

TWO-DIMENSIONAL ANALYSIS OF THE INTERDIGITED BACK-CONTACT SOLAR CELL

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Abstract—Using two-dimensional computer analysis, the interdigitated back contact silicon solar cell (IBC) was analyzed at high illumination levels and the results were compared with the conventional Front Junction cell. The change of effectiveness of Chockley-Read-Hall bulk and surface recombination centers at high currents as well as the induced internal electric field are argued to explain the improved efficiency predicted for IBC cells at high illumination levels. For a $100\text{ }\mu\text{m}$ cell thickness and lifetime $\tau_{p0} = 10\text{ }\mu\text{sec}$ the efficiency is indicated to increase from 7.5% at 1 sun to 14.0% at 100 suns AMO, when a surface recombination velocity (s_0) equal to 1000 cm/sec is assumed. The substrate thickness to provide maximum efficiency was found to be approximately $50\text{ }\mu\text{m}$. It is confirmed that the surface lifetime is a significant factor in determining the device conversion efficiency. Since surface recombination dominates the efficiency, a new IBC cell design with a front doping gradient has been introduced to suppress the surface recombination. The IBC cell with $10^{18}/\text{cm}^3$ front surface n^+ -doping concentration is optimum for an impurity diffusion depth of $10\text{ }\mu\text{m}$, $s_0 = 1000\text{ cm/sec}$, $\tau_{p0} = 10\text{ }\mu\text{sec}$, for which an efficiency of 12% is computed at 1 sun AMO. A useful efficiency of about 8% at 1 sun AMO, even with $s_0 = 10^5\text{ cm/sec}$, is predicted with front doping.

1. INTRODUCTION

As long as the cost of light concentrators is cheaper than solar cells, the trend is to use concentrators and cells which operate efficiently at high intensity of illumination rather than using large areas of solar cells. However the conventional Front Junction solar cell at high light intensity faces serious limitations in efficiency because the large collected current causes a significant voltage drop across the upper layer series resistance, which reduces the output voltage at a given current[1]. On the contrary, the interdigitated back contact solar cell is known to have less series resistance and large bulk lifetime because of its relatively lightly-doped bulk region. This structure of p^+-i-n^+ solar cell is expected to achieve nearly maximum theoretical efficiency at high intensity of illumination[2]. However a two-dimensional analysis of this structure has theretofore not been reported.

Recent work by Dunbar and Hauser[3] has employed numerical techniques to solve the one-dimensional ambipolar current flow equations for the conventional solar cell. The two-dimensional and temperature-dependent analysis of the conventional solar cell has also been reported[1]. By applying the two-dimensional numerical techniques developed by Spaderna[1], this study is aimed at investigating the behavior of the IBC solar cell structure under high illumination levels. The effects of cell geometry and surface recombination on efficiency are considered. The IBC cell with a doping gradient at the front surface is also analyzed.

2. THEORY AND NUMERICAL METHOD OF SOLUTION

The geometry (Fig. 1) for this two-dimensional computer calculation is based on the interdigitated back con-

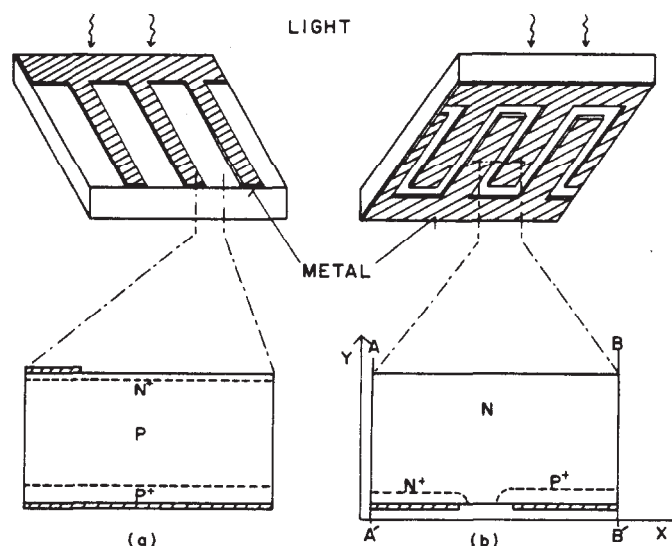


Fig. 1. (a) Front-junction solar cell structure. (b) Interdigitated back-contact solar cell structure.

