Mechanism for the anomalous degradation of Si solar cells induced by high fluence 1 MeV electron irradiation

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An anomalous increase in the short-circuit current I_{sc} of *n*-on-*p* Si space solar cells, followed by an abrupt decrease in I_{sc} and cell failure has been observed under high fluence ($>10^{16}$ cm^{-2}) 1 MeV electron irradiation. A model to explain these phenomena by expressing the change in carrier concentration *p*, of the base region as a function of the electron fluence is proposed in addition to the well-known model where I_{sc} decreases by minority-carrier lifetime reduction under irradiation. The reduction in *p* due to majority-carrier trapping by radiation-induced defects has two effects: broadening of the depletion layer which increases the generated photocurrent, and also an increase in the resistivity of the base layer, resulting in the abrupt decrease of I_{sc} and failure of the solar cells.
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Si space solar cells, for use in the Engineering Test Satellite-VI (ETS-VI) experiment conducted by NASDA, have shown anomalous behavior, notably an increase in the short-circuit current I_{sc} followed by an abrupt decrease of I_{sc} and cell failure, under high fluence irradiation with high-energy electrons or protons. In this study, we propose a model to explain these phenomena by calculating the change in the carrier concentration of the base region as a function of the electron fluence in addition to the well-known effect of short-circuit current degradation by minority-carrier lifetime reduction.

The samples used in this study were BSF structure n^+-p-p^+ Si space solar cells with *p*-base layer resistivity of 10 Ω cm and a junction depth of 0.15 μm. 1-MeV electron irradiation was carried out using a Cockcroft Walton accelerator at room temperature. The irradiation fluence ranged from 10^{14} to 10^{17} electrons/cm^2. AM0 properties of Si space solar cells were measured using a solar simulator and the capacitance–voltage ($C-V$) method was used to measure the carrier concentrations.

Figure 1 shows changes in the properties of Si space solar cells with 1-MeV electron irradiation. It is found that (I) a gradual degradation of Si cell properties with fluence is observed under irradiation fluences below 10^{16} cm^{-2} (II) an anomalous increase in short-circuit current I_{sc} and decrease in open-circuit voltage V_{oc} is observed in an intermediate fluence region from 2×10^{16} cm^{-2} to about 5×10^{16} cm^{-2}, and (III) an abrupt decrease in I_{sc} and failure of Si space solar cells are observed under higher fluence irradiation.

In this study, a mechanism for the anomalous radiation degradation of Si space solar cells induced over a wide range of 1-MeV electron irradiation fluences is proposed. As is well known, (I), a gradual degradation of Si cell properties for fluences below 10^{16} cm^{-2} can be understood by minority-carrier diffusion length (lifetime) degradation[1] under high-energy electron irradiation. The change in minority-carrier diffusion length L (lifetime τ) is expressed by:[1]

$$\Delta(1/L^2)=1/L_\phi^2-1/L_0^2=\Sigma I_{ri}\sigma_i v\phi/D=K_L\phi, \tag{1}$$

where suffixes 0 and ϕ indicate values before and after irradiation, respectively, I_{ri} is the introduction rate of recombination centers by electron irradiation, σ_i is the capture cross section of minority carriers by recombination centers, v is the thermal velocity of minority carriers, D is the minority-carrier diffusion length, K_L is the damage coefficient for minority-carrier diffusion length, and ϕ is the electron fluence.

As a mechanism for the last stage of degradation (III) under higher fluence irradiation (above 5×10^{16} cm^{-2}), a decrease in the carrier concentration and an increase in the resistivity in the *p*-type base layer are proposed to account for the abrupt decrease in the I_{sc} of the Si cells. Figure 2 shows calculated and experimental changes in the carrier concentration of the base layer as a function of 1-MeV electron fluence. The change in carrier concentration, Δp, in the base layer is expressed by:[1]

