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Short Circuit Currents Improvements of In-doped Silicon (n) Structure

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ABSTRACT

Theoretical and practical calculations of short circuit currents of In-doped Silicon (n) structure have been calculated. Theoretically maximum value of generated current was 5.25 mA at $0.5x10^{17}$ cm^{-3} *indium concentrations. Practically the ideal I-V characteristic of the structure is obtained with indium thickness of 1500 °A annealed at 1100 °C for an hour. This structure has a knee voltage at 0.8 V with very small value of reverse saturation current and 1.6 ideality factor. The maximum photogenerated current about 2.3 mA is obtained at* $0.396x10^{17}$ cm^{-3} *of indium concentration. Theoretical & practical results agree that the maximum photo generated current occurs at zero cell output voltage.*

KEYWORDS: In-doped Silicon, IPV Effect, Silicon (n) Responsivity

INTRODUCTION

Silicon solar cells have different design and material requirements from most other silicon electronic devices. Not only ideal passivation of silicon surfaces is required, but bulk properties must also be free of defects and uniformly high quality for high energy conversion efficiency. This is because some wavelengths of light have to pass several microns through the silicon before absorption that producing carrier to be collected by the cell (Green, 1995). Improved techniques for crystal growth producing single crystal wafers of silicon used boron diffusion with the efficiency of about 6% led to the first report of modern silicon cell in 1954 (Chapin et al., 1954). Keevers showed that the impurity photovoltaic effect (IPV) can indeed improve theoretical efficiency limits (Keevers and Green, 1995). In order to improve and extend the sub-band gap response, indium should be added to an n-type layer of silicon cell. In fact indium acts as an electrical dopant responsible for changing the surface layer (10.2-0.5 um) of n-type wafer to a p-type, as well as the optical dopant (IPV effect) (Keevers and Green, 1994).

THE NET RECOMBINATION

In the standard SRH model (Shockley and Queissey, 1961), electrons and holes can be captured by impurity level and thermally excited from it. The six impurities related transitions included in the modified SRH model are shown in Fig. 1.

Under steady state condition the impurity level occupancy does not change with time, so that the net rate for electron capture (E_{cap}) by the impurity is balanced by the net rate of hole capture (H_{cap}), the net recombination rate (U) via an impurity level is found to be: (Shockley and Read, 1952).

$$U = \frac{np - n_1^* p_1^*}{\tau_{no}\left[p + p_1^*\right] + \tau_{po}\left[n + n_1^*\right]} \tag{1}$$

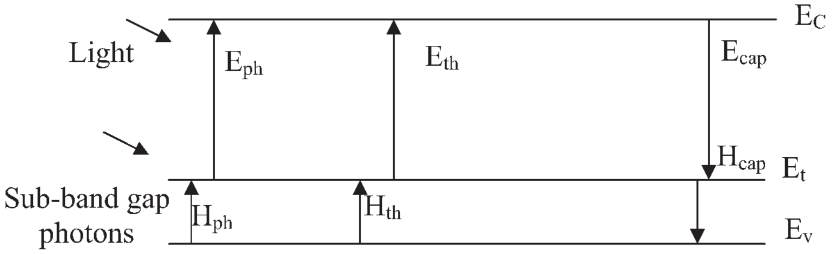

Figure 1. Modified Shockley-Read-Hall (SRH) transition model.

Where n and p are the electron and hole concentrations, τ_{no} and τ_{po} are SRH low injection lifetime for electrons and holes and they can be expressed as follows:

$$\left.\begin{array}{l}\tau_{no}=1/C_nN_t\\ \tau_{po}=1/C_pN_t\end{array}\right\} \qquad (2)$$

$$\left.\begin{array}{l}n_1^*=n_1+\tau_{no}g_{n\max}\\ p_1^*=p_1+\tau_{po}g_{p\max}\end{array}\right\} \qquad (3)$$

Where n_1 and p_1 are the impurity electron and hole concentration, N_t is the impurity concentration. C_n and C_p are the electron and hole capture coefficients; finally g_{nmax} is the optical emission rate of electrons from the impurity level which is fully occupied, while g_{pmax} is the optical emission rate of holes from the impurity level which is completely empty. The basic idea of equation (1) is that for some impurities incorporated into a solar cell, the recombination rate may be positive or negative. As far as SRH recombination mechanism is concerned, the impurity acts either to increase recombination (U is positive), in other words, decrease the carrier lifetime, consequently decreasing current generation, or to increase current generation in the cell (U is negative). In order to increase the current generation (makes U negative), this requires:

$$n_p-n_1^*p_1^*<0 \qquad (4)$$

So $n_1^*p_1^*$ must be as large as possible. Using equation (3) , equation (4) can be rewritten as:

$$np-(n_1+\tau_{no}g_{n\max})(p_1+\tau_{po}g_{p\max})<0 \qquad (5)$$

For midgap impurity levels $n_1 \cong p_1 \cong n_i$, therefore place a strong requirements on both photoemission terms in equation (5). A shallow impurity level gives rise to an asymmetry between n_1 and p_1. For the case here of shallow acceptor $p_1 >> n_1$ which means that only one of the photoexcitation process is crucial for $\mathbf{n_1^*p_1^*}$ to be large.

