Spectral Response of Gamma and Electron Irradiated Pin Photodiode

S. Onoda, T. Hirao, J. S. Laird, H. Mori, T. Okamoto, Y. Koizumi, and H. Itoh

***Abstract*–The optical spectral response of Si pin photodiodes was examined after gamma and electron irradiation. We observed both a significant decrease in the peak optical response and peak position with increasing total dose. This effect was successfully explained by modeling the degradation of the minority carrier diffusion length in the base region. The diffusion length damage factor was estimated in the context of the Non-Ionization Energy Loss (NIEL). A close agreement was found between the observed degradation behavior and that predicted by NIEL.**

***Index Terms*—pin photodiode, optical spectral response, Non-Ionizing Energy Loss (NIEL), equivalent displacement damage dose, minority carrier diffusion length.**

I. INTRODUCTION

Since photonic devices intended for space must exhibit a high radiation hardness, many studies have examined the effect of various radiation types on the overall device performance [1]. Devices installed on spacecraft are generally shielded from trapped radiation, cosmic rays and solar flares. However, bremsstrahlung produced as high-energy electrons decelerate by stopping in shielding materials easily penetrates most materials. Additionally, the absorbed bremsstrahlung dose can become very large if a device is surrounded by high Z material. Although generated bremsstrahlung fluxes are typically 1 to 2 orders less than that of the primary particle, they can still pose problems to long-term device performance [2].

In recent years, the concept of Non-Ionizing Energy Loss (NIEL) has gained considerable acceptance in describing radiation effects in devices [3]-[5]. According to this concept, the observed degradation is independent of the radiation source. To date however, this concept has mostly been applied to the degradation of solar cell performance parameters such as maximum power, short circuit current, etc. under charged particle irradiation. Using NIEL to analyze device degradations with gamma rays has not been fully investigated in the case of photonic devices. In this paper, we apply the NIEL concept to the degradation of photodiode under gamma and electron irradiations.

II. EXPERIMENTS

The devices examined in this work were commercial Si pin photodiodes. The maximum optical sensitivity is 0.6A/W at 960nm. The junction diameter is 800μm.

All irradiations were performed at the gamma and electron irradiation facilities at the Japan Atomic Energy Research Institute (JAERI), Takasaki. All samples were irradiated at room temperature and in the dark. During irradiations all connections to samples were grounded. Samples extracted from the same batch were irradiated with gamma rays from a 11.3PBq Co^{60} source with an absorbed dose rate of 1kGy(Si)/h. The applied total absorbed dose ranged from about 1kGy(Si) to 1MGy(Si). During irradiations, all samples were set in a 3mm thick Al box to create a uniform electron flux at the sample surface. A Dynamitron electron accelerator was used to perform 1MeV and 2MeV electron irradiations. For these irradiations, cold nitrogen gas was circulated through the sample box to maintain a near constant temperature of about 30°C. This ensured that no in-situ annealing due to high current electron heating occurred. To compare the optical performance degradation due to gamma irradiation with that of electrons, appropriate electron doses were chosen to cover the same range. The applied electron flux was 9.0×10^{11}electrons/cm^{2}s. Irradiation times were selected to give fluences up to 5.0×10^{15}electrons/cm^2.

The quantum efficiency (defined as the ratio of the number of electrons generated to the number of photons) of the irradiated and un-irradiated photodiodes was measured from 300 to 1200nm in 10nm steps using the spectral response measurement system at the National Space Development Agency of Japan (NASDA). The optical spectral response in A/W was converted into QE in %. A Xenon discharge lamp (300-750nm) and a Tungsten Halogen lamp (750-1200nm) were used as light sources. The input light was passed through a monochrometer and its power density was kept at 50 μW/cm^2. The short-circuit current density of the photodiodes due to the input monochromatic light at each wavelength was measured.

