Mechanism for the anomalous degradation of silicon space solar cells

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We propose a mechanism to explain the anomalous degradation of n^+-p-p^+ silicon space solar cells. Distinct from previously known mechanisms, it has been shown that the anomalous increase and abrupt decrease of short-circuit current are caused by corresponding changes of the minority carrier lifetime and a conversion of conductivity type. The majority carrier density decreases abruptly due to trapping by the radiation-induced deep donors, which results in an increase of carrier lifetime and resistance, conversion of conductivity type, and anomalous change of solar cell performance. Peak values of the carrier lifetime and short-circuit current decrease with increasing illumination intensity and are sensitive to variations of the weak optical illumination. © *2000 American Institute of Physics.* [S0003-6951(00)01019-6]

The investigation of semiconductor devices, operating in a radiation environment, has attracted much interest because of their increased use in nuclear reactors and satellites. Recent experiments[1–9] have shown that n^+-p-p^+ silicon space solar cells may exhibit anomalous behavior under high fluence of high-energy proton or electron irradiation, notably an increase in the short-circuit current (J_{sc}), followed by its abrupt decrease and cell failure. To explain this effect a model has been proposed in Refs. 1, 3, 6, and 8, which is based on the formation of radiation-induced deep donors and broadening of the depletion region. In this work another mechanism is proposed, which is based on the effect of the anomalous increase of carrier lifetime with increasing concentration of traps.[10–12] Following Refs. 1–9, we consider a simplified n^+-p-p^+ silicon solar cell[1–9] of thickness $W = 50\,\mu$m and boron concentration in the p-base $N_a = 10^{15}\,\mathrm{cm}^{-3}$. It had been shown[7] that the dominant type of defects, arising as a result of the electron or proton bombardment of the cell, is a deep donor with an ionization energy $E_t = 0.18$ eV below the edge of the conduction band. Following Ref. 7, the deep donors are assumed to be either in the positively charged or neutral state. Due to lack of experimental data, recombination coefficient of electrons, C_n, and holes, C_p, are assumed to be equal to $C_n = 4\times10^{-7}$ and $C_p = 4\times10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$. Our estimations have been made for room temperature $T = 300$ K and photogeneration rates of free carriers $G = 10^{19}$ and $10^{21}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$. Mobility of electrons and holes is taken as $\mu_n = 1300$ and $\mu_p = 500\,\mathrm{cm}^2/\mathrm{V\,s}$. The electrical parameters of p-type silicon and solar cell performance have been investigated numerically as a function of deep donor concentration N_t in the range from 10^{12} to $10^{16}\,\mathrm{cm}^{-3}$.

Lifetime of electrons (τ_n) and holes (τ_p) are estimated using the Shockley–Read–Hall recombination theory and electroneutrality condition

$$\tau_n = \frac{1}{C_p N_t}\frac{n+n_1}{n_o\Delta p/\Delta n + p} + \frac{1}{C_n N_t}\frac{p+p_1}{n_o\Delta p/\Delta n + p}, \tag{1}$$

$$\tau_p = \frac{1}{C_p N_t}\frac{n+n_1}{p_o\Delta n/\Delta p + n} + \frac{1}{C_n N_t}\frac{p+p_t}{p_o\Delta n/\Delta p + n}, \tag{2}$$

$$p + \frac{N_t(C_n n_1 + C_p p)}{C_n(n+n_1) + C_p(p+p_1)} = n + N_a. \tag{3}$$

Here n_o, p_o, and Δn, Δp are the equilibrium and excess concentrations of electrons and holes, respectively, and $n = n_o + \Delta n$, $p = p_o + \Delta p$. The terms n_1 and p_1 are the statistical factors of the Shockley–Read theory.

Equilibrium concentration of electrons n_o and holes p_o are found from Eq. (3) using the relation $n_o p_o = n_i^2$. Excess carrier concentrations Δn and Δp are estimated for the stationary state, setting the carrier photogeneration rate G equal to their recombination rate $U = \Delta n/\tau_n = \Delta p/\tau_p$, taking into account the expressions for lifetimes τ_n, τ_p and the electroneutrality condition (3).

