relation $D = kT\mu/q$ and eqn. (27) gives

$$\vec{J} = kT(\mu_n - \mu_p) \vec{\nabla} n - q(\mu_n + \mu_p) n \vec{\nabla} \psi_i \quad (28)$$

or

$$\vec{\nabla} \psi_i = \frac{kT}{q} \left(\frac{\mu_n - \mu_p}{\mu_n + \mu_p} \right) \frac{1}{n} \vec{\nabla} n - \frac{\vec{J}}{q(\mu_n + \mu_p) n} \quad (29)$$

Equation (29) will be needed to calculate V_B from eqn. (23). The first term in eqn. (29) is called the Dember field and the second term is the resistive term. Inserting eqn. (29) into eqns. (2) and (3) gives

$$\vec{J}_n = qD \vec{\nabla} n + \frac{\mu_n}{\mu_n + \mu_p} \vec{J} \quad (30)$$

and

$$\vec{J}_p = -qD \vec{\nabla} n + \frac{\mu_p}{\mu_n + \mu_p} \vec{J} \quad (31)$$

where D is called the ambipolar diffusion coefficient and is defined as

$$D = \frac{kT}{q} \frac{2\mu_n \mu_p}{\mu_n + \mu_p} \quad (32)$$

If one assumes that D is a constant independent of n , then substituting eqn. (30) into the continuity eqn. (4) gives

$$D \nabla^2 n = r - g_{ph} \quad (33)$$

In actuality μ_n and μ_p depend on n due to carrier-carrier scattering. The approach taken here is to evaluate D at the average value of n in the base. This will require an iterative approach because n will prove to depend on D . At this point, the problem of determining n in the base has been reduced to that of solving a "Poisson like" equation.

4.5. Recombination

To calculate the terminal current the various recombination terms in eqn. (18) need to be evaluated. Various regions of the cell require different approaches.

4.5.1. Diffusion region recombination

Part of the integration in eqn. (18) 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 illustrated in Fig. 6. It is allowable to move the surface of integration to this point because the net hole current entering the n -type diffusion area, for example, either recombines within the diffu-

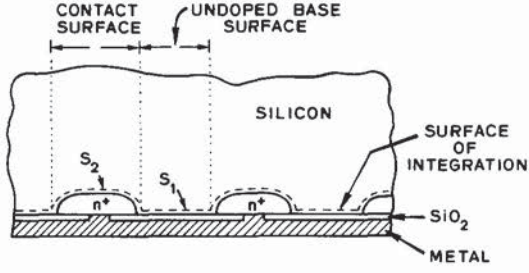


Fig. 6. Modified surface of integration.

sion 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 is being neglected.)

It has been shown that the minority carrier hole injection into a highly doped n-type region can always be written, provided the doped region is everywhere low-level injected

$$J_p = J_{0n} \left(\frac{pn}{n_i^2} - 1 \right) \quad (34)$$

where J_{0n} is a temperature dependent constant, to be called the diffusion saturation current, and p and n are evaluated in the neutral base at the edge of the space charge region [16]. 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 considered an experimental parameter. The latter approach is used here.

In the case of a highly injected base one has

$$J_p = J_{0n} \left(\frac{n^2}{n_i^2} - 1 \right) \quad (35)$$

for the hole current density entering an n-type diffusion. Similarly

$$J_n = J_{0p} \left(\frac{n^2}{n_i^2} - 1 \right) \quad (36)$$

for the electron current density entering a p-type diffusion.

4.5.2. Recombination in the base

To perform the remainder of the bulk recombination integration the recombination in the lightly doped, highly injected base needs to be evaluated. It will be assumed that

$$r = \frac{n - n_i}{\tau} + B_r(n^2 - n_i^2) + C_A(n^3 - n_i^3) \quad (37)$$

The first term in eqn. (37) accounts for defect mediated bulk recombination. τ is the high level defect related recombination lifetime which is usually considerably greater than the low level lifetime. It is very processing dependent and is considered a measured experimental parameter. The second term results from radiative recombination. It varies as $pn = n^2$ because an electron and hole participate simultaneously in the process. B_r has the experimental value of $2 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$ [17]. The final term arises from Auger recombination. C_A is the high-level ambipolar Auger coefficient (the sum of C_n and C_p) and has the approximate (not very accurately known) value of $4 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$ [18].

4.5.3. Surface recombination

Surface recombination is assumed to be linear in excess carrier density at the surface, and hence is modeled by a phenomenological recombination velocity s

$$\hat{n} \cdot \vec{J}_p = qs(n - n_i) \quad (38)$$

where n is evaluated at the undoped surfaces of the base. s will be considered an experimental parameter to be measured and input into the model. The determination of τ and s will be discussed in Section 5.

4.6. Variational solution of the base carrier density

Up to this point the analysis has been nearly exact in the sense that any approximations, such as assuming constant ϕ_n and ϕ_p across space charge layers, introduced negligible error. It remains to solve eqn. (33) for the base carrier density given appropriate boundary conditions. Unfortunately, further approximation is needed to solve this equation because of the three dimensional nature of the point-contact cell as well as the complicated spatial dependence of r and g_{ph} .

4.6.1. Neglecting bulk recombination

As a first approximation bulk recombination r will be neglected in eqn. (33). The effects of bulk recombination will still affect cell characteristics through eqn. (17), but the bulk recombination current will be calculated assuming carrier densities that would result when there is no recombination. This is equivalent to the common procedure of calculating the base recombination in a bipolar transistor by using carrier densities calculated neglecting recombination. Such an approximation proves to be correct to second order in the device thickness over the minority carrier diffusion length and is very accurate when the diffusion length is greater than the device thickness. In ref. 1 it is shown that the resulting error is at most several percent for the conditions of interest in the point-contact cell.

