The Limiting Efficiency of Silicon Solar Cells under Concentrated Sunlight

PATRICK CAMPBELL AND MARTIN A. GREEN, SENIOR MEMBER, IEEE

Abstract—**The intrinsic limits on the energy conversion efficiency of silicon solar cells when used under concentrated sunlight are calculated. It is shown that Auger recombination processes are even more important under concentrated sunlight than nonconcentrated sunlight. However, light trapping can be far more effective under concentrated light due to the better defined direction of incident light. As a result of these effects, the limiting efficiency lies in the 36–37-percent range regardless of concentration ratio compared to the limiting value of 29.8 percent for a nonconcentrating cell with isotropic response.**

I. Introduction

TWO RECENT independent studies [1], [2] have shown that Auger recombination processes place the most severe intrinsic bounds on the performance of silicon solar cells under one sun operation. For a cell with an isotropic response, the upper bound on energy conversion efficiency imposed by these processes is 29.8 percent under a global AM1.5 spectrum at 28°C [2].

It is shown in the present paper that bounds imposed by Auger recombination become even more restrictive as the level of incident sunlight concentration increases. On the other hand, photovoltaic systems of any appreciable concentration ratio track the sun and use only the direct component of sunlight. Angles of incidence of sunlight on the cell in such systems become well defined and present the opportunity for very effective light trapping schemes.

Some unexpected results arise from these compensating effects. For example, it is shown that the upper bound on the efficiency of a concentrating silicon solar cell is 36–37 percent under direct-beam AM1.5 illumination irrespective of concentration ratio. A cell could reach this limit only if its thickness were optimal for the particular concentration ratio of interest and if it were designed with an acceptance angle matching the angular spread of light emerging from the concentration system.

II. Short-Circuit Current Limits

As for 1-sun cells, the short-circuit current obtainable from a concentrating cell will depend primarily on the number of photons absorbed by the material from the incident light, each ideally producing an electron-hole pair.

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The authors are with the Joint Microelectronics Research Center, University of New South Wales, Kensington, Australia 2033.

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In terms of the illuminating spectrum $S(\lambda)$, the upper bound on the short-circuit current density will be given by

$$J_{sc} = q \int_0^\infty S(\lambda) a(\lambda)\, d\lambda \tag{1}$$

where $a(\lambda)$ refers to the absorbance of the material and λ is the wavelength of light.

It has been shown [2] that a cell with an isotropic response that uses a light trapping scheme based on randomizing light internally can achieve an absorbance equal to

$$a_I(\lambda) = \alpha(\lambda) \Big/ \left[\alpha(\lambda) + \frac{1}{4n^2 W}\right] \tag{2}$$

where $\alpha(\lambda)$ is the intrinsic absorption coefficient of the cell material, n is its refractive index, and W its thickness. This shows that the effective path length of weakly absorbed light can be enhanced by a factor of up to $4n^2$ times (about 50 for silicon) [3] compared to a cell with an absorbing rear contact. For the purposes of this paper, a cell with an isotropic response is one whose response to light does not depend on the direction from which the light comes.

In concentrating systems, the light reaching the cell is not usually isotropic. Generally, the light striking the cell falls within a restricted range of angles defined by the geometry of the concentrating system. For example, Fig. 1 shows the essential details of the geometry of the Fresnel lens and cell in the Martin Marietta concentrating system [4] which was the first concentrating photovoltaic system to be deployed on a reasonably large scale [5]. It is not difficult to calculate from this geometry that all light from the lens striking the cell will be confined to an angle within 34° of the normal to the cells surface. There is, therefore, no benefit to be gained by the cell having a half-angle of acceptance θ any greater than this.