tact solar cell fabricated by Schwartz[2]. Two metal contacts are formed on n^+ - and p^+ -regions at the back surface, and the doping profiles assumed are the complementary error function. The bulk n -type doping is taken as $3 \times 10^{14}/\text{cm}^3$. Boundary conditions are used to couple the unit segment to the rest of the whole solar cell by applying the symmetry property along the lines $A-A'$ and $B-B'$ in Fig. 1. On the front surface the boundary conditions of no electric field in y -direction and no current out of the model are interpreted by the equivalent numerical boundary conditions. The effect of an electric field at the surface due to band bending and surface charges is crudely considered to be a component of the surface recombination velocity chosen. A numerical scheme for the surface recombination is introduced by assuming Shockley-Read-Hall-type recombination centers located just beneath the front surface. The effect of bandgap shrinkage due to heavy doping is added as an additional quasielectric field by interpolating graphically the curve by Mock[4], as well as by the introduction of a doping-dependent intrinsic carrier concentration[5]. For heavy doping the latter increases the equilibrium minority carrier concentration by orders of magnitude.

The carrier flow equations for the steady-state in a semiconductor are given by[6]

$$\nabla \cdot \mathbf{J}_p = -q(R - G), \quad (1)$$

$$\nabla \cdot \mathbf{J}_n = +q(R - G), \quad (2)$$

$$\nabla^2 \psi = -\frac{q}{\epsilon}(p - n + N), \quad (3)$$

where eqns (1) and (2) are the steady-state continuity equations for holes and electrons respectively, and (3) is Poisson's equation for the electric potential ψ . P and n are hole and electron carrier densities, N is the net ionized impurity concentration, and R and G refer the net recombination and the photogeneration rate respectively. The expressions for hole and electron current densities are given as

$$\mathbf{J}_p = -q\mu_p p \nabla \psi - qD_p \nabla p = -q\mu_p p \nabla \phi_p, \quad (4)$$

and

$$\mathbf{J}_n = -q\mu_n n \nabla \psi + qD_n \nabla n = -q\mu_n n \nabla \phi_n. \quad (5)$$

Here the drift term should be understood to include the effect of the quasi-field due to bandgap narrowing in the regions of a heavy doping gradient. The assumption of Boltzmann statistics and the Einstein relations allows the definition of the quasi-Fermi potentials for holes and electrons, ϕ_p and ϕ_n . The lack of maturity of the treatment of degeneracy and deionization due to heavy doping induced us to assume the classical statistics.

The mobilities μ_p and μ_n for holes and electrons are given as updated by Li *et al.*[7,8]. Their results are for majority carriers, but they are also assumed valid for minority carriers. The mixed mobility μ_{LI} of lattice and

impurity scattering reads

$$\mu_{LI} = \mu_L f(x), \quad (6)$$

where $f(x)$ is a mixing function of the lattice and the impurity scattering mobilities. However the lattice scattering mobility as given is not convenient to use in computer work because it is given in table form. An accurate empirical expression[9] though is available for the lattice mobility. (It is assumed that all impurities are ionized at room temperature and neutral impurity scattering is neglected.) The carrier-carrier scattering effect, important at carrier densities in excess at $10^{17}/\text{cm}^3$, is included as reported by Howard[10] in a p^+-i-n^+ diode study. The final expression for the mobility, μ , ends up as

$$\frac{1}{\mu} = \frac{1}{\mu_{LI}} + \frac{1}{\mu_{cc}}, \quad (7)$$

where μ_{cc} is the carrier-carrier scattering mobility.

