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The study of 1 MeV electron irradiation induced defects in N-type and P-type monocrystalline silicon

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ABSTRACT

Despite extensive use of GaAs cells in space, silicon cells are still being used. The reason is that not only they provide a good compromise between efficiency and cost, but also some countries do not have the required technology for manufacturing GaAs. Behavior of a silicon cell under any levels of charged particle irradiation could be deducted from the results of a damage equivalent 1 MeV electron irradiation using the NASA EQflux open source software package. In this paper for the first time, we have studied the behavior of a silicon cell before and after 1 MeV electron irradiation with 10^{14}, 10^{15} and 10^{16} electrons-cm^{-2} fluences, using SILVACO TCAD simulation software package. Simulation was carried out at room temperature under AM0 condition. Results reveal that open circuit voltage and efficiency decrease after irradiation while short circuit current shows a slight increase in the trend around 5×10^{16} electrons-cm^{-2}, and short circuit current loss plays an important role on efficiency changes rather than open circuit voltage.

1. Introduction

Solar cells convert solar energy into electricity directly. Silicon cells are still being used in satellites, despite the extensive use of III-V semiconductors. Since satellites are exposed to high energy particles in space, understanding the behavior of a cell under irradiation is very important (Bhat et al., 2014; Hisamatsu et al., 1998; Yamaguchi, 2001). Bombardment of a cell with high energy electrons and protons leads to that cell's degradation and as a consequence output power of the cell decreases (Cooley and Janda, 1963). As mentioned earlier, silicon cells are chosen for studying because of their cost effectiveness and reliability. Electron degradation of silicon cells is characterized in many articles. A.Hamache et al. did a modeling for silicon cells with a software called SCAPS in which he studied the J-V curve under many fluences of 1 MeV electrons irradiation and focused on the type conversion of the base silicon (Hamache et al., 2014). Tadashi Hisamatsu et al. studied the effects of 10 MeV protons and 1 MeV electrons irradiation on electrical properties of space solar cells and reported a slight increase in J_{SC} around 5×10^{16} electron-cm^{-2} (Hisamatsu et al., 1998). Morita et al. have reported an abrupt decline in short circuit current to nearly zero by 1 MeV electrons at the fluence of 5×10^{16} electron-cm^{-2} (Morita et al., 1997). Bhat et al. have studied changes in silicon solar figures of merit under 8 MeV electrons irradiation (Bhat et al., 2014). Walker has worked on defects which are generated in silicon by 1 MeV electrons irradiation (Walker, 1973). Electrons with energy of 1 MeV are the most essential particles in studying space radiation. They are used not only as basic particles in studying the effects of radiation on solar cells, but also they can be produced in laboratory environments easily (Tada et al., 1982).

When a high energy electron strikes a semiconductor, different physical processes happen in which ionization and atomic displacements have the highest share of importance among the others. Solar cell designers try to focus on them while designing cells (Walker, 1973). In ionization, a small fraction of energy is transferred to a valence electron by a colliding particle. As a consequence, this electron jumps up to the conduction band and a pair of electron-hole is created (Tada et al., 1982; Johnston, 2010). When an electron with energy more than 45 KeV collides with a silicon crystal, an atom from the crystal lattice is displaced and a vacancy-interstitial atom is produced (Cooley and Janda, 1963). At room temperature, vacancies are mobile. They move to different positions and generate stable defects. These defects act as traps and recombination centers for both electrons and holes (Hamache et al., 2014; Walker, 1973). Recombination centers have comparable capture cross sections for electrons and holes and energy levels near mid gap while traps have different capture cross sections for electrons and holes and energy levels that can be anywhere in the band gap (Meftah et al., 2009). Firstly, these centers capture a minority carrier and then a majority carrier, as a result, an electron-hole pair is annihilated (Tada et al., 1982).

Some defects are created in silicon cells by electron irradiation.

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These defects introduce energy levels within the silicon band gap in both N and P type silicon. Displacement defects play an important role on minority carrier life time in silicon (Tada et al., 1982). Eq. (1) shows the relationship between minority carrier life time and fluence of incident radiation (Cooley and Janda, 1963; Tada et al., 1982; Johnston, 2010).