Figure 1(a) shows the dependence of lifetime of electrons $\tau_n(1)$ on the concentration of deep donors. When $N_t < N_a$ and $N_t > N_a$, τ_n decreases with increasing N_t, as was suggested in Refs. 1, 3, 6, and 8, and then increases when $N_t \approx N_a$ [Fig. 1(a)]. These results contradict the suggestion of Refs. 1–9 about the decrease of the minority carrier diffusion length and agree with results of Refs. 10–12. In Fig. 1(a), lifetimes of holes have not been shown since they equal that of electrons for all deep donor concentrations and carrier photogeneration rates considered.

An abrupt decrease in the total carrier density and an increase in the resistance in the base layer are proposed as a mechanism for the anomalous increase of carrier lifetimes under high fluence irradiation. Figures 1(b) and 1(c) show the calculated changes in the total equilibrium carrier concentration $n_o + p_o$ [Fig. 1(b)] and resistance [Fig. 1(c)] as a function of the deep donor concentration for different intensities of carrier photogeneration rates. For $N_t < N_a$, holes are the majority carriers $p_o \approx N_a$ [Fig. 1(b)] and the lifetimes of electrons $\tau_n \approx \tau_{po} n_1/p_o$ decrease with increasing trap concentration N_t. For $N_t > N_a$, the conductivity will be reversed from p type to n type and holes become the minority carriers. Then the free electron density will be increased due to their thermal emission from the deep donor level and $p_o \ll n_o$

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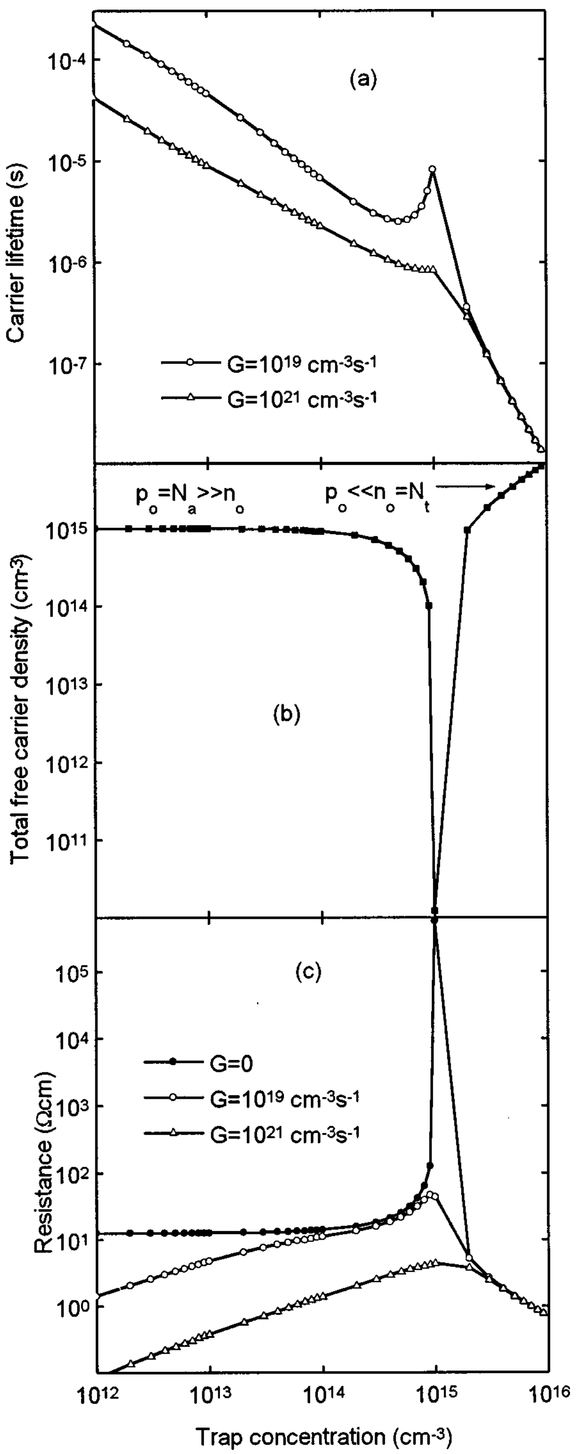

FIG. 1. Dependence on concentration of deep donors of (a) the electron lifetime, (b) the total free carrier density n_o+p_o, and (c) the resistance for photogeneration rates of free carriers G, $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$:0 (●), 10^{19} (○), and 10^{21} (△).