The recombination process in bulk (R_{bulk}) includes the Shockley-Read-Hall (SRH) model via trapping centers and Auger band-to-band recombination. However the surface recombination (R_{surt}) may control the whole device characteristics because of the large front surface of the IBC cell and relatively thin wafer compared to the bulk life-distance of minority carriers. These recombination rates are given by

$$R_{\text{bulk}} = \frac{pn - n_i^2}{\tau_{p0}(n + n_i) + \tau_{n0}(p + n_i)} + \Gamma n(pn - n_i^2), \quad (8)$$

$$R_{\text{surt}} = s_0 \frac{pn - n_i^2}{(n + n_i) + (p + n_i)}, \quad (9)$$

where τ_{p0} and τ_{n0} are lifetime parameters, and Γ is the Auger coefficient taken from [11]. The bulk lifetime parameter $\tau_{n0} = 3\tau_{p0}$ is assumed and the recombination center level is taken as at the intrinsic Fermi level. The surface capture crosssections for electrons and holes are assumed equal and s_0 is the surface recombination velocity[12].

The electron-hole generation rate for any spectrum of light, and at a distance y from a semiconductor front surface is given by the equation

$$G(y) = \int \phi_{ph}(\lambda) \alpha(\lambda) \exp[-\alpha(\lambda)y] d\lambda, \quad (10)$$

where $\alpha(\lambda)$ is the absorption coefficient, and $\phi_{ph}(\lambda)$ is the incident photon flux. Using the absorption coefficient for silicon as measured by Dash and Newman[13] with the additional data of Phillip and Taft[14], and the solar spectrum data (air mass zero) by Thekaekara[15], the function $G(y)$ has been calculated.

The conventional finite difference method with successive line over-relaxation (SLOR) is used to solve the three fundamental eqns (1)–(3), numerically simultaneously. The segment shown in Fig. 2, by symmetry, when replicated, will reproduce the entire cell shown in

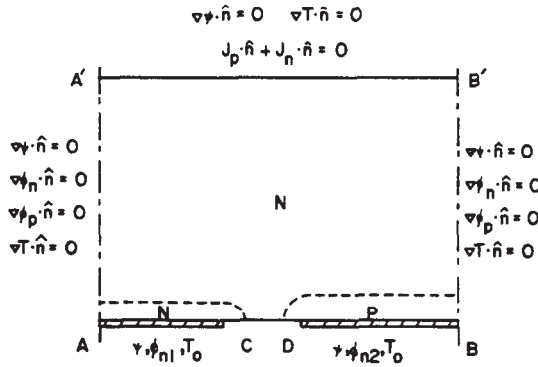


Fig. 2. A section of the IBC solar cell structure showing specifications of boundary conditions.

Fig. 1(b). It is assumed that in the semiconductor n^+ and p^+ regions, at the surface just under the metal ohmic contacts AC and DB that carrier equilibrium prevails, i.e. $\phi_p = \phi_n$. (An alternative way of imposing this boundary condition is to assume a large surface recombination velocity, s_0 , in these places.) Since no current can pass through the remainder of the upper and lower surfaces ($A'B'$ and CD), there $(J_p + J_n) \cdot \hat{n} = 0$ where $\hat{n}$ is the unit normal to these surfaces; by symmetry considerations this must also be true at the boundaries AA' and BB' . Since the electric field at these latter surfaces must all be zero, $\nabla\psi \cdot \hat{n} = 0$ there. Electric potentials are specified at the metal contacts and hence at the semiconductor surface just under these contacts. No light reflection from the front surface is assumed.

3. RESULTS

3.1 Current flow in the IBC cell

Figure 3 shows the calculated current flow lines as well as the electrical equipotential contours for a silicon IBC cell structure (Fig. 2) operating at 100 suns AMO illumination, under short-circuit conditions, with an assumed surface recombination velocity of 1000 cm/sec,