By restricting the acceptance angle of the cell, it is possible to utilize more effective light trapping schemes. It is possible in principle to increase the path length enhancement factor for weakly absorbed light from $4n^2$ to $4n^2/\sin^2 \theta$ as shown below. The ideal absorbance for a cell with a restricted acceptance angle with internal randomization of light becomes

$$a_\theta(\lambda) = \alpha(\lambda) \Big/ \left[\alpha(\lambda) + \frac{\sin^2 \theta}{4n^2 W}\right]. \tag{3}$$

Fig. 2 shows two different ways of achieving this lim-

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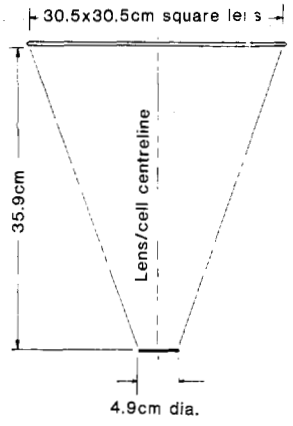

Fig. 1. Schematic diagram of the lens and solar cell geometry in a widely deployed Fresnel lens photovoltaic concentrating system.

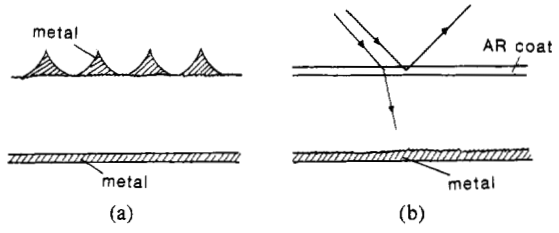

Fig. 2. Schematic diagram of two approaches that would, in principle, allow the maximum possible advantage to be taken of light trapping for directed light: (a) Cell with top contacts forming compound parabolic dishes which concentrate light onto a fraction of the cell top surface; (b) cell with antireflection coating with a directional angular response which, in the limit, couples all light within a certain acceptance angle of the normal into the cell but reflects all light outside this angle.

iting performance in principle. In Fig. 2(a), the metallization on the top surface of the cell forms compound parabolic dish reflectors [6]. These are designed to concentrate light incident over an angle of 2θ onto a fraction $\sin^2 \theta$ of the cell surface [6]. Light would equivalently be able to escape from only a fraction $\sin^2 \theta$ of the top surface. Assuming all reflectors are ideal (no reflection losses) as in the isotropic illumination cell, this provides the $1/\sin^2 \theta$ boost in light trapping performance as described by (3).

In Fig. 2(b), an alternative approach is shown whose limiting performance may be simpler to approach in practice. In this case, the cell antireflection coating is designed to have a high degree of angular selectivity so that, in the limit, all light falling within a given range of angles is accepted by the cell and all light incident outside this range is reflected (Fig. 2(b)). Since reciprocity of transmission across the interface from each direction applies, the angles of ray escape from within the cell would be correspondingly limited [3]. The escape cone [3] for a cell which reflects all light incident outside an angle θ to the normal would be identical to that which would be observed for a material of refractive index $n/\sin \theta$. This again gives the limiting absorbance of (3) for this approach.

Applying the heightened absorbance of (3) to (1), the limiting J_{sc} was computed over a range of cell thickness for a series of values of θ, under direct-beam AM1.5 sunlight [7]. The results are shown in Fig. 3. The absorption coefficient data of [8] and [9] were used at the critical wavelengths.

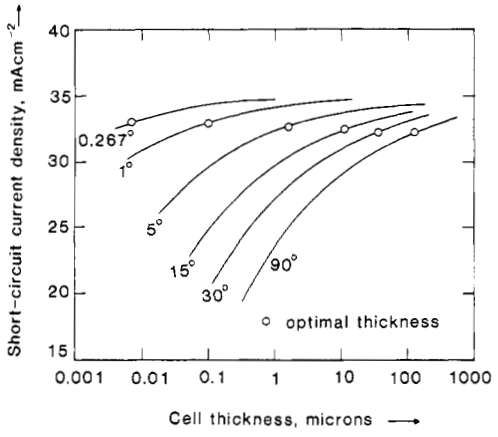

Fig. 3. Maximum cell short-circuit current density as a function of cell thickness for a range of cell acceptance angles θ calculated using (3) of the text (direct beam AM1.5 illumination, 75.2 mW · cm^{-2}).