$\approx N_t$ [Fig. 1(b)]. Consequently, the minority carrier lifetime $\tau_p \approx \tau_{p_o} n_1/n_o$ decreases with increasing N_t [Fig. 1(a)]. The results shown in Fig. 1(b) for $N_t > N_a$ contradict the suggestions of Refs. 1–9 about a reduction of the total free carrier density. If $N_t = N_a$, all of the free holes thermally generated from the shallow acceptor level N_a will be captured by the deep donors, resulting in an abrupt decrease of total free carrier density n_o+p_o [Fig. 1(b)], and increase of resistance [Fig. 1(c)] and carrier lifetimes $\tau_n \approx \tau_p \approx \tau_{p_o} n_1/(2n_i)$ [Fig. 1(a)] by several orders of magnitude.[12] Here n_i is the intrinsic concentration. The peak value of the carrier lifetime and resistance decreases with increasing illumination intensity [Figs. 1(a) and 1(c)] and disappears at high photogeneration rates G. Note that even a very small illumination intensity of $\sim 1\ \mathrm{mW/cm}^2$ may cause a considerable decrease of the maximum value of the resistance at $N_t = N_a$ by four orders of magnitude.

The abrupt increase of the resistance with increasing concentration of deep centers may be considered as an experimental tool to determine when the semiconductor is completely compensated, i.e., to establish when the condition $N_a = N_t$ is satisfied. The subsequent abrupt decrease of the resistance indicates conversion of the conductivity type and contradicts the suggestion of Refs. 1–9 about an increase of the resistance.

The anomalous dependence of the minority carrier density and lifetime on the deep donor concentration is proposed as a mechanism for the anomalous degradation of silicon solar cells. Figure 2 shows dark-saturation current J_s, short-circuit current J_{sc}, and open-circuit voltage V_{oc} estimated from the expressions

$$J_s = q D_n n_o L_n^{-1} \tanh(W/L_n), \tag{4}$$

$$J_{\mathrm{sc}} = q\Phi \cosh^{-1}(W/L_n), \tag{5}$$

$$V_{\mathrm{oc}} = (kT/q)\ln(J_{\mathrm{sc}}/J_s + 1), \tag{6}$$

as a function of the deep donor concentration N_t. Here q is the absolute electron charge, $L_n = \sqrt{D_n \tau_n}$ is the diffusion length, and $D_n = \mu_n kT/q$ is the diffusion coefficient of electrons. Φ is the carrier photogeneration rate at the illuminated surface. Due to the conversion of the conductivity type, in Eqs. (4)–(6) at $N_t > N_a$, n_o and L_n are replaced by p_o and L_p, respectively.

Comparing Fig. 1(a) with Fig. 2(b) and analyzing the expression for the short-circuit current (5), one can see that the initial slight decrease, anomalous increase, and subsequent abrupt decrease of short-circuit current are caused by corresponding changes of the minority carrier lifetime. This result differs from that of Refs. 1–9, which assumed that the anomalous increase of the short-circuit current J_{sc} was related to the broadening of depletion region width, while its followed abrupt decrease was caused by the increase of resistance or the decrease of the drift length of carriers.

The dependence of the peak value of short-circuit current on the photogeneration rate of free carriers [Fig. 2(b)] correlates well with that of the minority carrier lifetime [Fig. 1(a)]. This result supports the validity of the mechanism proposed in this work.

The slight increase of the dark current with increasing donor concentration for $N_t < N_a$ and its decrease for $N_t > N_a$ [Fig. 2(a)] are related to changes of the minority carrier lifetime. The abrupt increase and decrease of J_s is caused by changes of the minority carrier density and lifetime, taking place when $N_t = N_a$. The dependence of J_s on the photogeneration rate of free carriers correlates well with that of the lifetime [Fig. 1(a)] and confirms our proposed mechanism. The analyses of Fig. 2(a) show that the dark current is sensitive to variations of weak illumination intensities.

The analyses of the expression for open-circuit voltage (6) and a comparison of Figs. 2(a) and 2(c) show that the