4.6.2. Neglecting bulk generation

The remaining g_{ph} term still prevents solution of eqn. (33). The approach taken here is to neglect it also. The photoproduction is thereby confined to

an infinitesimally thin layer at the front of the device. The bulk of the photocurrent actually occurs in the first $10\text{ }\mu\text{m}$ in any case, with the bulk remainder distributed at deeper levels. The following procedure is adopted. The total photogeneration is calculated for cell structure as described in Section 3. This generation is then assumed to all occur at the front surface of the cell. This is certainly a conservative assumption for back surface cells because it moves the generation further, on average, from the collecting junctions.

Equation (33) for the base carrier density has now been reduced to Laplace's equation

$$\nabla^2 n = 0 \quad (39)$$

4.7. Carrier density solution

Many techniques are available for solving Laplace's equation, but probably the most powerful one for generating analytic solutions to three-dimensional problems is the variational method [19]. To use this method physical insight is applied to find a functional form for n which seems reasonable. This trial function contains variable fitting parameters but must meet the desired boundary conditions everywhere. The variational theorem then asserts that the trial function which minimizes the squared error from the true solution is that which minimizes the functional

$$F = \int_v (\vec{\nabla} n) \cdot (\vec{\nabla} n) dv \quad (40)$$

The trial function used here is constructed as follows. Figure 7 shows the point-contact cell structure. The cell has an array of small hemispherical point contacts on the back with n and p rows alternating. The cell is clearly periodic with horizontal period S_2 and vertical period S_1 . Therefore, only the indicated unit cell of area $S_1 S_2$ will be analyzed. Incident photons generate electron-hole pairs near the front surface. These carriers then diffuse toward the back side where they either recombine along the way or are collected at their respective contact. This suggests dividing the cell into the three regions shown in Fig. 7. Each section will have its own analytic function for carrier density. First there is the diffusion region where the carrier flow is essentially one-dimensional as carriers diffuse toward the back surface. Here the one-dimensional solution of Laplace's equation is used. As the carriers near the contact they begin to flow radially in to be collected. This flow is approximated as completely radial inside a hemisphere of radius r_1 , called the collection region. r_1 is a variational parameter to be optimized using eqn. (40). Between the collection regions lies a region where one can imagine that n is nearly constant at a value nearly equal to that at the edge of the collection region. The approximation is made that it is exactly constant in this region, which will be called the stagnant region. This value of n in the stagnant region is the only other variational parameter.

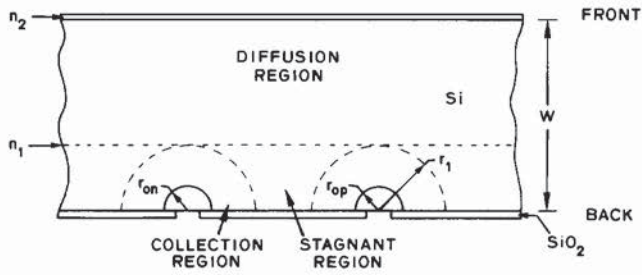
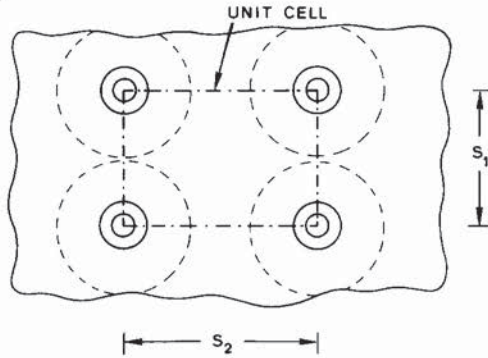
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Fig. 7. Geometry of the point-contact cell and the regions used for the variational solution.

Treating the diffusion region first it is seen that the electron and hole fluxes will be equal there so that the total current is zero. This results because no current leaves the top surface. Then eqns. (30) and (31) become

$$\vec{J}_p = -\vec{J}_n = -qD\vec{\nabla}n \quad (41)$$

Noting that the flow is one-dimensional, and letting x measure distance from the top surface

$$J_p = -qD \frac{dn}{dx} \quad (42)$$

If n_2 is the carrier density at the front and n_1 that at the back of the diffusion region then eqn. (42) implies that

$$n(x) = n_2 - \frac{J_p}{qD} x \quad (43)$$

and

$$J_p = qD \frac{n_2 - n_1}{W - r_1} \quad (44)$$

At the front surface holes are created at a rate J_{ph}/q . In addition, they recombine at a rate $(n_2 - n_i)s$. Thus the net hole current density diffusing toward the back is

$$J_p = J_{ph} - q(n_2 - n_i)s \quad (45)$$

Equating (45) and (44) and solving for n_2 gives

$$n_2 = \frac{n_1 + \frac{W - r_1}{D} \frac{J_{ph}}{q} - n_i}{1 + \frac{W - r_1}{D} s} + n_i \quad (46)$$

Throughout the development n_1 will be considered the independent variable which, when fixed, determines the terminal voltage and current.

Moving on to the collection region, the appropriate spherical solution of Laplace's equation is

$$n(r) = \frac{A}{r} + B \quad (47)$$

where r is the radial distance from the contact and A and B are constants of integration. These are determined from the boundary conditions that $n(r_1) = n_1$ and $n(r_0) = n_0$. r_0 is the radius of the contact under consideration and n_0 is the value of n just inside the neutral base at the contact diffusion space charge region. This yields

$$n(r) = \frac{n_1 r_1 - n_0 r_0}{r_1 - r_0} - \frac{1}{r} \frac{r_1 r_0}{r_1 - r_0} (n_1 - n_0) \quad (48)$$

Finally, in the stagnant region

$$n = n_1 \quad (49)$$

where n_1 is constant.