Due to the large values of p_1 ($\cong 1.8 \times 10^{16}$ cm^{-3}) compared with small value of n_1 ($\cong 6.4 \times 10^3$ cm^{-3}) (Green and Keevers, 1995) for indium doped silicon structures, hole emission from the indium level is generally thermal and not optical. Here indium is considered as a shallow-level impurity which provides both reasonable access to the sub-band gap spectrum and depends only on one of the weak impurity optical processes. Smallness of n_1 indicates that electron photoemission term g_{nmax} is crucial if recombination rate to be negative thus;

$$n_1^*p_1^* \cong p_1\tau_{no}g_{n\max} \qquad (6)$$

PHOTO GENERATED CURRENT SIMULATION

Photogenerated current (J_{in}) inside the cell due to indium doping is given by (Aboush, 1985):

$$J_{in} = q\int_{o}^{xj}\left[-U(x)\right]dx \tag{7}$$

Where q is the electronic charge and x_j is the junction depth. Substituting equation (1) in equation (7) yields:

$$J_{in} = q\int_{o}^{x_j}\frac{np - n_1^* p_1^*}{\tau_{no}\left(p + p_1^*\right) + \tau_{po}\left(n + p_1^*\right)}dx \tag{8}$$

Substituting τ_{no}, τ_{po}, n_1^* and p_1^* from equation (2) and (3) in equation (8) and knowing that:

$$n_1 = g_t N_c e^{-\frac{E_c - E_t}{KT}}$$
$$p_1 = \frac{1}{g_t} N_v e^{-\frac{E_t - E_v}{KT}} \tag{9}$$

Where g_t is the impurity level degeneracy, N_c and N_v are the effective density of states in the conduction and valance band respectively, E_c and E_v are the conduction and valance band edges, E_t is the effective impurity level, k is Boltzman constant and T is the temperature in ^oK gives:

$$J_{in} = q\int_{o}^{x_j}\frac{np - \left[\left(g_t N_c e^{-\frac{E_c - E_t}{KT}} + \frac{g_{n\max}}{C_n N_t}\right)\left(\frac{N_v e^{-\frac{E_t - E_v}{KT}}}{g_t} + \frac{g_{p\max}}{C_p N_t}\right)\right]}{\frac{1}{C_n N_t}\left[p + \left(\frac{N_v e^{-\frac{E_t - E_v}{KT}}}{g_t} + \frac{g_{p\max}}{C_p N_t}\right)\right] + \frac{1}{C_p N_t}\left[n + \left(g_t N_c e^{-\frac{E_c - E_t}{KT}} + \frac{g_{n\max}}{C_n N_t}\right)\right]}dx \tag{10}$$

Knowing the values of g_t, N_c, N_v, p, C_n, C_p and $x_j = 0.3$ μm, equation (10) can be solved numerically using the Matlab program and values of photogenerated current can be calculated. Photogenerated current depends on photon flux density, which is a function of spectrum wavelength, impurity concentration, and depth inside the cell and the cell reflectivity.

Fig. 2 shows the calculated short circuit current from the model as a function of indium concentration for two values of rear cell reflectivity (Rb). It is clear from the figure that the short circuit current is significantly generated when indium concentration was higher than 10^{14} cm^{-3} and less than 10^{18} cm^{-3}. Maximum current (5.75mA) is obtained at 0.5×10^{17} cm^{-3} of indium concentration which is completely compensate the background dopant of the wafer. When indium overcompensates the n-type dopant, then indium level is not fully occupied which reduces photon flux available for crucial electron process. Also it is obvious that we can make use of rear cell reflectivity to enhance generated current.

Fig. 3 shows the calculated photogenerated current as a function of indium concentration with different cell output voltage. Usually maximum generated current is occurs at zero cell output voltage, photo generation is dominant. Increasing cell voltage to a value of 0.7 V will result in a rapid decreasing of photogenerated current. As the cell operating voltage increases, the carrier concentration increases (exponentially depends on applied voltage). Recombination in the cell therefore, increases in the same manner, until eventually the recombination current dominates the cell.