Since the sun subtends a half-angle at the Earth's surface of 0.267°, this would be the minimum possible value of θ for a terrestrial cell. Any concentration of sunlight would increase the half-angle subtended at the cell. Hence, the curve for this value of θ corresponds to a one sun cell directly tracking the sun and using only the direct component of sunlight. At the other extreme, the maximum possible concentration of sunlight is given by $1/\sin^2 \theta$ [6], numerically equal to 46 050. For this limiting value of concentration, the cell would have to accept light incident from all angles on its top surface ($\theta = 90°$). This is equivalent to the case of a cell with isotropic response as discussed elsewhere [2].

From the above, it is obvious there is a definite relationship between concentration ratio and the cell acceptance angle. One way of expressing this relationship is that the maximum concentration ratio for which a cell of half-angle acceptance θ can be useful is given by 46 050 $\sin^2 \theta$.

III. Open-Circuit Voltage Limits

Fundamental constraints on the open-circuit voltages of silicon cells have been identified only very recently [1], [2]. Regardless of silicon doping level, the open-circuit voltages of silicon cells are limited by Auger recombination processes. Under conditions where the base of the cell remains in low injection, the open-circuit voltage limit is given by

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{J_L \operatorname{cotanh} (W_B/L_B)}{q n_i^2 \sqrt{D_B C_B}} + 1 \right) \qquad (4)$$

where kT/q is the thermal voltage, J_L is the light generated current density (equal to J_{sc} in most circumstances), W_B is the thickness of the base region of the cell, L_B is the minority-carrier diffusion length, q is the electronic charge, n_i the intrinsic carrier concentration, D_B is the relevant minority-carrier diffusion coefficient, and C_B is the rele-

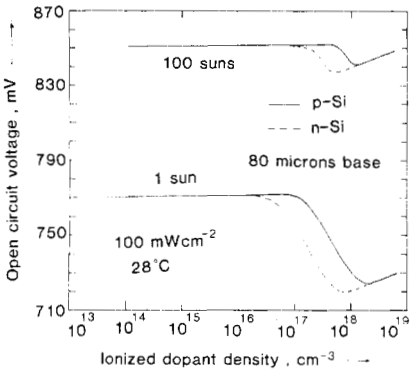

Fig. 4. Maximum possible open-circuit voltage for an 80-μm-thick silicon cell as a function of substrate doping level for illumination under both 1- and 100-suns illumination (AM1.5, 100 mW · cm^{-2}, 28°C).

vant Auger recombination coefficient, C_n for n-type material and C_p for p-type material [1].

Under high-injection conditions in the base of the cell, the voltage limit becomes [1].

$$V_{oc} = \frac{2}{3}\frac{kT}{q}\ln\left\{\frac{J_L}{qn_i^3(C_n + C_p)\,W_B}\right\}. \tag{5}$$

Between these two extremes, the open-circuit voltage is given by implicit relationships described elsewhere [1]. Both (4) and (5) show that the highest open-circuit voltages will be attained when cells are thin, provided J_L can be maintained by light trapping schemes as previously discussed. For concentrating cells, it will be shown that the limiting efficiency can only be obtained in cells thinner than about 100 μm. As an example of the constraints on open-circuit voltage imposed by Auger recombination, Fig. 4 shows the limiting value as a function of base doping level for an 80-μm-thick cell under both one sun illumination and 100-suns illumination calculated using the full implicit relationships [1].

At low doping levels, the limiting open-circuit voltage is seen to be virtually independent of doping level. This corresponds to the region where the cell is in high injection on open circuit. The open-circuit voltage limit in this region accordingly is well described by (5). As the doping level increases, a decrease in voltage is observed as the cell goes out of high injection and the open-circuit approaches that given by (4). At very high doping levels, a slight increase in open-circuit voltage is shown in Fig. 4. This occurs as a result of a decreasing D_B with doping level in (4). However, the high doping region in which this occurs is not of interest when calculating efficiency limits since even in the Auger limit, diffusion lengths are too small to allow reasonable current collection.