The variational functional, eqn. (40), can now be evaluated. In the diffusion region

$$|\vec{\nabla} n| = \frac{n_2 - n_1}{W - r_1} \quad (50)$$

so that

$$\int |\vec{\nabla} n|^2 dv = \frac{S_1 S_2}{W - r_1} (n_2 - n_1)^2 \quad (51)$$

In the stagnant region

$$\int |\vec{\nabla} n|^2 dv = 0 \quad (52)$$

In each collection region, recalling that each collection region has one quarter of a sphere in the unit cell

$$|\vec{\nabla}n| = \frac{1}{r^2} \frac{r_1 r_0}{r_1 - r_0} (n_1 - n_0) \quad (53)$$

so that

$$\int |\vec{\nabla}n|^2 dv = \frac{1}{4} \int_{r_0}^{r_1} 4\pi r^2 \frac{1}{r^4} (n_1 - n_0)^2 \left(\frac{r_1 r_0}{r_1 - r_0} \right)^2 dr = \pi (n_1 - n_0)^2 \left(\frac{r_1 r_2}{r_1 - r_2} \right) \quad (54)$$

The total functional is the sum of eqns. (51), (52) and (54). Letting subscripts n and p refer to the n and p collection regions, one has

$$F = \frac{S_1 S_2}{W - r_1} (n_2 - n_1)^2 + \pi (n_1 - n_{0p})^2 \frac{r_1 r_{0p}}{r_1 - r_{0p}} + \pi (n_1 - n_{0n})^2 \frac{r_1 r_{0n}}{r_1 - r_{0n}} \quad (55)$$

The proper method of solution is now to fix the values of n on the boundary (n_2, n_{0n}, n_{0p}) and minimize with respect to n_1 and r_1 . Minimizing first with respect to n_1

$$\frac{\partial F}{\partial n_1} = 0 = 2 \frac{S_1 S_2}{W - r_1} (n_1 - n_2) + 2\pi \frac{r_{0p} r_1}{r_1 - r_{0p}} (n_1 - n_{0p}) + 2\pi \frac{r_{0n} r_1}{r_1 - r_{0n}} (n_1 - n_{0n}) \quad (56)$$

This can be solved for n_1 ,

$$n_1 = \frac{\left(\frac{S_1 S_2}{W - r_1} \right) n_2 + \left(\frac{\pi r_{0p} r_1}{r_1 - r_{0p}} \right) n_{0p} + \left(\frac{\pi r_{0n} r_1}{r_1 - r_{0n}} \right) n_{0n}}{\left(\frac{S_1 S_2}{W - r_1} \right) + \left(\frac{\pi r_{0p} r_1}{r_1 - r_{0p}} \right) + \left(\frac{\pi r_{0n} r_1}{r_1 - r_{0n}} \right)} \quad (57)$$

Note that n_1 is a weighted average of the values on the boundary, as would be expected from the linear form of Laplace's equation.

Minimizing next with respect to r_1

$$\frac{\partial F}{\partial r_1} = 0 = \frac{S_1 S_2 (n_2 - n_1)^2}{(W - r_1)^2} - \pi (n_1 - n_{0p})^2 \left(\frac{r_{0p}}{r_1 - r_{0p}} \right)^2 - \pi (n_1 - n_{0n})^2 \left(\frac{r_{0n}}{r_1 - r_{0n}} \right)^2 \quad (58)$$

Equations (57) and (58) are a pair of simultaneous equations in n_1 and r_1 . Their solution is facilitated by a relation between the terminal current and contact carrier densities derived next.

Treating the p-type contact first, the hole current in the collection region is given by eqn. (31). Under normal operation the electron current near the p-contact will be small because it would come from the contact

recombination. In a high quality cell operating near its maximum power point, the terminal current will be only slightly less than the total generation current. Any contact recombination will come from the remainder and will be considerably less than the total current. Setting $J = J_p$ in eqn. (31) gives, after some manipulation

$$\vec{J}_p = -2qD_p \vec{\nabla} n \quad (59)$$

Note that the hole diffusion coefficient has been effectively doubled by the neutralizing, but stagnant electron population present. This is analogous to the doubling of the diffusion constant in the base of a bipolar transistor under high level injection [20].

Since there is no recombination in the collection region, the total current I entering the contact is constant at $I = \pi r^2 J_p$. Noting that $|\vec{\nabla} n| = dn/dr$ in spherical coordinates, we have, defining positive current as inwards

$$J_p = 2qD_p \frac{dn}{dr} = \frac{I}{\pi r^2} \quad (60)$$

or

$$dn = \frac{I}{2\pi qD_p} \frac{dr}{r^2} \quad (61)$$

Integrating

$$n = n_{0p} + \frac{I}{2\pi qD_p} \int_{r_{0p}}^r \frac{dr}{r^2} = n_{0p} + \frac{I}{2\pi qD_p} \left(\frac{1}{r_{0p}} - \frac{1}{r} \right) \quad (62)$$

When $r = r_1$, $n = n_1$, so that

$$n_1 = n_{0p} + \frac{I}{2\pi qD_p} \left(\frac{1}{r_{0p}} - \frac{1}{r_1} \right) \quad (63)$$

Equations (62) and (63) can be combined to yield

$$n = n_1 - \frac{I}{2\pi qD_p} \left(\frac{1}{r} - \frac{1}{r_1} \right) \quad (64)$$

and

$$n_{0p} = n_1 - \frac{I}{2\pi qD_p} \left(\frac{1}{r_{0p}} - \frac{1}{r_1} \right) \quad (65)$$

Equation (65) is simple to interpret. When there is no current being drawn from the contact, $n_{0p} = n_1$. As the current is removed from the p-contact n_{0p} becomes less than n_1 because of the need for holes to diffuse through the collecting region. In fact, it is seen that there is a maximum amount of current the contact can support given by setting $n_{0p} = 0$.