ELECTRICAL & SPECTRAL RESPONSE OF LAB. PREPARED SAMPLES

Few samples of In-doped Si (p)/Si (n) structures were prepared. A thin layer of indium was deposited on top of an n-type single crystal silicon wafer, using thermal vacuum deposited technique. In order to form a pn junction indium must be diffused into silicon wafer for depth between 0.2-0.5 µm by annealing. Wafer was placed inside an evacuated silicon quartz tube and heated up to the required temperature (450 – 1100 ^{o}C) for an hour. For more details about the sample preparation and fabrication see reference (Khallel, 2000).

The effect of different annealing temperatures on dark I-V characteristics is shown in Fig. 4. S1 and S2 seem to have comparable forward and reverse characteristics. Differences between S1 and S2 in one hand and S3 in the other hand are that reverse dark current is much smaller in S3 than that in others. It is concluded that annealing temperature of S1 and S2 is not enough to form the required pn junction at right depth with good ideality factor. Junction depth is expected to be very shallow for S1 and S2 samples, while in S3 indium is diffused deeply into the silicon wafer, but forward and reverse I-V characteristics of S3 seems to be the same and ideality factor still high.

To have a better idea about junction formation, I-V characteristics of other samples with different indium thicknesses (different concentrations) at high annealing temperature (1100 ^{o}C) are shown in Fig. 5. S6 (500 ^{o}A indium thickness) gives high leakage current, since depletion region is narrow (low carrier concentration) and junction depth is still very small (shallow). It is clear from S3 (2000 ^{o}A indium thickness) that indium is diffused deeply into silicon wafer, which prevents junction formation under these conditions. Therefore I-V characteristics more or less are a resistive one (Same characteristics in forward and reverse bias). S4 and S5 (1000 ^{o}A and 1500 ^{o}A indium thickness, respectively) have a knee voltage around 0.85 V and very small reverse current which starts to build up at –4 Volt of reverse voltage. S4 gives an optimum characteristic and will be used in the following discussion. Ideality factor around 1.6, which indicates a reduction in recombination process inside the structure.

Table 1. Calculated parameters of the prepared samples annealed at 1100 ^{o}C and under AM 1.5 illuminations at 300 ^{o}C working temperature.

Sample No.	**thickness (^{o}A)**	**Barrier Voltage (V)**	**Ideality Factor**	**concentration (cm^{-3})**	**I_{SC} (mA/cm^{2})**
S3	2000	0.85	2.5	1.37x1018	0.5
S4	1500	0.75	1.6	3.96x1016	2.3
S5	1000	0.62	1.92	2.65x1015	0.6
S6	500	0.35	3.2	5.36x1010	0.1

C-V characteristics of different samples (S3, S4, S5 and S6) are measured and the values of indium concentrations, ideality factors, and short circuit currents of the samples are calculated and tabulated in table 1.

Fig. 6 shows the variation of short circuit currents for samples (S3, S4, S5, and S6) versus incident light wavelength of different indium thicknesses. It is clear that S4 produce a maximum short circuit current at 0.9 μm wavelength. This means that an optimum junction depth is formed so that the electron-hole pairs are almost collected inside the junction yielding a maximum current generation. Indium concentration for S4 was calculated from C-V characteristics to be equal to 3.96×10^{16} cm^{-3} and it seems to compensate all the background n-type dopant which is equal to 2×10^{16} cm^{-3}. Looking back at Fig. 6 it is obvious that there is no photo response of these samples at wavelength less than 0.45 μm. This is thought to be the formation of surface layer which acts as a filter for generation and recombination phenomena to take place at the layer. The current starts increasing at $\lambda>$ 0.5 μm and a maximum current obtained at $\lambda=$ 0.9 μm. As λ increases about 0.9 μm the current starts decreasing gradually and still have a significant value of 34% at $\lambda=$ 1.1 μm. At this range of wavelength most of the photogenerated currents is due to the sub-band gap absorption mechanism (IPV effect) which extend the sample photo response to near infrared (1.1 μm) or more (Mohamad, W.F. and Khallel, K., 2000). Photon energies absorbed by emitter and base regions of the pn junction varies with junction depth. Since at low photon energies, most of carriers are generated in the base because of low absorption coefficients. But as photon energy increases, the diffused side of the junction takes place (Wenham, S. et al., 1994). The effect of junction depth and indium concentration on short circuit current is shown in Fig. 7. When the junction depth is shallow the probability of collecting carriers generated at the top (near surface) decreases which in turn causes photocurrent to decrease. Also a very shallow junction will be produced at low indium concentration (N_t), consequently small current will be generated. This result agreed with that obtained from simulation. At lower values of N_t, the generation factor (g_{nmax}) will be small giving small product of $n_1^* p_1^*$ (See equations 2 & 3) which gives positive recombination. In other hand increasing junction depth, decreases the sheet resistance of diffused layer (Mohamad, W.F. and Shehatha, M. 2001), thus enabling the use of larger grid line spacing, and utilizing relatively more light flux. This causes current collection efficiency to be increased. Also as the indium concentration increased to a large value (> 10^{17} cm^{-3}), the junction is deeply diffused and carrier lifetime will be decreased, consequently small photogenerated current is collected at very high concentration. Comparing practical results with simulation results shows similarity. Large indium concentration will result in a lower value of carrier lifetime (equation 2). So at lower value of carrier lifetime recombination will be positive and recombination current will be dominant.