$$\Delta p=p_0-p_\phi=\Sigma I_{tj}f(E_{tj})\phi\approx R_c\phi, \tag{2}$$

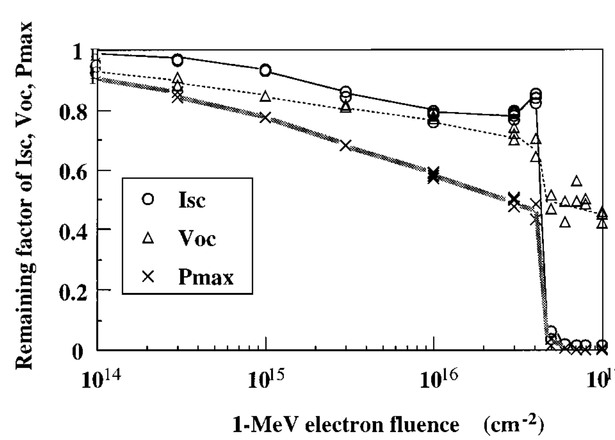

FIG. 1. Changes in the properties of Si space solar cells as a function of 1-MeV electron fluence.

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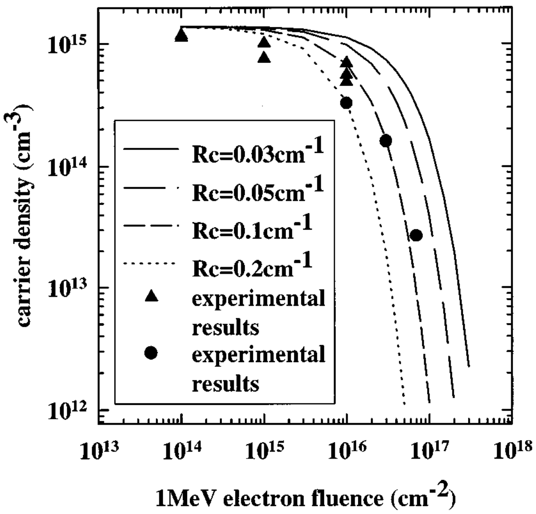

FIG. 2. Calculated and experimental changes in the carrier concentration of the *p*-type base layer as a function of 1-MeV electron fluence.

where I_{tj} is the introduction rate of majority-carrier trap centers by electron irradiation, $f(E_{tj})$ is the capture rate of majority carriers by majority-carrier trap centers, and R_c is the carrier removal rate as a function of electron irradiation fluence. The carrier concentration p_ϕ in the *p*-Si base layer after irradiation is approximated from Eq. (2) as follows:

$$p_\phi = p_0 \exp(-R_c \phi / p_0). \tag{3}$$

The carrier removal rate R_c, determined from $C-V$ measurements for the irradiated *p*-Si base layer is about 0.15 cm^{-1}. As a result of the significant decrease in the carrier concentration in the base layer at high electron irradiation fluences, a significant increase in the series resistance of the Si solar cell is thought to be induced. An increase in the series resistance of the Si cell is expected to gradually cause a decrease in the short-circuit current and subsequently abrupt failure of the Si cell.

As further evidence of this mechanism, the anomalous increase in short-circuit current and decrease in open-circuit voltage (II), observed in the intermediate fluence region from 2×10^{16} cm^{-2} to about 5×10^{16} cm^{-2}, can be explained by broadening of the depletion layer. The resulting increase in the contribution of the depletion region to the short-circuit current leads to an overall increase in short-circuit density J_{sc} but also a decrease in the open-circuit voltage V_{oc} of the solar cells. The contribution of the depletion layer J_D, to the short circuit current J_{sc}, and the open circuit voltage are, respectively, expressed by:

$$J_D = 1 - \exp(-\alpha W), \tag{4}$$

$$V_{oc} = (nkT/q)\ln(J_{sc}/J_0 + 1), \tag{5}$$

$$J_0 \propto qDWn_i/2L^2, \tag{6}$$

where α is the optical absorption coefficient, W is the width of the depletion layer, n is the diode ideality factor, k is the Boltzmann constant, T is the absolute temperature, q is the electronic charge, J_0 is the dark saturation current density, and n_i is the intrinsic carrier concentration.