A similar treatment of the n-type collection area gives

$$n = n_1 - \frac{I}{2\pi D_n} \left(\frac{1}{r} - \frac{1}{r_1} \right) \quad (66)$$

and

$$n_{0n} = n_1 - \frac{I}{2\pi D_n} \left(\frac{1}{r_{0n}} - \frac{1}{r_1} \right) \quad (67)$$

Since the current I in both p- and n-type collection regions must be the same, eqns. (65) and (67) imply a relation between n_{0n} and n_{0p} .

Equations (57) and (58) can now be solved. Neglecting recombination implies from eqn. (43) that

$$\frac{n_2 - n_1}{W - r_1} = \frac{I}{qDS_1S_2} \quad (68)$$

Inserting eqns. (65), (67) and (68) into eqn. (58) yields

$$0 = \frac{I^2}{q^2 D^2 S_1 S_2} - \frac{I^2}{4\pi q^2 D_p^2 r_1^2} - \frac{I^2}{4\pi q^2 D_n^2 r_1^2} \quad (69)$$

The current cancels and eqn. (69) can be immediately solved for r_1

$$r_1^2 = \frac{S_1 S_2}{4\pi} \left(\frac{D^2}{D_p^2} + \frac{D^2}{D_n^2} \right) \quad (70)$$

Using the definition of D , eqn. (32), and defining $D_n/D_p = \mu_n/\mu_p = b$

$$r_1 = \left(\frac{S_1 S_2}{2\pi} \right)^{1/2} \left[\frac{2(b^2 + 1)}{(b + 1)^2} \right]^{1/2} \quad (71)$$

Fortunately, r_1 does not depend on the thickness of the cell or explicitly on the current but is merely a fraction of the geometric mean distance between collection spheres. Unfortunately, it does depend on the injection level because b does. b goes from 2.7 at low values of n to 2.5 at typical values of n of $1 \times 10^{17} \text{ cm}^{-3}$ at the maximum power point and to 2.3 at the highest values of n observed, $2 \times 10^{17} \text{ cm}^{-3}$. The expression in square brackets in eqn. (71) assumes the values 1.101, 1.088 and 1.075 for these values of b , respectively. Since the optimum value of r_1 minimizes the error, small departures in r_1 should have only a second order effect on accuracy. Accordingly the small variation of r_1 with b is undoubtedly insignificant within the accuracy of the present techniques. This is amply demonstrated by calculating the cell efficiency for the optimized cell design presented below. Using these three values of b gives design point efficiencies of 0.280410, 0.280418 and 0.280440. Therefore, b will be permanently set to 2.5 in eqn. (71) giving

$$r_1 = 0.434(S_1 S_2)^{1/2} \quad (72)$$

This completes the derivation of the base carrier density. Given n_1 , I and J_{ph} , the value of n can be found everywhere through eqns. (71), (67), (65) and (43). The final form of n is shown in Fig. 8. The decrease in carrier density as carriers diffuse from front to back followed by a more rapid drop when converging into the contact, is evident.

4.8. Evaluating the cell terminal current

To calculate the terminal current the various recombination terms in eqn. (18) need to be evaluated. This will be done sequentially for the various parts of the cell.

4.8.1. Diffusion region recombination

Inserting eqn. (43) into (37), performing the integration in (19) throughout the diffusion region, and defining normalized carrier densities $\gamma_1 = n_1/n_i$ and $\gamma_2 = n_2/n_i$ gives, after considerable manipulation

$$I_{rec} = qS_1S_2(W - r_1) \left[\frac{n_i}{\tau_{eff}}(\gamma_1 - 1) + K \right] \quad (73)$$

where

$$K = (\gamma_2 - \gamma_1) \left(\frac{n_i}{2\tau} + B_r n_i^2 \gamma_1 + \frac{3}{2} C_A n_i^3 \gamma_1^2 \right) + (\gamma_2 - \gamma_1)^2 \left(\frac{1}{3} B_r n_i^2 + C_A n_i^3 \gamma_1 \right) + (\gamma_2 - \gamma_1)^3 \left(\frac{1}{4} C_A n_i^3 \right) \quad (74)$$

$$\gamma_2 = \frac{\gamma_1 - 1 + \frac{W - r_1 J_{ph}}{D} \frac{q}{q}}{1 + \frac{W - r_1}{D} s} + 1 \quad (75)$$

and

$$\frac{1}{\tau_{eff}} \equiv \frac{1}{\tau} + B n_i (\gamma_1 + 1) + C_A n_i^2 (\gamma_1^2 + \gamma_1 + 1) \quad (76)$$

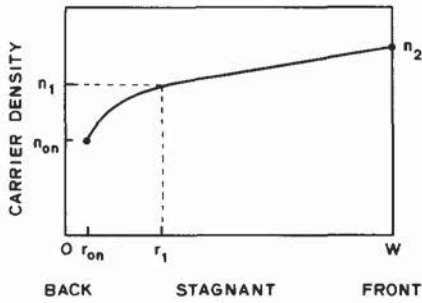


Fig. 8. Base carrier density along a line from one contact diffusion to the front surface.

τ_{eff} is the effective recombination lifetime when $n = n_1$, including Auger and radiative recombination. Note that between eqns. (74) and (75) the Auger recombination component increases as the *fourth* power of the device thickness and *third* power of the photocurrent. This places severe upper bounds on the maximum usable thickness and current of back-surface contact cells.