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_\tau \phi \tag{1}$$

Where τ, is the minority carrier life time in final state, τ_0 is the minority carrier life time in initial state, K_τ is the damage coefficient and K_τ is the radiation fluence. According to the Eq. (1) by an increase in the incident fluence, recombination of carriers goes up and minority carrier life time decreases.

Traps are divided into two groups; electron traps with energy levels located under the conduction band and hole traps with energy levels above the valence band. The energy level of an electron and a hole trap is demonstrated as $E_c - E_t$ and $E_v + E_t$ respectively. They are characterized by some parameters like their type, energy levels, capture cross sections and density. Trap density is in a linear relationship with fluence, and as a result higher fluences lead to a bigger trap density (Hamache et al., 2014; Crespin, 2004).

In this article, for the first time we studied the effects of 1 MeV electron irradiation on solar figures of merit with a simulator called SILVACO TCAD package. The behavior of the silicon cell has been studied in the presence of different fluences of 1 MeV electrons.

2. Simulation

Like any device simulator, SILVACO solves the basic semiconductor equations. The basic equations are: the Poisson equation, relating the charge to the electrostatic potential Ψ, the continuity equations for electrons and holes and the transport equations. The silicon cell simulated in this work has a similar structure to that of Tadashi Hisamatsu for comparison (Hisamatsu et al., 1998). It is a 50 µm thick n^+-p-p^+ structure. Emitter, base and back surface field region specifications are shown in Table 1 (Hamache et al., 2014; Hisamatsu et al., 1998). The junction depth is 0.15 µm. Boron was doped in base and Phosphorus in emitter.

The cell is illuminated from the n^+ side by AM0 spectrum at room temperature and solar figures of merit are plotted for different fluences of 1 MeV electrons. Electron irradiation creates displacement defects in silicon lattice which act as recombination centers or traps for free careers (Hamache et al., 2014). A lot of work is carried out to specify these defects so that a large number of defects are reported in silicon. For simplicity of calculations we have used the most common reported defects (Walker, 1973; Karazhanov, 2000). These are given in Table 2 (Walker, 1973; Karazhanov, 2000). In SILVACO TCAD, "trap statement" is used for considering the effects of traps on the output results of the cell. We need to mention four parameters in "trap statement"; type, energy level, density and capture cross sections of traps. Electron traps are acceptors and hole traps are called donors. Energy level, density and capture cross sections are all presented in Table 3 (Walker, 1973; Karazhanov, 2000).

In this article we studied the solar figures of merit before and after 1 MeV electrons irradiation with 10^{14}, 10^{15} and 10^{16} electrons-cm^{-2} fluences. Solar cell figures of merit include current density-voltage (J-V), internal and external quantum efficiencies (QE) and power.

Table 1
The different specifications of the simulated silicon cell.

	Thickness (µm)	Doping density (cm^{-3})
Emitter (n^+)	0.15	10^{19}
Base (p)	49.70	10^{15}
Back surface field region (p^+)	0.15	5×10^{18}

Table 2
Trap energy levels within the band gap in silicon irradiated with 1 MeV electron at room Temperature.

	Activation energy	
Energy Levels (eV)	E_v + 0.4	E_c-0.12
	E_v + 0.28	E_c-0.17
	E_v + 0.2	E_c-0.42
	–	E_c-0.52

Table 3
Capture cross sections and density of traps in silicon for different fluences of 1 MeV electrons.