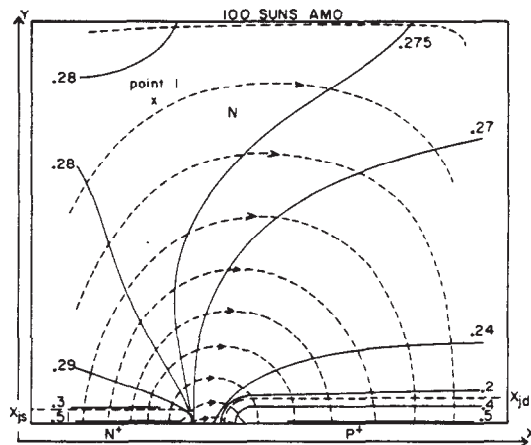


Fig. 3. The current flow lines (dotted) and electric equipotential contours (solid) for a silicon IBC cell operating at 100 suns AMO, 300°K, under short-circuit conditions. Each current line represents about 5 ma/cm, $\tau_{p0} = \tau_{n0}/3 = 10 \mu\text{sec}$, thickness = 199 μm , width = 117 μm , $x_{js} = 3.2 \mu\text{m}$, $x_{jd} = 6.3 \mu\text{m}$.

at 300°K. Note the lack of orthogonality of the current flow lines and equipotentials, except near the junctions. This indicates that the electrical carriers move both due to diffusion plus some drift field in the bulk of the device (see eqns 4 and 5). Figure 4 graphs the minority hole carrier flow lines as well as the quasi-Fermi contours under the same conditions as Fig. 3. The mutual orthogonality of these contours results from the requirements of eqns (4) and (5).

Current crowding is noticed near the edges of metal contacts as shown in Figs. 3 and 4. The hole carriers are focused to the p^+ -contact corner. Electron carriers are correspondingly concentrated at the n^+ -contact corner. The cell series resistance will be increased by this current crowding under very high illumination levels, reducing the efficiency. However the fill factor (FF) computed remains almost the same from 1 sun AMO ($FF = 0.79$) to 100 suns AMO ($FF = 0.75$) with $s_0 = 1000 \text{ cm/sec}$ and $\tau_{p0} = 10 \mu\text{sec}$.

A small internal electric field is induced in the uniformly doped n -region due to the difference of mobility of hole and electron carriers. This electric field aids the collection of holes by the p^+ - n junction, increasingly as the illumination intensity is increased and results in improved cell conversion efficiency. Table 1 quantifies this effect.

3.2 The effect of recombination on efficiency

Some of the photo-generated carriers recombine through SRH, Auger and surface recombination mechanisms prior to junction collection, whence they contribute to the output current. The SRH recombination rate given by eqn (8) is reduced to p/τ_{p0} in an n -type semiconductor at a low level injection ($pn \gg n_i^2$, and $p \ll n$). At a high level injection ($pn \gg n_i^2$, and $p \sim n$), the formula approaches to $p/(\tau_{p0} + \tau_{n0})$, which is a smaller value than that of the low injection. Hence SRH recombination increases with a decreasing rate as the intensity of light increases. The surface recombination of eqn (9) behaves similarly. It approaches $s_0 p/2$ at high level in-

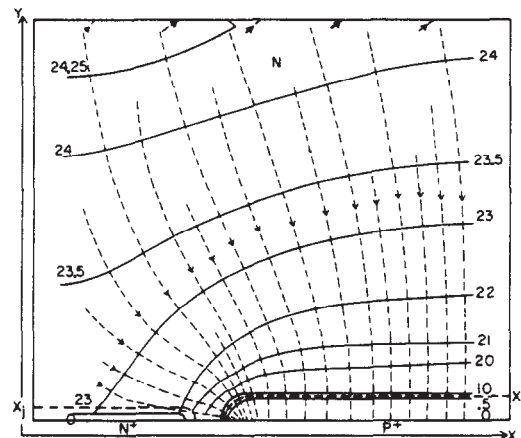


Fig. 4. The quasi-Fermi potential contours for holes (solid) and the hole current flow lines (dotted) are shown for the IBC cell operating under the same conditions as in Fig. 3. The quasi-Fermi potentials are indicated in units of kT/q . Each current flow line represents 2.5 ma/cm.

Table I. The induced electric field and the carrier drift and diffusion current components at one point in the n -region (point 1 in Fig. 3) under various illumination levels (F and C represent field and current, L , illumination level).