4.8.2. Collection region recombination

In the collection region the integration to be performed, eqn. (19), is more complicated. Thus the effective lifetime will be assumed constant at the value it assumes at n_1 . This is a conservative assumption because the carrier density decreases toward the contact. (It is assumed never to be low enough that low-level injection and its concomitant lower lifetime obtains, however.) For the p-type region we have, inserting eqn. (64) into (19)

$$\begin{aligned} I_{\text{rec}} &= \frac{q}{\tau_{\text{eff}}} \int_{r_{0p}}^{r_1} (n - n_1) dv \\ &= \frac{1}{\tau_{\text{eff}}} \int_{r_{0p}}^{r_1} (n_1 - n_i) \pi r^2 dr - \frac{qI}{2\pi q D_p} \int_{r_{0p}}^{r_1} \left(\frac{1}{r} - \frac{1}{r_1} \right) \pi r^2 dr \end{aligned} \quad (77)$$

Evaluating this, and converting to normalized carrier density, gives

$$I_{\text{rec}} = \frac{qn_i}{\tau_{\text{eff}}} (\gamma_1 - 1) \frac{\pi}{3} (r_1^3 - r_{0p}^3) - \frac{Ir_1^2}{12D_p\tau_{\text{eff}}} \left(1 - 3 \frac{r_{0p}^2}{r_1^2} + 2 \frac{r_{0p}^3}{r_1^3} \right) \quad (78)$$

Similarly, for the n-type collection region

$$I_{\text{rec}} = \frac{qn_i}{\tau_{\text{eff}}} (\gamma_1 - 1) \frac{\pi}{3} (r_1^3 - r_{0n}^3) - \frac{Ir_1^2}{12D_n\tau_{\text{eff}}} \left(1 - 3 \frac{r_{0n}^2}{r_1^2} + 2 \frac{r_{0n}^3}{r_1^3} \right) \quad (79)$$

4.8.3. Stagnant region

The carrier density in the stagnant region is constant so that recombination there is simply the volume of this region times $(n_1 - n_i)/\tau_{\text{eff}}$. This gives

$$I_{\text{rec}} = \frac{qn_i}{\tau_{\text{eff}}} (\gamma_1 - 1) \left(S_1 S_2 r_1 - \frac{2\pi}{3} r_1^3 \right) \quad (80)$$

4.8.4. Front surface

The front surface recombination is equally simple. Inserting n_2 into eqn. (19)

$$I_{\text{rec}} = qS_1 S_2 sn_i (\gamma_2 - 1) \quad (81)$$

where γ_2 is given by eqn. (75).

4.8.5. Back surface in the collection region

At the back surface in the collection regions one obtains

$$I_{\text{rec}} = q \int_{r_{0p}}^{r_1} (n - n_i) \pi r \, dr$$

$$= qsn_i(\gamma_1 - 1) \frac{\pi}{2} (r_1^2 - r_{0p}^2) - qs \frac{IS_1S_2}{4qD_p r_1} (r_1 - r_{0p})^2 \quad (82)$$

for the p-type collection region and

$$I_{\text{rec}} = qsn_i(\gamma_1 - 1) \frac{\pi}{2} (r_1^2 - r_{0n}^2) - qs \frac{IS_1S_2}{4qD_n r_1} (r_1 - r_{0n})^2 \quad (83)$$

for the n-type collection region.

4.8.6. Back surface in the stagnant region

Here

$$I_{\text{rec}} = qsn_i(\gamma_1 - 1)(S_1S_2 - \pi r_1^2) \quad (84)$$

4.8.7. Diffused region injection

Finally, there is injection into the diffused regions. From eqns. (19), (35), (36), (65) and (67)

$$I_{\text{rec}} = \pi r_{0n}^2(\gamma_{0n}^2 - 1) J_{0n} + \pi r_{0p}^2(\gamma_{0p}^2 - 1) J_{0p} \quad (85)$$

where

$$\gamma_{0p} = \gamma_1 - \frac{I}{2\pi q D_p n_i} \left(\frac{1}{r_{0p}} - \frac{1}{r_1} \right) \quad (86)$$

and

$$\gamma_{0n} = \gamma_1 - \frac{I}{2\pi q D_n n_i} \left(\frac{1}{r_{0n}} - \frac{1}{r_1} \right) \quad (87)$$

4.8.8. Terminal current

On a per-unit-area basis the terminal current from eqn. (18) becomes

$$J = J_{ph} - J_{\text{rec}} \quad (88)$$

where each of the terms have been divided by S_1S_2 . To compute J_{rec} the preceding recombination terms are added and divided by S_1S_2 . When J_{rec} is then inserted into eqn. (88) a quadratic equation in J results because of the J^2 term in eqn. (85). This quadratic can be solved giving the terminal current in terms of γ_1 . Some rather laborious algebra yields

$$J = \frac{-B + (B^2 + 4AC)^{1/2}}{2A} \quad (89)$$

where

$$A = \frac{J_{0p}'}{J_{dp}^2} + \frac{J_{0n}'}{J_{dn}^2} \quad (90)$$

$$B = 1 - b - \frac{2\gamma_1 J_{0p}'}{J_{dp}} - \frac{2\gamma_1 J_{0n}'}{J_{dn}} \quad (91)$$

$$C = J_{ph} - r(\gamma_1 - 1) - d - J_{0p}'(\gamma_1^2 - 1) - J_{0n}'(\gamma_1^2 - 1) \quad (92)$$

$$r = \frac{qWn_i}{\tau_{eff}} + 2qsn_i - \frac{qs\pi n_i}{2S_1 S_2} (r_{0p}^2 + r_{0n}^2) \quad (93)$$

$$b = \frac{r_1^2}{12D_p\tau_{eff}} \left(1 - 3\frac{r_{0p}^2}{r_1^2} + 2\frac{r_{0p}^3}{r_1^3} \right) + \frac{sr_1}{4D_p} \left(1 - \frac{r_{0p}}{r_1} \right) \\ + \frac{r_1^2}{12D_n\tau_{eff}} \left(1 - 3\frac{r_{0n}^2}{r_1^2} + 2\frac{r_{0n}^3}{r_1^3} \right) + \frac{sr_1}{4D_n} \left(1 - \frac{r_{0n}}{r_1} \right) \quad (94)$$

$$d = q(W - r_1)K + qsn_i(\gamma_2 - \gamma_1) \quad (95)$$

$$\frac{1}{J_{dp}} = \frac{S_1 S_2}{2\pi q D_p} \left(\frac{1}{r_{0p}} - \frac{1}{r_1} \right) \quad (96)$$

$$\frac{1}{J_{dn}} = \frac{S_1 S_2}{2\pi q D_n} \left(\frac{1}{r_{0n}} - \frac{1}{r_1} \right) \quad (97)$$

$$J_{0p}' = \frac{\pi r_{0p}^2}{S_1 S_2} J_{0p} \quad (98)$$

and

$$J_{0n}' = \frac{\pi r_{0n}^2}{S_1 S_2} J_{0n} \quad (99)$$

The K in eqn. (95) is given by eqn. (74).