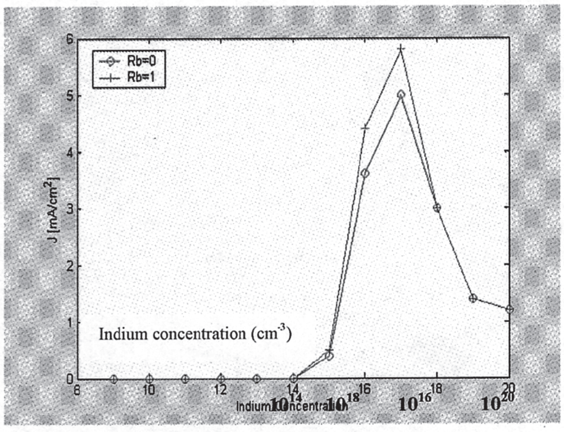

Figure 2. Simulated short circuit current versus indium concentration for two values of reflectivity

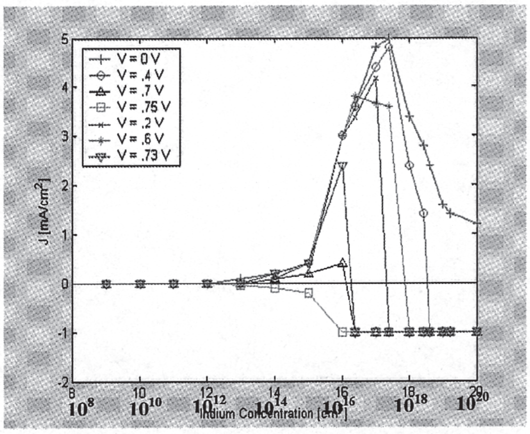

Figure 3. Simulated generated current versus concentration with different output voltages

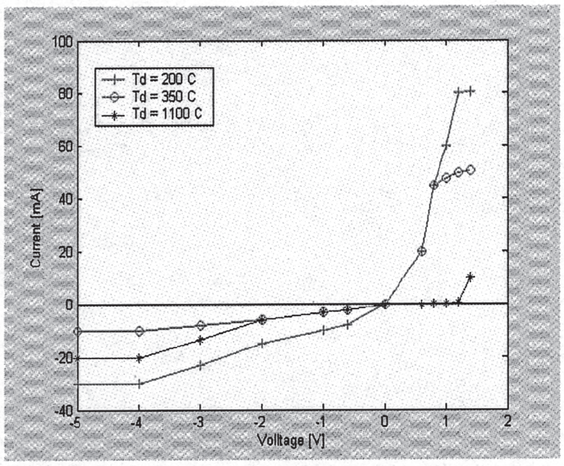

Figure 4. I V characteristics of the samples of 2000 indium thickness with different annealing temperatures.

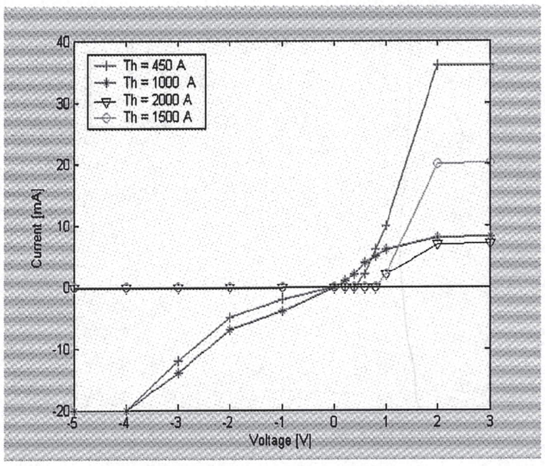

Figure 5. I V characteristics of the samples at constant annealing temperature and different indium thickness.