F & C L	Induced electric field (V/cm)	Drift Current (mA/cm ²)		Diffusion current (mA/cm ²)	
		electron	hole	electron	hole
1 sun	0.44	27.4	1.5	47.9	20.6
10 suns	1.15	240.	39.	485.	207.
100 suns	1.92	3049.	1261.	5000.	2148.

jection, which is a half of the low injection value. The induced electric field in the uniformly doped n -region separates holes and electrons and reduces the recombination rate even more. The enhanced electric field also increases the drift current component in the n -region, which increases the short circuit current at higher illumination levels (see Table I). Computer calculations show that the collection efficiency increases from 55.6% at 1 sun to 75.5% at 100 suns AMO. The improved collection efficiency increases the short circuit current as the light intensity increases. As long as SRH and surface recombination control the short circuit current and the fill factor remains almost unchanged, the overall energy conversion efficiency is increased at higher illumination levels.

The efficiency as a function of illumination level is plotted in Fig. 5 with surface recombination velocity as a parameter. The IBC cell with thickness $100\ \mu\text{m}$, $\tau_{p0} = 10\ \mu\text{sec}$ and $s_0 = 1000\ \text{cm/sec}$ is computed to achieve about 7.5% efficiency at 1 sun, 11.4% at 10 suns and 14.0% at 100 suns AMO. On the contrary, the efficiency of the conventional front junction cell was reported to decrease [1] with increased illumination as shown in Fig. 5. Although the conventional cell used for comparison here was not optimized for high level illumination, results indicate this is a general trend.

The short circuit current is strongly affected by surface recombination since the diffusion length of minority carrier ($\tau_{p0} = 10\ \mu\text{sec}$) for the present model is comparable with the thickness of the cell ($100\ \mu\text{m}$). What happens with high s_0 is that the generated carriers are forced to diffuse into the surface recombination centers instead

of being collected by the junctions. The current near the front surface is seen to be directed toward the front surface within a few μm of the surface. The effect of the surface recombination is to reduce the conversion efficiency from 7.5% at $s_0 = 10^3\ \text{cm/sec}$ to 1.0% at $10^5\ \text{cm/sec}$, as shown in Fig. 6. Figure 6 also shows the ratios of the total surface recombination to the total generation vs s_0 . 32 and 89% of the total generated carriers are recombined at the front surface when $s_0 = 10^3\ \text{cm/sec}$ and $10^5\ \text{cm/sec}$ respectively. Typical current-voltage (I-V) characteristics calculated for this cell vs illumination intensity is shown in Fig. 7, with the current given per unit incident sun.

3.3 The effect of cell thickness

The effect of thickness on IBC cell performance is plotted only at 1 sun AMO and $s_0 = 1000\ \text{cm/sec}$ (see Fig. 8). However similar behavior is found at different levels of illumination and different s_0 values.

Since some of the photons with lower energy pass through a solar cell with a finite thickness without being absorbed, more carriers can be generated in a thicker cell. However the average distance for the generated carriers to travel to the collecting junction becomes larger, which reduces the collection efficiency. Hence there is an optimum cell thickness.

The total generation rate for a cell with thickness $200\ \mu\text{m}$ is increased 140% above that of a cell $10\ \mu\text{m}$ thick. The collection efficiency decreases monotonically with thickness from 85.9% at $10\ \mu\text{m}$ to 31.5% at $200\ \mu\text{m}$ (see Fig. 8). The energy conversion efficiency calculated

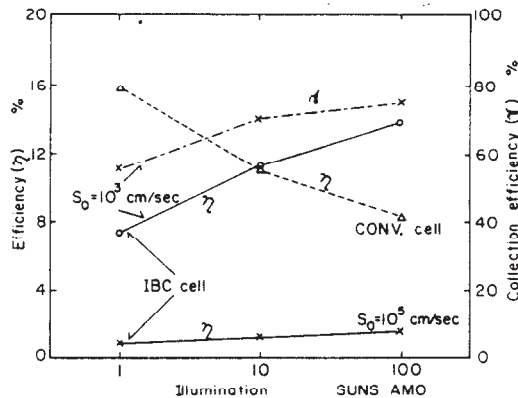


Fig. 5. The energy conversion efficiency and the collection efficiency of the silicon IBC cell vs illumination intensity. The conversion efficiency of the IBC cell increases with increasing illumination, whereas the front-junction cell efficiency decreases.