4.9. Evaluating the terminal voltage

The cell voltage is calculated using the methods developed in Section 4.3. V_{jn} and V_{jp} are readily calculable from eqns. (21), (22), (86) and (87) giving

$$V_{jp} = \frac{kT}{q} \ln(\gamma_{0p}) = \frac{kT}{q} \ln \left(\gamma_1 - \frac{J}{J_{dp}} \right) \quad (100)$$

and

$$V_{jn} = \frac{kT}{q} \ln(\gamma_{0n}) = \frac{kT}{q} \ln \left(\gamma_1 - \frac{J}{J_{dn}} \right) \quad (101)$$

To calculate V_B we need to define a path of integration from the p to n contact, evaluate $\vec{E}$ along this path, and integrate. The path will be to follow a radius line in the p-type collection region, cross the stagnant region, and enter the n-type collection region along another radius line. The electric field in the collection region is given by eqn. (29). Using eqn. (59) and remembering that $\vec{J} = \vec{J}_p$ in this region gives

$$\vec{E} = -\frac{kT}{q} \frac{1}{n} \vec{\nabla} n \quad (102)$$

Integrating through the p-type collection region gives the drop, V_{Bp}

$$V_{Bp} = - \int_{r_{0p}}^{r_1} \frac{kT}{q} \frac{1}{n} \frac{dn}{dr} dr = -\frac{kT}{q} \ln \left(\frac{n_1}{n_{0p}} \right) \quad (103)$$

Note that V_{Bp} is negative, corresponding to a voltage loss, as it must.

V_{jp} can also be written as

$$V_{jp} = \frac{kT}{q} \ln \left(\frac{n_{0p}}{n_i} \right) = \frac{kT}{q} \ln \left(\frac{n_1}{n_i} \right) - \frac{kT}{q} \ln \left(\frac{n_1}{n_{0p}} \right) \quad (104)$$

The first term is the junction voltage that would obtain if there were no decrease in carrier density through the collection region, and the second term can be considered the junction potential loss due to this decrease. Interestingly, from eqn. (103) it is seen that the resistive drop V_{Bp} equals the voltage drop due to the carrier decrease.

Using eqn. (86), eqn. (103) can be written

$$V_{Bp} = -\frac{kT}{q} \ln \left(\frac{\gamma_1}{\gamma_1 - \frac{J}{J_{dp}}} \right) \quad (105)$$

For the n-type collection region

$$V_{Bn} = -\frac{kT}{q} \ln \left(\frac{\gamma_1}{\gamma_1 - \frac{J}{J_{dn}}} \right) \quad (106)$$

There will be no voltage drop, *i.e.*, negligible drop compared to $V_{Bp} + V_{Bn}$, through the stagnant region where $\vec{\nabla} n = 0$ so that combining eqns. (100), (101), (105) and (106) gives the terminal voltage

$$V = 2 \frac{kT}{q} \ln \left[\left(\gamma_1 - \frac{J}{J_{dp}} \right) \left(\gamma_1 - \frac{J}{J_{dn}} \right) / \gamma_1 \right] + V_c + V_m \quad (107)$$

where V_c and V_m account for the contact and metal losses (they are negative).

For a given value of γ_1 the terminal voltage can be found from eqn. (107) because J is already known from eqn. (89). Because of their compli-

cated form, V cannot be solved in terms of J , or vice versa, necessitating the retention of γ_1 as the independent variable.

4.10. Modeling results

The previous point-contact cell modeling equations have been implemented in a computer code which was used to explore cell design and operation. This code calculates efficiency by first picking a value of γ_1 , assuming values for μ_n and μ_p in the diffusion region, and then calculating γ_2 from eqn. (75). At this point, μ_n and μ_p are recalculated at the average carrier density in the diffusion region. Various mobility *versus* carrier density relationships have been incorporated with little difference in computed efficiencies. For the results presented here the mobility formulas of Caughey and Thomas [21] were used. These are for doped regions, rather than highly injected regions, and slightly underestimate the mobility compared to measurements in such regions [22]. γ_2 is recalculated using the new mobility values and the procedure repeated eight times. This is found to guarantee self-consistency between the front surface carrier density and the average mobility in the diffusion region. The terminal current and voltage are now calculated using eqns. (89) and (107). Finally, γ_1 is varied and the whole procedure repeated until the maximum power output is found. The efficiency can then be calculated, knowing the photocurrent as described in Section 3.

The modeling code was used to optimize the cell design. It was found that smaller contacts invariably result in higher efficiency. (Smaller contacts have to be closer together, of course.) Therefore, $6\text{ }\mu\text{m}$ was chosen as the design size, this being a compromise between lithographic difficulty and efficiency. The cell thickness and contact spacings were then varied to optimize efficiency. The resulting optimum thickness was $60\text{ }\mu\text{m}$ and contact spacing was $20\text{ }\mu\text{m}$. The major parameters for this cell are presented in Table 3.