	ΔE(eV)	N_t(cm^{-3})	σ(cm^2)
$10^{14}\left(\frac{e}{cm^2}\right)$	E_V+0.4	3×10^{12}	2.6×10^{-12}
	E_V+0.28	5.4×10^{13}	3.4×10^{-13}
	E_V+0.20	9.6×10^{12}	6×10^{-13}
	E_C−0.12	9.8×10^{13}	3×10^{-14}
	E_C−0.17	1.2×10^{13}	10^{-14}
	E_C−0.42	2.2×10^{13}	2×10^{-15}
	E_C−0.52	5.5×10^{12}	3.7×10^{-15}
$10^{15}\left(\frac{e}{cm^2}\right)$	E_V+0.4	4.5×10^{13}	2.6×10^{-12}
	E_V+0.28	5.6×10^{13}	3.4×10^{-13}
	E_V+0.20	3.1×10^{13}	6×10^{-13}
	E_C−0.12	1.1×10^{14}	3×10^{-14}
	E_C−0.17	3.8×10^{14}	10^{-14}
	E_C−0.42	3.5×10^{14}	2×10^{-15}
	E_C−0.52	3×10^{13}	3.7×10^{-15}
$10^{16}\left(\frac{e}{cm^2}\right)$	E_V+0.4	4×10^{14}	2.6×10^{-12}
	E_V+0.28	1.98×10^{14}	3.4×10^{-13}
	E_V+0.20	3.23×10^{14}	6×10^{-13}
	E_C−0.12	3.48×10^{14}	3×10^{-14}
	E_C−0.17	3.48×10^{15}	10^{-14}
	E_C−0.42	3.33×10^{15}	2×10^{-15}
	E_C−0.52	3.24×10^{14}	3.7×10^{-15}

Since the cell structure is n^+-p-p^+, it is expected that the defects will be mainly created in the thickest region which is p-type base (Hamache et al., 2014). In numerical simulation, many possibilities may be considered, the effects of donor and acceptor traps on J-V characteristics are calculated separately and finally all of them are taken into account. As it was reported by Tadashi Hisamatsu et al., a slight increase in normalized short circuit current density, J_{SC}, must be observed. This slight increase is thought to be responsible for type conversion of the base silicon (Hamache et al., 2014). In the next stage, J_{SC} characteristic is calculated taking all the traps into account. To see which traps are responsible for this phenomenon, effects of acceptor and donor traps on J_{SC} are considered separately. In the last step, internal and external quantum efficiency and power diagrams of the irradiated cell are plotted, and efficiency of the cell is calculated. The impact of current and voltage loss on efficiency is also studied.

3. Results and discussions

The effects of donor traps, acceptor traps and all the traps together on J-V characteristics under different fluences of 1 MeV electrons are shown in Fig. 1(a), (b) and (c) respectively.

There is an experimental equation (Eq. (2)) between I_{SC} and fluence (Φ). Similarly, there is a relationship between V_{OC} and Φ. We can explain the behavior of curves by these two experimental equations. When fluence increases, I_{SC} and V_{OC} decrease according to Eqs. 2 and 3 (Walker, 1973).