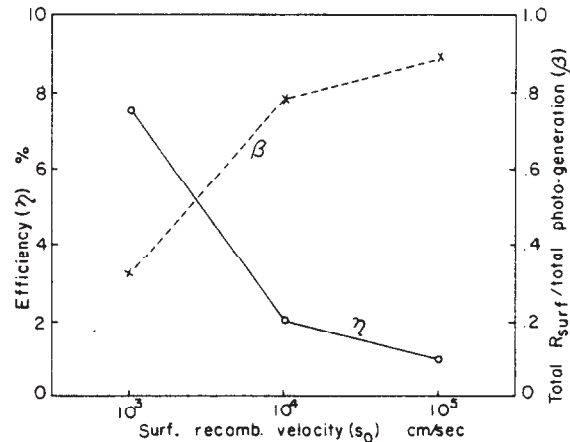


Fig. 6. The ratio of the total surface recombination rate to the total photogeneration rate, and the cell conversion efficiency vs surface recombination velocity at 1 sun AMO.

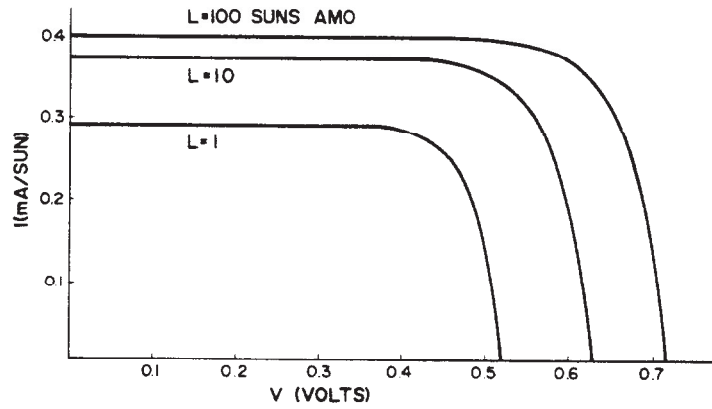


Fig. 7. Typical I-V characteristics for an IBC cell under concentrated illumination, computed for $\tau_{p0} = \tau_{n0}/3 = 10 \mu\text{sec}$, $s_0 = 1000 \text{ cm/sec}$, thickness = $100 \mu\text{m}$. The current is normalized to 1 sun.

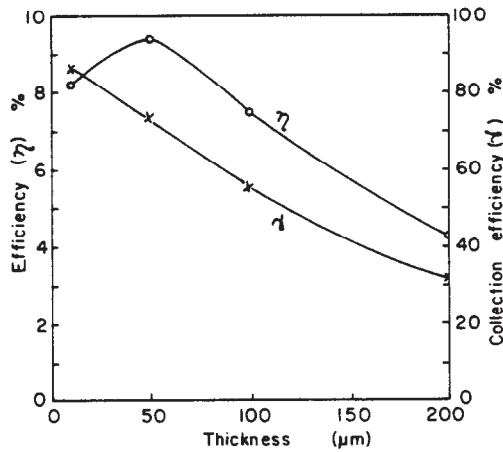


Fig. 8. The IBC cell conversion efficiency and the collection efficiency vs cell thickness. The maximum efficiency is predicted to occur at a cell thickness of $50 \mu\text{m}$, at 1 sun AMO, $s_0 = 1000 \text{ cm/sec}$, $\tau_{p0} = 10 \text{ sec}$.

from the above factors is illustrated in the Fig. 8. The maximum efficiency of about 9.4% is achieved by the cell with thickness around $50 \mu\text{m}$, for $\tau_{p0} = 10 \mu\text{sec}$. If the effective lifetime is scaled upward by a factor of 25, this optimum thickness may increase as much as 5 times.