The technological parameters shown in Table 3 require very high quality processing for their realization but are representative of the best that

TABLE 3

Optimized point-contact cell technological and design parameters

<i>Technological parameters</i>	
Defect related base lifetime	1 ms
Diffused region saturation current	$3 \times 10^{-13}\text{ A cm}^{-2}$
Surface recombination velocity	2 cm s^{-1}
Specific contact resistance	$1 \times 10^{-6}\text{ }\Omega\text{ cm}^2$
<i>Design parameters</i>	
Cell thickness	$75\text{ }\mu\text{m}$
p to n contact spacing	$20\text{ }\mu\text{m}$
n to n contact spacing	$20\text{ }\mu\text{m}$
Contact diameter	$6\text{ }\mu\text{m}$
Back surface reflectance	0.95
Specific metal resistance	$3 \times 10^{-4}\text{ }\Omega\text{ cm}^2$

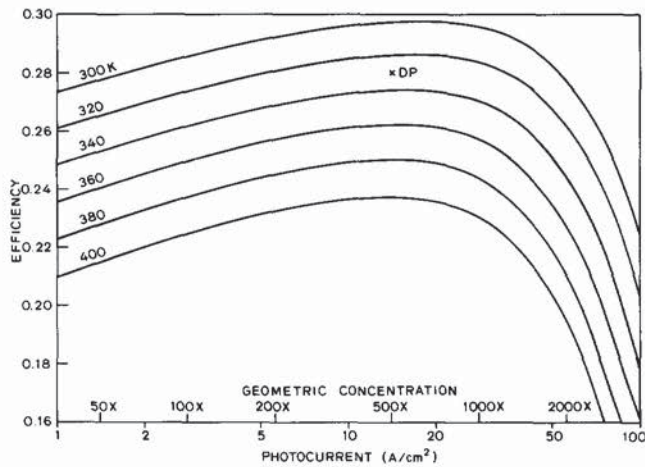


Fig. 9. Computed performance of an optimized point-contact cell. DP indicates the cell design point.

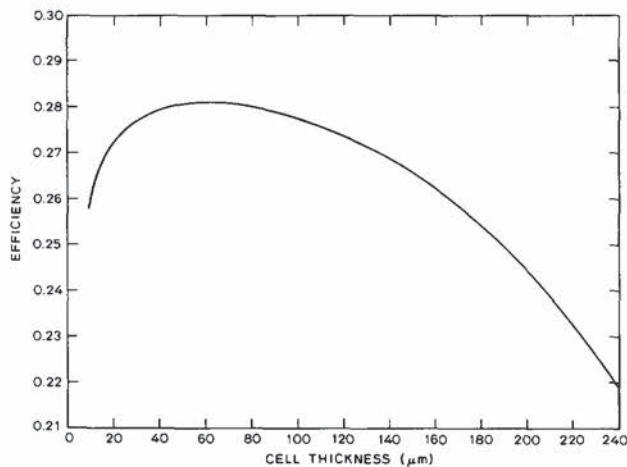


Fig. 10. Point-contact cell efficiency vs. cell thickness.

has been seen in the laboratory. The calculated efficiencies are, therefore, indicative of what one might hope of point-contact cells in a mature process. These efficiencies are shown in Fig. 9. The design point efficiency is 28.0%.

Figure 10 shows the predicted efficiency of the previous cell when the thickness is varied. The rapid degradation for thicker cells is apparent. Figure 11 shows the effect of varying the contact spacing. The required spacing is seen to be surprisingly small.

It is seen that an optimized point-contact cell is predicted to have high efficiency; however, very good recombination related parameters are required to achieve this goal. In fact, because of its lightly doped base and back

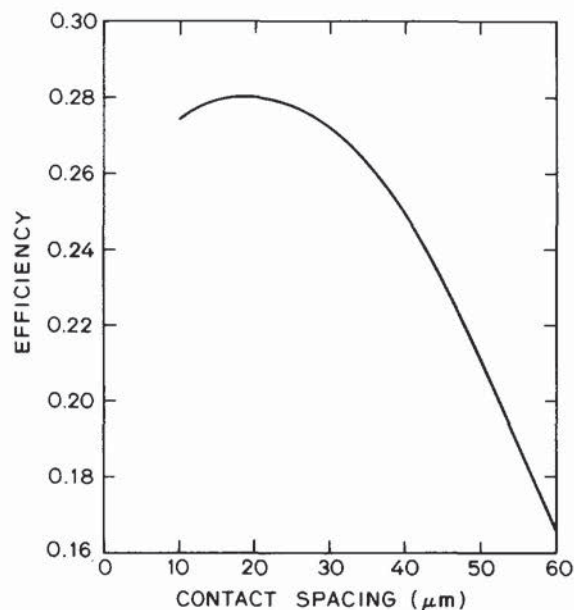


Fig. 11. Point-contact cell efficiency vs. contact spacing.

contacts, the point-contact cell is considerably more sensitive to these parameters than conventional cells.

5. Experimental results

In this section a process for fabricating point-contact cells and some preliminary experimental results are presented.

5.1. Cell processing

As discussed in Section 4.10, obtaining high efficiency requires very good recombination related parameters; approaching those shown in Table 3. Therefore, the cell processing was done in a class 100 clean-room environment using careful cleaning and handling procedures. The recombination lifetime was monitored throughout the process by incorporating test wafers for photoconductivity decay measurements [23]. By using wafers of different thicknesses, the surface and bulk recombination components were separated.

It was found necessary to use float-zone silicon to achieve the target bulk lifetime of 1 ms. The surfaces were passivated with a thermally grown SiO_2 layer. This layer is grown in dry O_2 followed by a 15 min Ar anneal at 1000 °C. Following a forming-gas anneal at 450 °C the measured recombination velocity is around 25 cm s^{-1} . This is higher than desired; therefore, an additional aluminum anneal [4] was performed resulting in a measured recombination velocity of around 5 cm s^{-1} [24].