At doping levels of interest in calculating limiting efficiencies, the open-circuit voltage in the limit will be so large that the cell will be in high injection on open circuit. Equation (5) can therefore be used to calculate the limit on the open-circuit voltage. To reach this limiting voltage, the bulk quality of the cell has to be high and the cell surfaces have to be well passified [1]. For example, to reach the limiting open-circuit voltage for the 1-sun cell of Fig. 4, the defect determined lifetime in the bulk silicon has to be a lot larger than 1.3 ms and the surface recombination velocity has to be a lot less than 6 cm/s [1], assuming no increase in doping concentration near cell surfaces. For the 100-sun cells, the requirements become far less severe. The corresponding lifetime figure reduces to 60 μs while the recombination velocity figure increases to 130 cm/s. This indicates that, despite the fact that the constraints imposed by Auger recombination were first identified for one sun cells [1], [2], these constraints are likely to become apparent at the earliest point in time for concentrating cells.

IV. Fill Factor Limits

The ideal value of the fill factor of a solar cell can be approximated by the following expression in the absence of parasitic series or shunt resistance [10]:

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \tag{6}$$

where v_{oc} is the normalized value of the open-circuit voltage given by $V_{oc}/(\gamma kT/q)$ where γ is the ideality factor of the cell. For cells limited by Auger recombination, the ideality factor approaches a value of $\frac{2}{3}$ under high-injection conditions [1], [2]. Hence, using (6) with $\gamma = \frac{2}{3}$ will allow the upper bound on the cell fill factor to be found.

For concentrating cells operating in high injection, fill factors can be significantly less than ideal due to the loss of conductivity modulation near the maximum power point [11]. For cells operating near the Auger limit, this problem is considerably reduced because of the high carrier concentrations resulting from the high operating voltages which are attained. For concentration ratios such as used in any practical system to date, loss of conductivity modulation will not be a problem in the Auger limit. However, for some of the very high concentration ratios theoretically obtainable, this will not be the case.

The conductivity modulation loss mechanism is difficult to treat analytically because of the nonlinearities involved. A numerical approach is used in [11]. In the present paper, a relatively simple analysis will be used to identify regions where it becomes physically impossible to attain the fill factor bound of (6) and the upper bounds on efficiency calculated using it become unduly optimistic.

Loss of conductivity modulation will not be a problem if there is negligible ohmic voltage drop across the bulk regions of the cell. If this is the case, the carrier concentrations at the maximum power point will be given by (e.g., see [1])

$$n = p = n_i \exp(q \cdot V_{mp}/2kT) \tag{7}$$

where V_{mp} is the voltage at the maximum power point. The magnitude of the ohmic voltage drop across the bulk regions, if small, will be given by

$$\Delta V = \frac{J_{mp} W_B}{q(\mu_n + \mu_p)\,n} \tag{8}$$

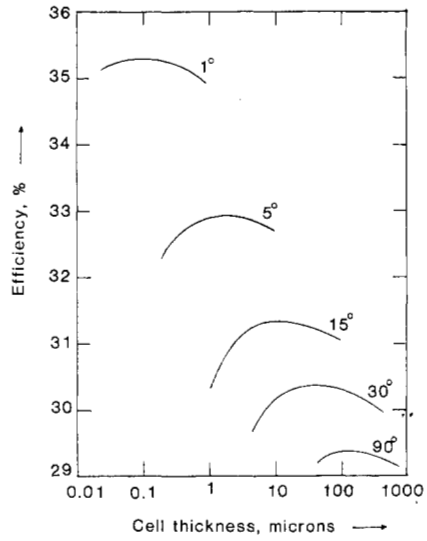

Fig. 5. Maximum possible silicon solar cell efficiency under 1-sun illumination as a function of cell thickness for a range of cell acceptance angles (direct beam AM1.5 illumination, 28°C).