3.4 The front doping gradient effect

The front n^+ -doped IBC cell is designed with a doping gradient penetrating below the front surface as shown in Fig. 9, otherwise keeping all same device parameters as the uniformly doped IBC cell. The front surface n^+ -profile is assumed to follow a complementary error function. A front junction depth of $10 \mu\text{m}$ is assumed. As suggested [17], the doping gradient at the front surface tends to suppress the surface recombination. The potential gradient established by the doping gradient pushes minority carrier holes away from the front surface. That is the doping gradient separates holes and electrons near the surface, which decreases the surface recombination rate. The total recombination and the surface recombination initially decreased with increased front doping concentrations up to $10^{18}/\text{cm}^3$ at 1 sun AMO and $s_0 = 10^3 \text{ cm/sec}$.

At uniform doping (marked as C_{BB} in Fig. 9), the surface recombination is 32% of the total generation. But

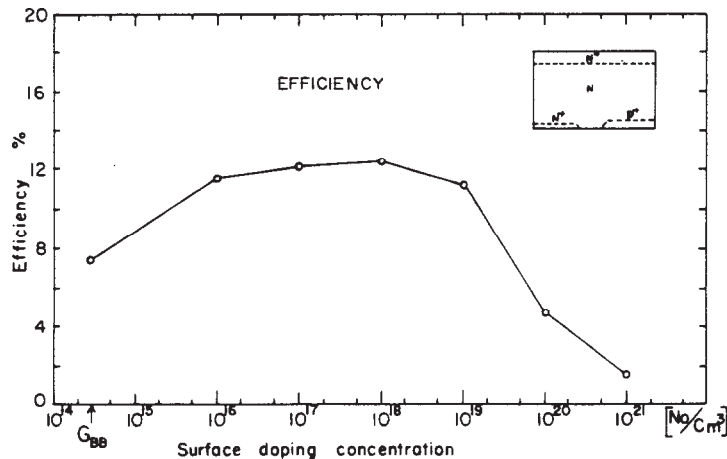


Fig. 9. The conversion efficiency of a front doping gradient IBC cell vs surface doping concentration showing that the optimum surface doping is about $10^{18}/\text{cm}^3$, at 1 sun AMO, $s_0 = 1000 \text{ cm/sec}$.

it drops quickly to 3.8% even with a small front surface doping concentration of $10^{16}/\text{cm}^3$. Although the surface recombination at first decreases monotonically with increasing front doping concentration, the total recombination rises again at concentrations above $10^{18}/\text{cm}^3$ because of the increased Auger recombination in the front doped region. The Auger recombination increases to 75% of the total generation at $10^{21}/\text{cm}^3$ front doping concentration. There must be an optimum front surface concentration, which is computed to be near $10^{18}/\text{cm}^3$ as seen in Fig. 9. A 12.2% efficiency is predicted even at 1 sun AMO. Using this concentration ($10^{18}/\text{cm}^3$), the efficiency vs the illumination level is plotted in Fig. 10, for $s_0 = 10^3$ and 10^5 cm/sec.

Since the majority carriers are so numerous in the doped front n^+ -region, there no longer exists high level injection even at 100 suns AMO in the front surface n^+ -region. The effective lifetime near the surface is hence almost independent of the illumination level. But the bulk of lightly doped n -region still remains in the high level injection, where the recombination rate decreases with increasing illumination level. For $s_0 = 1000$ cm/sec, the surface recombination is negligible compared to the bulk recombination and Auger recombination, so the efficiency continues to increase. However the controlling factor is surface recombination when $s_0 = 10^5$ cm/sec. The ratio of surface recombination to the total generation increases from 10 to 100 suns AMO. The effective lifetime near surface is reduced so much due to the heavy doping that the collection efficiency is not improved even at 100 suns AMO. Consequently the efficiency with $s_0 = 10^5$ cm/sec drops somewhat as shown in Fig. 10.

The most noticeable point about the IBC cell with the front doping gradient is that it achieves a useful efficiency of about 8% even with 1 sun AMO, $s_0 = 10^5$ cm/sec, while the IBC cell with uniform doping manages only a low efficiency of 1.0% as shown in Fig. 10. This factor should be considered when long term surface stability and cell reliability is considered.