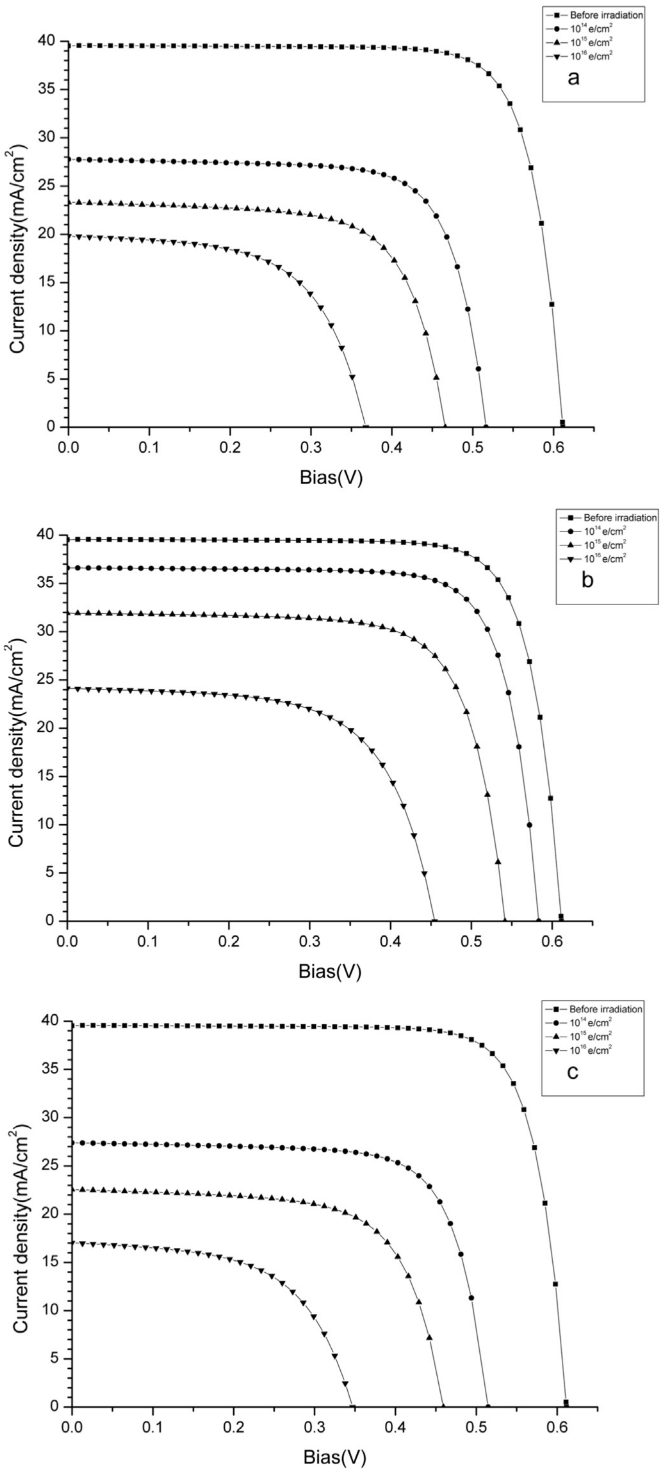

Fig. 1. The calculated J-V characteristics of the simulated cell under 1 MeV electron irradiation taking into account (a) all the donor traps, (b) all the acceptor traps and (c) acceptor and donor traps together.

$$I_{SC} = I_{SC_0} - CLog(1 + \frac{\phi}{\phi_X}) \quad (2)$$

$$V_{OC} = V_{OC_0} - CLog(1 + \frac{\phi}{\phi_X}) \quad (3)$$

The constant C represents the decrease in I_{SC} per decade in radiation fluence in the logarithmic scale, the ϕ_X represents the radiation fluence at which I_{SC} or V_{OC} starts to change to a linear function of the logarithm of the fluence (Tada et al., 1982). Short circuit current loss is related to

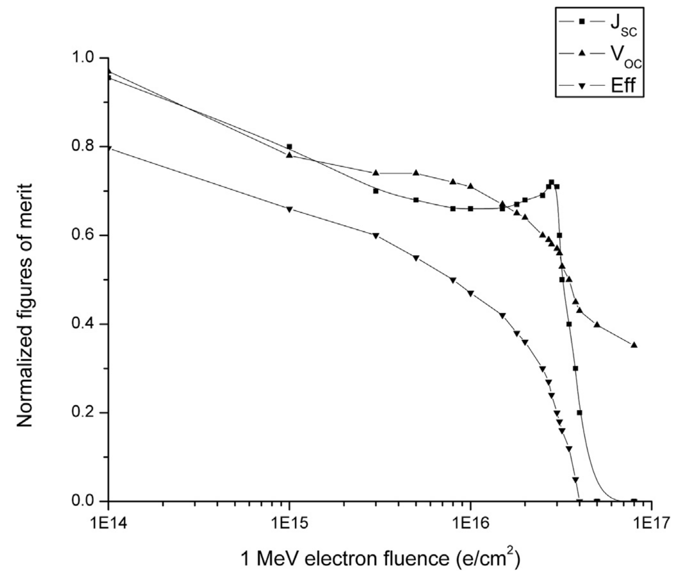

Fig. 2. The calculated normalized solar figures of merit under 1 MeV electrons irradiation taking all the traps into account.