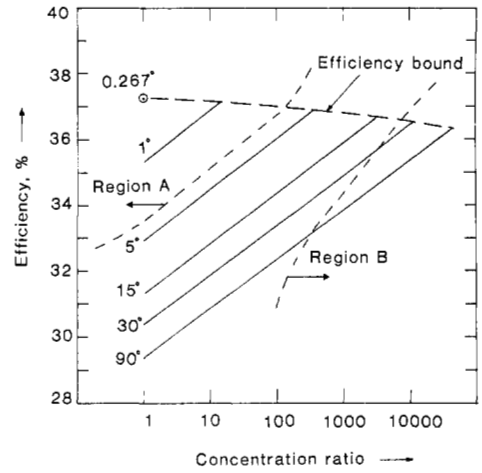

Fig. 6. Limiting silicon solar cell efficiency as a function of concentration ratio for different cell acceptance angles (direct beam AM1.5 illumination, 75.2 mW · cm^{-2}, 28°C). In region *A* at low concentration levels, cells have to be below 1 μm in thickness to achieve the performance levels shown. This gives rise to practical problems as well as problems with the present formulation. In region *B*, ohmic voltage drops in bulk regions become larger than 5 mV and the ratio of diffusion length to cell thickness becomes less than 3. The efficiency limits shown in this region therefore are not attainable, even in principle.

where J_{mp} is the current density at the maximum power point. Provided the voltage drop given by (8) is small ($<< kT/q$), the device should perform ideally and the fill factor bound is obtainable in principle. If this voltage drop is large, the fill factor bound is not obtainable in principle and loss of conductivity modulation might result in very poor fill factor. J_{mp} and V_{mp} in (7) and (8) can be related to J_{sc} and V_{oc} by [10]

$$V_{oc} = V_{mp} + \frac{\gamma kT}{q} \ln [V_{mp}/(\gamma kT/q) + 1] \quad (9)$$

$$J_{sc} = J_{mp}(V_{mp} + \gamma kT/q)/V_{mp}. \quad (10)$$

V. Efficiency Limits

As described by (3), absorbance will increase with cell thickness for any given acceptance angle θ as will J_{sc}, as expected. At the same time, the open-circuit voltage and fill factor will decrease as given by (5) and (6), respectively. These competing effects will lead to an optimal cell thickness for any value of θ. The computed dependencies are shown in Fig. 5.

Because of the improved light trapping possible at small acceptance angle, the optimum cell thickness decreases as the acceptance angle decreases. The optimum thickness decreases from 130 μm to less than 1 μm as the acceptance angle decreases from 90° (isotropic response) to below 5°. The optimum efficiency and thickness for a cell with an isotropic response under one sun illumination (29.4 percent and 130 μm) differ slightly from the values calculated elsewhere [2] (29.8 percent and 100 μm) due to the different solar spectrum used in the calculation (direct beam rather than global since concentrating systems are of present interest).

The calculations for cell thickness less than 1 μm are included to indicate trends. Apart from practical problems in fabricating cells of this thickness with present technology and in maintaining the increasingly severe demands placed on the reflective properties of the interfaces, the absorbance will differ from that given by (3) once the wavelength of light in silicon becomes comparable to cell thickness [2].

Repeating the calculations of Fig. 5 for different concentration ratios allows Fig. 6 to be prepared, which shows the maximum possible silicon cell efficiency as a function of concentration ratio and the cell acceptance angle. An interesting and unexpected result of these calculations is that the limiting value of cell efficiency is virtually independent of concentration ratio, lying close to 37 percent regardless of this ratio.

This is in contrast to the normal experience whereby, provided series resistance effects are negligible, the efficiency of a cell will increase with increasing concentration ratio. The difference is that, in the present case, cell design is optimized for acceptance angle and thickness for any particular concentration ratio desired.