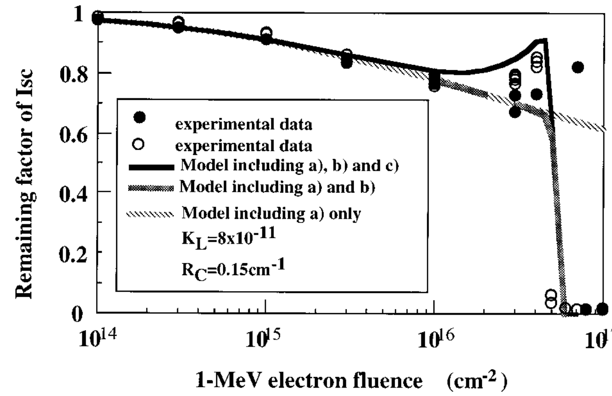

FIG. 3. Comparison of experimental results for short-circuit current degradation of Si space cells with 1-MeV electron irradiation and analytical results calculated by taking into account (a) only degradation of minority carrier diffusion length *L*, (b) degradation of *L* and carrier removal, and (c) degradation of *L*, carrier removal and depletion width broadening.

Therefore, in this analysis, three mechanisms are included: a decrease in minority-carrier lifetime in order to explain (I) the gradual degradation of Si cell properties observed under low fluence irradiation (below 10^{16} cm^{-2}), depletion width broadening to explain (II) the anomalous increase in short-circuit current and decrease in open-circuit voltage in the intermediate fluence region (from 2×10^{16} cm^{-2} to about 5×10^{16} cm^{-2}) and carrier removal to explain (III) the abrupt failure of Si space solar cells under higher fluence irradiation (above 5×10^{16} cm^{-2}). AM0 solar cell properties of Si cells as a function of 1-MeV electron irradiation have been calculated using Eqs. (1), (3), and (4)–(6) and the usual expressions of Hovel.[2]

Figure 3 compares experimental data with modeled results which consider (a) degradation of only the minority-carrier diffusion length *L*, (b) degradation of *L* and carrier removal, and (c) degradation of *L*, carrier removal, and depletion width broadening. The close fit between case (c) and the experimental data supports the analysis outlined above.

Figure 4 shows a comparison of experimental results for short-circuit current degradation of Si space cells with 1-MeV electron irradiation and analytical results calculated

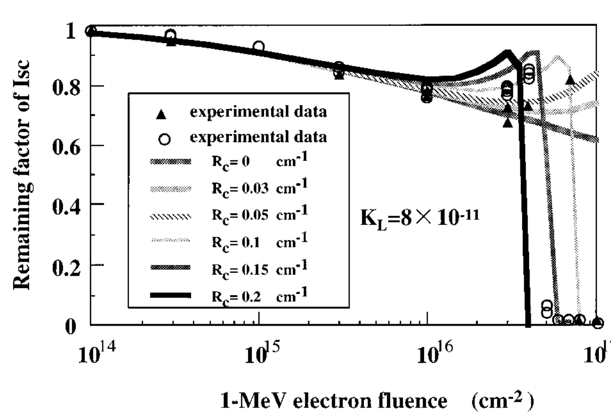

FIG. 4. Comparison of experimental results with modeled values of the decline of the short circuit current I_{sc}, as a function of 1-MeV electron fluence for several values of carrier removal rate R_c.

according to model (c) by using different values of the carrier removal rate R_c. A best-fit of the R_c value to the experimental result was obtained with a value of R_c of 0.1–0.15 cm^{-1}. The damage coefficient for minority-carrier diffusion length K_L determined from fitting to experimental results is 8×10^{-11}.

In conclusion, a model to explain the anomalous behavior, notably an increase in the short-circuit current I_{sc}, followed by an abrupt decrease in I_{sc} and cell failure, induced by high fluence ($>10^{16}$ cm^{-2}) 1 MeV electron irradiation has been proposed. The increase in short-circuit current observed in an intermediate fluence region (from 2×10^{16} cm^{-2} to about 5×10^{16} cm^{-2}) can be explained by depletion width broadening. Abrupt failure of Si cells observed under higher fluence irradiation (above 5×10^{16} cm^{-2}) can be explained by a decrease in the carrier concentration and an increase in the resistivity of the *p*-type Si base layer.

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[1] M. Yamaguchi, C. Uemura, and A. Yamamoto, J. Appl. Phys. **55**, 1429 (1984).
[2] H. J. Hovel, *Semiconductors and Semimetals* (Academic, New York, 1975), Vol. 11, p. 14.