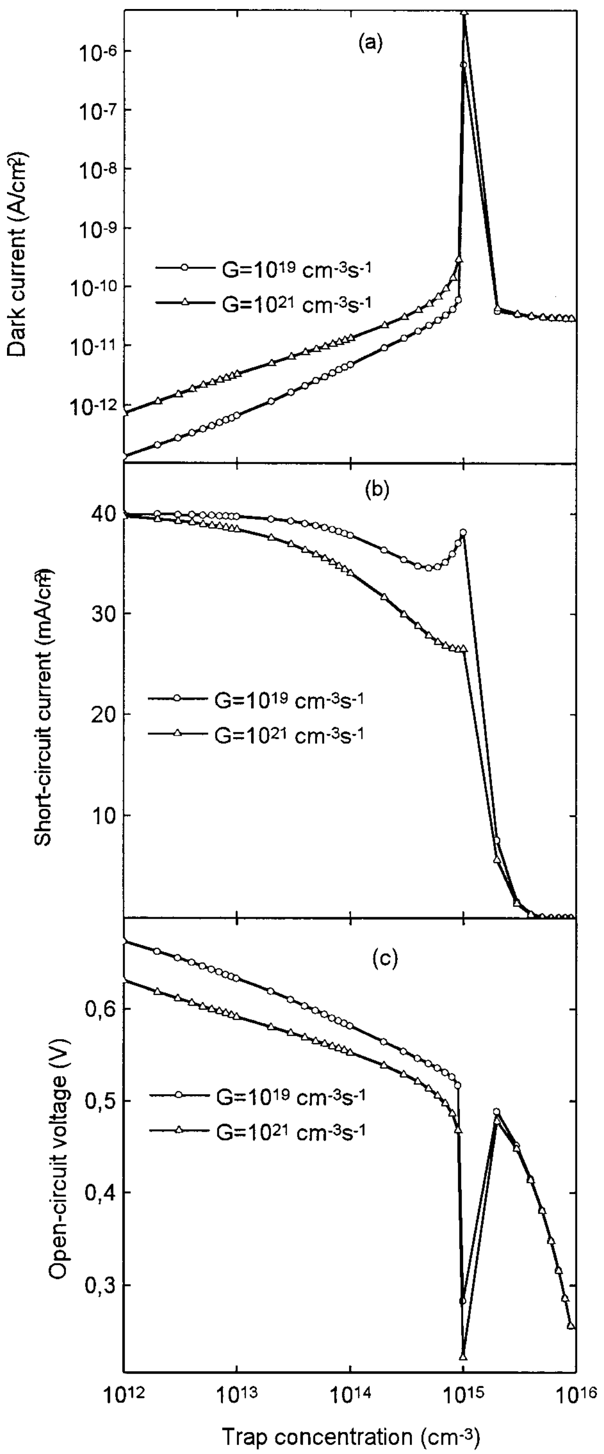

FIG. 2. Dependence on concentration of deep donors of (a) the dark-saturation current, (b) the short-circuit current, and (c) the open-circuit voltage of n^+-p-p^+ silicon solar cells for photogeneration rates of free carriers $G=10^{19}$ (○) and 10^{21} (△) $cm^{-3}\,s^{-1}$.

initial abrupt decrease and increase of V_{oc} [Fig. 2(b)] are defined by the abrupt increase and decrease of the dark current. The anomalies take place as a result of the abrupt decrease and increase of total free carrier density n_o+p_o. The subsequent decrease of V_{oc} with increasing dose of proton or electron irradiation is related to that of the short-circuit current. Nonmonotonic dependence of open-circuit voltage on the deep donor concentration had been observed experimentally in Refs. 1 and 4. However, this result had been ignored and was not discussed.

It should be noted that the anomalous degradation of the cell performance is inherent in solar cells with deep defects. It may take place, if the base thickness W is comparable with minority carrier diffusion length L_n. When $W \gg L_n$, the anomalous increase of lifetime [Fig. 1(a)] would not cause the above anomalous changes of the cell parameters, since, as it follows from Eq. (5), $J_{sc} \approx q\Phi$, which does not depend on L_n. This is one of the reasons why this effect had not been observed before.[1–9]

In conclusion, the deep donors formed under the high fluence of high-energy protons or electrons irradiation in p-type silicon may cause several effects. The capture of majority carriers by the deep donors may cause an abrupt decrease of the total carrier density, increase of the resistance and carrier lifetime, and a conversion of the conductivity type, explaining anomalous degradation of the n^+-p-p^+ silicon space solar cells, etc. The anomalous changes of the short-circuit current are caused by that of the minority carrier lifetime. Variation of the dark current and open-circuit voltage as a function of radiation fluence is nonmonotonic because of the conversion of the conductivity type. The anomalous changes of the free carrier lifetime and solar cell performance are relative effects taking place when the semiconductor is compensated by deep centers, and can be used as an experimental tool to define whether the base region of the cell is completely compensated or not.

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