The parameters of the cells giving maximum possible performance can be estimated by noting from Fig. 5 that the ratio of optimum thickness W_{opt} to $\sin^2 \theta$ varies only slowly as θ varies, lying in the range 100–400 μm. From Section II, a cell with θ matching the angular spread of radiation will permit a maximum possible concentration ratio of 46 050 $\sin^2 \theta$. The highest possible cell performance will arise at this concentration ratio (C_m).

At this concentration, an optimally thick cell will develop an open-circuit voltage equal to

$$V_{oc} = \frac{2kT}{3q} \ln \left(\frac{J_{sc1} C_m}{qn_i^3 (C_n + C_p) W_{opt}} \right) \quad (11)$$

where J_{sc1} is the short-circuit current density under one sun illumination (~32.5 mA/cm^2). Substituting numerical values gives a value of V_{oc} at the optimum of between

920 and 950 mV regardless of concentration ratio. The limiting efficiency is given by

$$\eta = \frac{C_m J_{sc} V_{oc} FF}{C_m P_{in}} \tag{12}$$

where P_{in} is the input power density (75.2 mW · cm^{-2} for the present direct-beam spectrum). Substituting values gives an efficiency between 36 and 37 percent regardless of concentration ratio, in agreement with the more detailed calculations of Fig. 6.

Also shown in Fig. 6 are regions at low and high concentration where the previous theory is not strictly valid. At low concentration levels (Region *A*), this arises because of the extremely thin cells (< 1 μm) required to reach optimum performance. Besides practical difficulties with such cells, interference effects will require modifications to the form of (3). At large concentration ratios (Region *B*), resistive drops in the bulk of the cell due to insufficient conductivity modulation will cause fill factors and hence efficiencies to be inherently incapable of reaching the limits described. This effect will be compounded by the reduced value of diffusion length relative to cell thickness at high concentration ratio. In Region *B*, this ratio becomes less than 3. The present analysis will become increasingly less accurate as this region is entered, although the results shown will remain conservative.

The performance advantage of silicon concentrating cells is the limit over a nonconcentrating cell with isotropic response arises from an open-circuit voltage advantage. This latter arises from a combination of higher short-circuit current levels and reduced cell thickness as a result of the more effective light trapping which becomes possible under concentration. As is normal when specifying concentrator cell efficiency, no account is taken in the previous calculations of the fact that concentrating systems are inherently incapable of using the indirect component of sunlight at reasonable concentration levels. The effect of this inefficiency is normally incorporated at the system level in the geographically dependent factor, which relates annual energy generation to the nameplate power rating of the system.

VI. Practical System

As an example of the features of a cell of limiting performance, idealized cell design for the practical system of Fig. 1 will be considered. The nominal concentration ratio of the Fresnel lens is 50 and the maximum angle from the normal of any ray from the lens striking the cell is 34°. Hence, this is the acceptance angle required for the cell. In principle, a concentrating system of this concentration ratio could be designed requiring a cell with an acceptance angle of only a few degrees. In the present case, this would require redesign of the Fresnel lens so that it could be placed further from the cell (with practical consequences such as the need for larger housings).

With 34° acceptance angle, the optimum cell thickness can be estimated from Fig. 5 as 50 μm. The limiting open-circuit voltage, fill factor short-circuit current density, and efficiency of this cell would be 841 mV, 0.901, 1.625A · cm^{-2} and 32.8 percent. To approach this limiting performance, several criteria would have to be satisfied. Within the range of acceptance angles, transmission of light into the cell would have to be high (> 99 percent). Outside this acceptance angle, reflectivity would have to be high (> 99 percent) for the scheme of Fig. 2(b). Reflectivity from the rear surface reflector would also have to be similarly high. If the above conditions are not satisfied, current output will be somewhat less than given above.