4. CONCLUSION

The energy conversion efficiency is predicted to increase at the higher illumination levels because of the improved collection efficiency due to the decreased SRH and surface recombination rates and an induced electric field. Computations for a given design predict that for $\tau_{p0} = 10 \mu\text{sec}$ the efficiency will increase from 7.5% at 1 sun to 14.0% at 100 suns AMO. For a thinner cell the collection efficiency increases but the total photogeneration decreases, so that the maximum efficiency is at a thickness of about 50 μm . This optimum thickness will increase with lifetime increase. The surface recombination which controls the efficiency of an IBC cell with

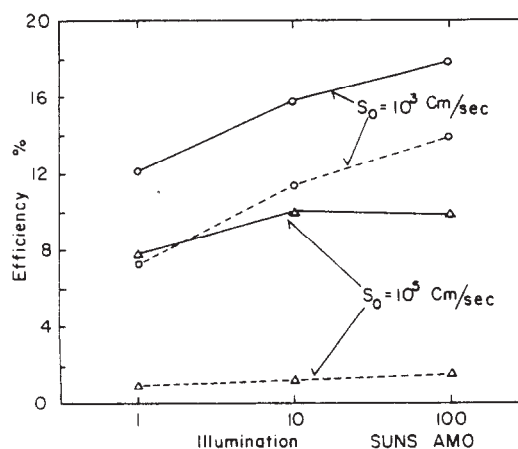


Fig. 10. The conversion efficiency of the silicon IBC cell with (solid) or without (dotted) a front doping gradient vs illumination level. The front doping gradient design is predicted to be less sensitive to surface recombination.

uniform doping can be partly suppressed by providing an n^+ doping gradient at the front surface. However Auger recombination takes over lifetime control at very heavy front doping ($\geq 10^{20}/\text{cm}^3$), and the optimum n^+ doping concentration is estimated to be about $10^{18}/\text{cm}^3$ with a $10 \mu\text{m}$ junction depth, $s_0 = 10^3$ cm/sec. The IBC cell design with a front doping gradient is predicted to achieve a useful conversion efficiency of about 8% even at 1 sun AMO and a 10^5 cm/sec surface recombination velocity.

REFERENCES

1. D. W. Spaderna and D. H. Navon, *IEEE Trans. Electron Dev.* **ED-25**, 1290 (1978).
2. M. D. Lammert and R. J. Schwartz, *IEEE Trans. Electron Dev.* **ED-24**, 337 (1977).
3. P. M. Dunbar and J. R. Hauser, *Solid-St. Electron.* **19**, 95 (1976).
4. M. S. Mock, *Solid-St. Electron.* **16**, 1251 (1973).
5. J. W. Slotboom and H. C. DeGraff, *Solid-St. Electron* **19**, 857 (1976).
6. K. Seeger, *Semiconductor Physics*. Springer-Verlag, Berlin (1973).
7. S. S. Li and W. R. Thurber, *Solid-St. Electron*, **20**, 609 (1977).
8. S. S. Li, *Solid-St. Electron* **21**, 1109 (1978).
9. C. Canali, G. Majni, R. Minder and G. Ottaviani, *IEEE Trans. Electron Dev.* **ED-22**, 1045 (1975).
10. N. R. Howard and G. W. Johnson, *Solid-St. Electron.* **8**, 275 (1965).
11. J. D. Beck and R. Conradt, *Solid-St. Commun.* **13**, 93 (1973).
12. A. S. Grove, *Physics and Technology of Semiconductor Devices*. Wiley, New York (1967).
13. W. C. Dash and R. Newman, *Phys. Rev.* **99**, 1151 (1955).
14. H. Phillipp, *J. Appl. Phys.* **43**, 2835 (1972).
15. M. P. Thekaekara, *J. Environ. Sci.* **13**, 6 (1970) or the equivalent data from the book (Edited by A. A. M. Sayigh), p. 40. Academic Press, New York (1977).
16. V. C. Alwin, D. H. Navon and L. J. Turgeon, *IEEE Trans. Electron Dev.* **ED-24**, 1297 (1976).
17. D. H. Navon, private communication.