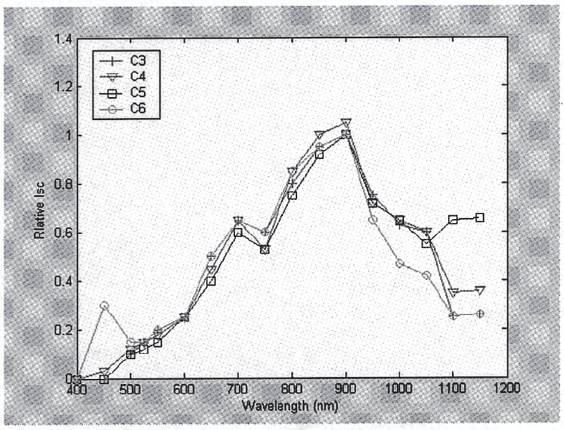

Figure 6. Relative current VS incident light Wavelength for the fabricated cells C3, C4, C5, C6 at P=10E

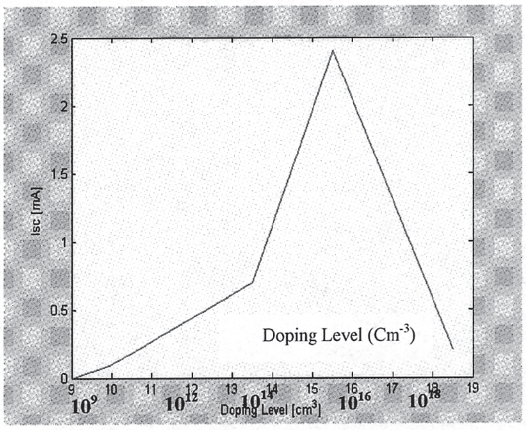

Figure 7. The short circuit current Versus indium concentration

CONCLUSIONS

On the basis of experimental results obtained and compared with computer simulation results of In-doped Si(p)/Si(n) structure, it can be concluded that; a significant photogenerated current is only obtained when indium is at least close to compensating front n-type dopant. In fact indium acts as an electrical dopant responsible of changing surface layer of n-type wafer to a p-type as well as the optical dopant. A maximum photogenerated current occurs at zero applied voltage, photo generation is dominant. Increasing applied voltage will result in rapid decreasing of photogenerated current. This is due to the exponential increase of carrier concentration, until eventually current dominates the cell. The current collection efficiency will be increased if junction depth of mid distance. Shallow junction will form a dead layer that reduces carrier collection. While a very deep junction reduces relative lifetime consequently recombination rate will be positive and recombination current will dominates.

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تحسين تيار دائرة القصر لخلايا السيلكون المطعم بالانديوم

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ملخص

تتطلب الخلايا الشمسية السيلكونية مواصفات معينة من حيث نوعية المواد المستخدمة وطريقة التحضير والتصميم. أن جسم الخلية يجب أن يكون خاليا من الشوائب والتشوهات. ولغرض زيادة كفاءة التحويل والحصول على أعلى تيار ممكن من هذه الخلايا فأن بعض الشوائب المقننة ومنها الانديوم تضاف بنسب معينة إلى خلايا السيلكون الشمسية. في هذا البحث تم تحضير عدة نماذج من الخلايا الشمسية وقد تم تغيير نسبة تطعيم الانديوم وكذلك درجات حرارة التحضير. وقد تم إجراء حسابات نظرية وعملية لقياس كمية تيار دائرة القصر للنماذج المحضرة ولفولتيات انحياز أمامية وعكسية.

لقد وجد نظريا بأن أعلى تيار لدائرة القصر هو بحدود 5.25 ملي أمبير في تركيز ($0.5 X 10^{17}$) لكل سم^3 أنديوم. أما عمليا فقد وجد بأن أعلى تيار يمكن الحصول عليه من هذه النماذج هو 2.3 ملي أمبير وذلك عند ترسيب أنديوم بسمك 1500 أنكستروم وتلدين الخلية في درجة حرارة 1100 درجة مئوية ولمدة ساعة واحدة. كذلك وجد من منحني التيار – الفولتية بأن هذا النموذج يمتلك ثنية في الفولتية عند القيمة 0.8 فولت وعامل مثالية مقداره 1.6. كذلك اثبتت القياسات النظرية والعملية بأن أعلى تيار يتم الحصول عليه عندما تكون الفولتية المسلطة على طرفي الخلية صفرا.