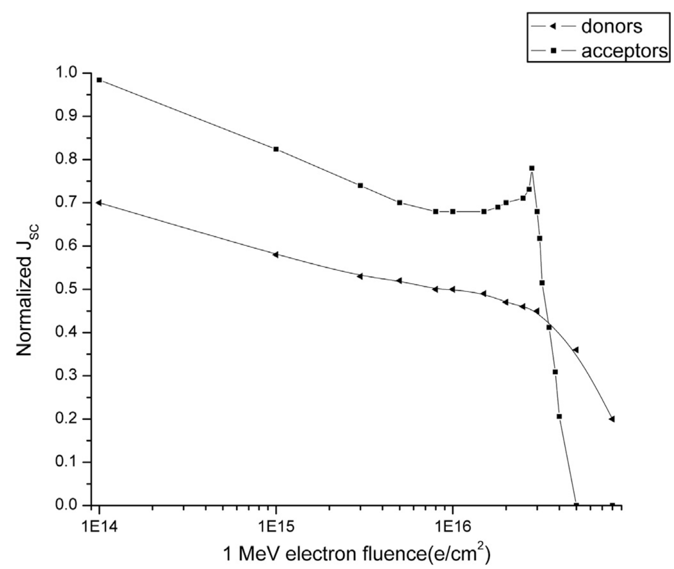

Fig. 3. The calculated J_{SC} under 1 MeV electrons considering the impact of donor and acceptor traps separately.

the decrease of minority carrier life time which is because of a rise in trap density (Bhat et al., 2014).

In experimental behavior, a slight increase in J_{SC} characteristic is observed. Fig. 2 shows the calculated normalized solar figures of merit including J_{SC}.

V_{OC}, J_{SC}, and Efficiency are normalized to un-irradiated values. As can be seen in Fig. 2, J_{SC} shows a slight increase in its trend according to experimental data. To be more precise, we calculated the effects of donor and acceptor traps on J_{SC} separately. Fig. 3 demonstrates the results of the study. According to Fig. 3, it is clear that acceptor traps are responsible for the slight increase in J_{SC} trend.

In the following, the normalized internal and external quantum efficiency and power diagrams of the simulated cell under different fluences of 1 MeV electrons are presented respectively.

As can be seen in Figs. 4 and 5, in short wavelengths quantum efficiency has not been affected by fluence a lot compared to long wavelengths. Short wavelengths have high Energy and low absorption depth. As a result they are absorbed in a short distance of the surface and their destructive effects can be ignored compared to long

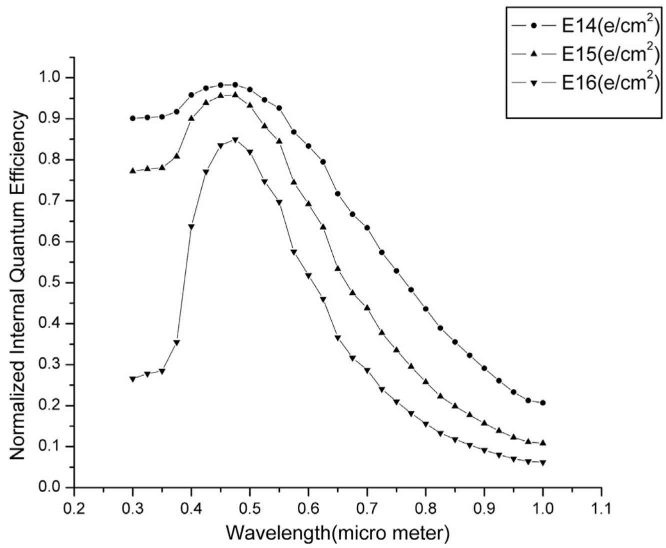

Fig. 4. Normalized internal quantum efficiency of the simulated cell under different fluences of 1 MeV electrons.

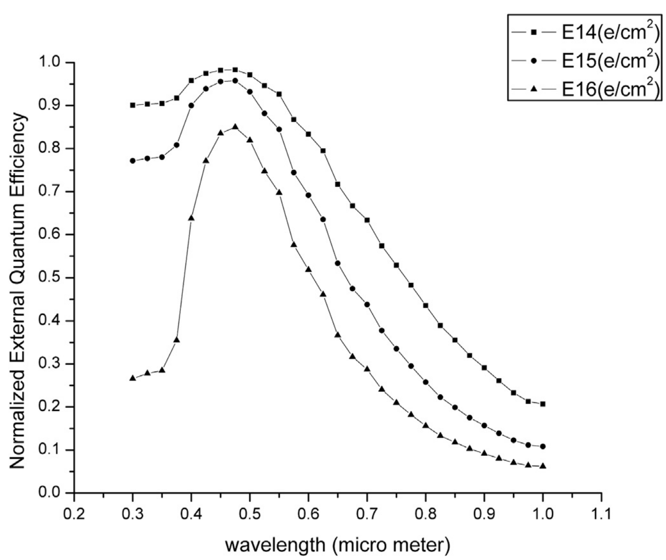

Fig. 5. Normalized external quantum efficiency of the simulated cell under different fluences of 1 MeV electrons.