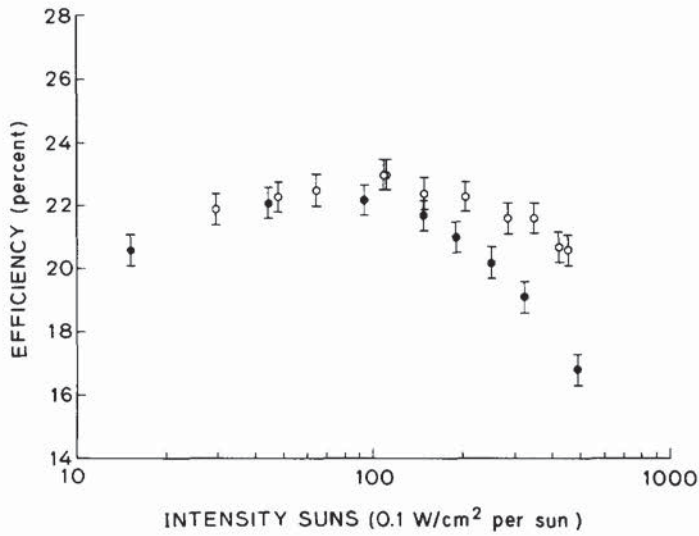


Fig. 12. Efficiency vs. incident intensity for 130 μm (open circles) and 233- μm (solid circles) cell.

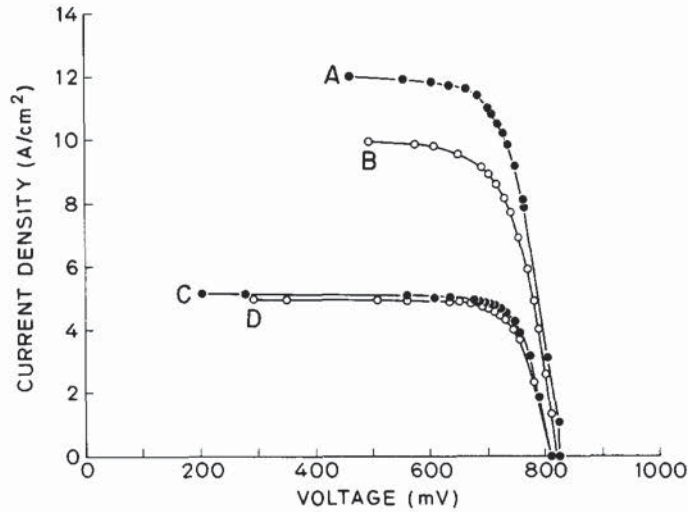


Fig. 13. Current density vs. voltage curves for the two cells in Fig. 12: curve A, 130- μm cell, 35.0 W cm^{-2} ; curve B, 233- μm cell, 32.5 W cm^{-2} ; curve C, 130- μm cell, 15.0 W cm^{-2} ; curve D, 233- μm cell, 14.9 W cm^{-2} .

The diffused regions were formed using doped CVD SiO_2 sources. These were driven-in at 1120°C for 2 h to produce deep diffusions with low saturation currents. The measured saturation current under metal contact areas was around $5 \times 10^{-13} \text{ A cm}^{-2}$ for both the p-type and n-type diffusions [25].

Metalization was done using e-beam aluminum evaporation. All patterning was performed in an integrated circuit laboratory using standard procedures.

5.2. Cell measurements

The illuminated current *versus* voltage characteristics were obtained using a four-point electrical measurement in sunlight concentrated by front surface mirrors. The cells were cooled during testing by spraying water directly onto the cell back side. The absolute power of the incident sunlight was found by comparing the power of the incident beam measured with a black-body calorimeter to an equivalent heat flow produced by resistive heating in the calorimeter [26].

Two thicknesses of cell were fabricated, 130 μm and 233 μm . The efficiencies of both cells are plotted in Fig. 12. The efficiency peaks at 23% at 11 W cm^{-2} incident flux for the thin cell. Notice that the thicker cell drops in efficiency faster at high intensities than the thin one. This is the result predicted from Auger recombination as discussed in Section 4. Two curves of current *versus* voltage for each cell are shown in Fig. 13 with some key features collected in Table 4. The decrease in internal quantum efficiency at high intensities is clearly evident for the thicker cell. The series resistance was found to be 26 $\text{m}\Omega$ by fitting the dark current *versus* voltage characteristics. It can be attributed entirely to the resistance of the 1 μm -thick metal lines.

5.3. Discussion

The cells reported here have the highest reported efficiency to date for silicon concentrator cells. Even so, these cells have only 1100 $\text{\AA}$ of SiO_2 for an anti-reflection coating. The measured one-sun photocurrent is 34.5 mA cm^{-2} which agrees with theoretical calculations for this structure. By incorporating a multi-layer anti-reflection coating along with texturizing this

TABLE 4

Cell characteristics at 150 and 350 suns concentration

Cell characteristics (cell area, 0.15 cm^2)				
Cell thickness (μm)	130	233	130	233
Incident power (suns $\pm 1\%$) (1 sun = 0.1 W cm^{-2})	150	149	350	325
V_{oc} (± 5 mV)	810	810	825	820
I_{sc} ($\pm 0.5\%$ A cm^{-2})	5.17	4.98	12.0	9.97
V_{mp} (± 8 mV)	704	701	701	690
I_{mp} ($\pm 1\%$ A cm^{-2})	4.83	4.67	11.0	9.15
Fill factor ($\pm 1.0\%$)	0.81	0.81	0.78	0.77
Cell mount temp. (± 1.0 $^{\circ}\text{C}$)	24	22	23	23
Efficiency (± 0.5) (Calibrated calorimetrically)	22.4%	21.7%	21.6%	19.1%

should increase to over 42 mA cm^{-2} , as discussed in Section 3. This should increase the efficiency to 28.5%, provided it can be implemented without compromising any of the other cell parameters. Minor improvements in series resistance and recombination parameters, and a decrease in cell thickness to $80 \text{ }\mu\text{m}$, should result in a cell with the predicted efficiency of 30% at 27°C . Efforts are continuing in these directions.

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