To reach the voltage limits, the lifetime due to bulk defects has to satisfy the following [1]:

$$\tau_{\text{def}} >> \left[\frac{q^2 W^2}{J^2(C_n + C_p)}\right]^{1/3}. \tag{13}$$

In this present case, it has to be a lot greater than 86 μs. At the cell surfaces, without any highly doped region near the surface, the surface recombination velocity has to satisfy [1]:

$$S << (J^2(C_n + C_p)\, W/q^2)^{1/3}. \tag{14}$$

In the present case, it has to be a lot less than 60 cm/s. If a heavily doped region lies near the surface, the corresponding condition becomes [1]

$$S << N_s^+ (J(C_n + C_p)^2\, W^2/q)^{1/3}$$

where N_s^+ is the effective density of ionized dopants at the surface. For a doping level near the surface of 10^{20} cm^{-3}, the recombination velocity has to be a lot less than 3×10^4 cm/s. The bulk doping level has to be less than 5×10^{16} cm^{-3} to ensure high injection is reached at the maximum power point. All of the above conditions would appear to be adequately met by present technology. At such operating voltages, there is sufficient conductivity modulation to restrict bulk ohmic drops to less than 1 mV.

VII. Conclusion

Two major conclusions arise from this work. The first is that Auger recombination imposes even more severe intrinsic bounds on the open-circuit voltage of concentrating silicon cells than is the case for one sun cells. Material and surface passivation quality required to reach these intrinsic voltage limits are within the scope of present technology.

The second major conclusion relates to the enhanced effectiveness of light trapping schemes which is possible in concentrating cells. Because concentrating systems of any appreciable concentration ratio track the sun and use the direct component of sunlight only, the angle of incidence of light upon concentrating cells is well defined. This allows a boost in the effectiveness of light trapping schemes by a factor as large as $1/\sin^2\theta$ where θ is the acceptance half-angle required by the cell. Peak performance is obtained in thinner cells than optimal for nonconcentrating applications. Two schemes are described for the first time which, in principle, allow full advantage to

be taken of light trapping in cells directionally illuminated.

The combination of the above effects produces an unexpected result. The upper limit on the efficiency of a concentrating silicon solar cell lies in the range 36–37 percent independent of concentration ratio. To reach this limiting efficiency, the cell must have minimum possible acceptance angle for any given concentration ratio and be of an optimal thickness.

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Patrick Campbell was born in Sydney, Australia, in 1950. He received the combined B.Sc. and B.E. degree in 1974 from the University of New South Wales. He is currently working toward the Ph.D. degree at the Joint Microelectronics Research Center, University of New South Wales. His dissertation concerns solar cells.

In 1982, he started working with the Solar Energy Group in the School of Physics at the University of New South Wales, where he has worked on the development of solar thermal concentrating systems.

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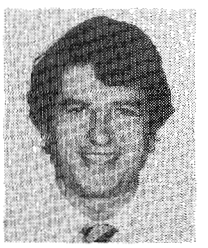

Martin A. Green (SM'81) was born in Brisbane, Australia, in 1948. He received the B.E. and M.Eng.Sc. degrees from the University of Queensland in 1969 and 1971, respectively, and the Ph.D. degree from McMaster University, Canada, in 1974.

In the same year, he joined the University of New South Wales, where he is currently an Associate Professor in the School of Electrical Engineering and Computer Science and Associate Director of the Joint Microelectronics Research Center established under the Commonwealth Research Centers of Excellence Program. He has spent shorter periods at the AWA Microelectronics Laboratory, Sydney; the Hitachi Central Research Laboratories, Tokyo; the University of Leuven, Belgium; and the Solar Energy Research Institute, Colorado. His research interests lie in the areas of silicon solar cells, ultraviolet and infrared photodetectors, and improved bipolar transistor design. He is author of the recently published textbook *Solar Cells: Operating Principles, Technology and System Applications.*

Dr. Green was awarded in 1981 the Pawsey Medal by the Australian Academy of Science and the Edgeworth David Medal by the Royal Society of New South Wales for his research work on tunneling metal-insulator-semi-conductor contacts. This work has led to the development of high-efficiency silicon solar cells and super-gain bipolar transistors.