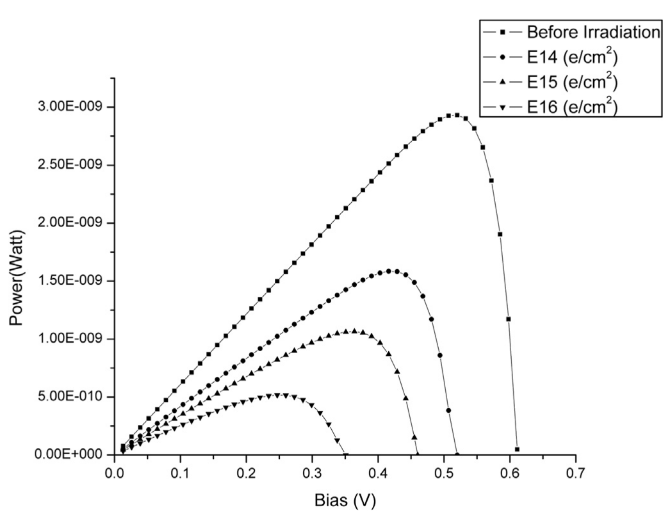

Fig. 6. Power of the simulated cell under different fluences of 1 MeV electrons.

Table 4
I_{MP}, V_{MP} and efficiency of the cell irradiated with 1 MeV electrons at room temperature.

Parameter	Before irradiation	1 MeV electron irradiation		
		10^{14} (e/cm^2)	10^{15} (e/cm^2)	10^{16} (e/cm^2)
I_{MP} (10^{-9} A)	7.31	6.66	5.7	3.96
V_{MP} (V)	0.507	0.494	0.442	0.351
Eff. (%)	14.4	12.37	9.5	5.3

wavelengths. Long wavelengths have low energy and high absorption depth, so they penetrate in the depth of the cell which is a larger area compared to the area in which short wavelengths are absorbed. As fluence increases, trap density rises, recombination increases and diffusion length gets smaller in this region. These all lead to low quantum efficiency (Bhat et al., 2014).

Fig. 6 demonstrates output power of the cell irradiated with 1 MeV electrons. Power is the product of volts multiplied by the amps. Both, current and voltage decrease, while fluence is increasing. So, reduction in power is what we had expected exactly from theoretical relationship between current and voltage.

Silicon cell efficiency is defined by Eq. (4):

$$\eta = \frac{V_{MP} I_{MP}}{P_{in}} \tag{4}$$

where V_{MP} and I_{MP} are the voltage and current in the maximum power point. P_{in} is the power of the incident light on the silicon cell. I_{MP}, V_{MP} and efficiency are all presented in Table 4. All data are obtained by simulation.

As can be seen in Table 4, when fluence increases,I_{MP} and V_{MP} decrease. As a result, efficiency decreases according to Eq. (4). As already mentioned, both voltage loss and current loss affect the efficiency. In this study we did some mathematical calculation in order to compare the impacts of these parameters on efficiency. It has been realized that current changes affects efficiency approximately 1.5 times more than voltage. Efficiency loss is related to minority carrier life time decrease (Bhat et al., 2014).

4. Conclusions

The effects of 1 MeV electron irradiation on a silicon cell with 3 different fluences (10^{14}, 10^{15} and 10^{16} electrons-cm^{-2}) have been studied with SILVACO software package. Electron irradiation introduces some defects in the silicon lattice. These defects act as traps and recombination centers. Some energy levels are created with in the band gap of silicon by these defects and as a result, electrical properties of the solar cell start to degrade. Results of the simulation reveal a slight increase in short circuit current around 5 × 10^{16} electrons-cm^{-2}, while open circuit voltage, quantum efficiencies and maximum output power decrease. The results are similar to previous work done by Tadashi Hisamatsu et al. and A.Hamache et al., another result of simulation is that the effect of current loss on efficiency is 1.5 times greater than the voltage loss.

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