III. RESULTS AND DISCUSSION

A. Optical spectral response of pin photodiode

Shown in Fig. 1(a,b) are the typical spectral response curves measured before and after irradiation. Shown on the right of Fig. 1(a) is the calculated average carrier injection level produced by the photon flux. The injection level changes from

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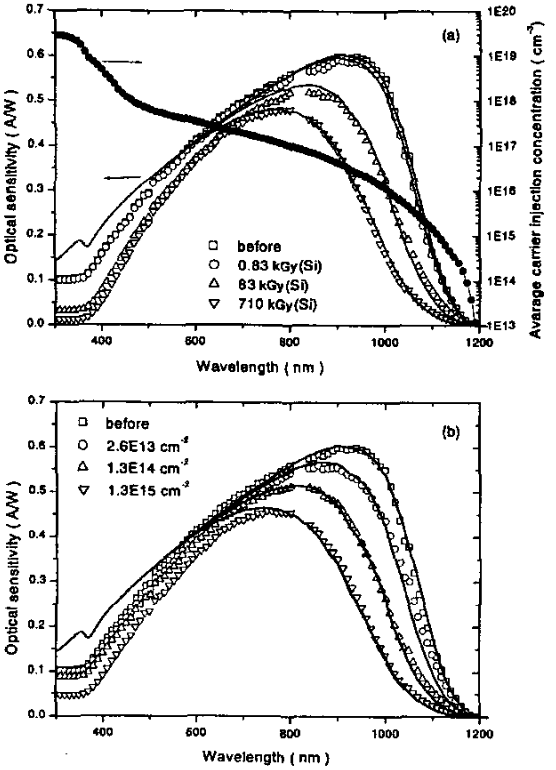

Fig. 1. The optical spectral response of Si pin photodiode irradiated by gamma rays (a) and 1MeV electrons (b). The solid lines are obtained from the Sze model. The solid circles in (a) describe the average carrier injection concentration.

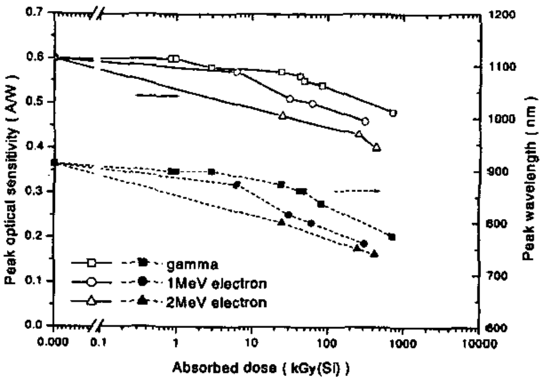

Fig. 2. The peak sensitivity and the peak wavelength of Si pin photodiode after gamma and electron irradiation. The blank symbols and the solid symbols indicate the peak sensitivity and the peak wavelength, respectively. Both the peak sensitivity and the peak wavelength decrease with increasing absorbed dose.

3×10^{19}cm^{-3} at 300nm, to about 1×10^{13}cm^{-3} at 1200nm. Before irradiation, the peak sensitivity of 0.6A/W occurred at 910nm.

For gamma and electron irradiation, the peak optical spectral response is seen to decrease significantly with total absorbed dose, while the peak position shifts towards the blue end of the spectrum. For the gamma case, the peak sensitivity decreased to 0.48A/W and the peak shifted to 775nm after a total absorbed dose of 710kGy(Si). As seen in Fig. 1(b), the peak sensitivity decreases to about 0.46A/W and the peak wavelength shifts to around 760nm after a 1MeV electron fluence of 1.3×10^{15}cm^{-2}. Although not shown here, the peak sensitivity for the case of 2MeV electrons decreased to 0.40A/W and shifted to 740nm after a fluence of 1.7×10^{15}cm^{-2}. Plots of the absorbed dose versus the peak sensitivity, and peak wavelength are given in Fig. 2. The degree of degradation for that of gamma rays is obviously smaller than that of 1MeV and 2MeV electrons.

The optical spectral response of a pin photodiode can be calculated by assuming the total photon-induced current I_{tot}, which is the sum of the drift current in depletion layer as well as any diffusion current. If the width of the p-layer is much thinner than the inverse absorption coefficient, $1/\alpha$, the photo-induced current in the p-layer does not contribute to the total photon-induced current. In this case, the optical sensitivity, S, of a pin photodiode can be expressed as follows:

$$S = \frac{I_{tot}}{P_{opt}} = \frac{q\eta}{h\nu} \tag{1}$$

where the quantum efficiency, η, is given by:

$$\eta = (1-R)\left(1-\frac{e^{-\alpha W}}{1+\alpha L_p}\right) \tag{2}$$

where P_{opt}, q, $h\nu$, R, α, W, and L_p are the incident optical power, electronic charge, photon energy, reflective coefficient, absorption coefficient, depletion width, and minority carrier diffusion length, respectively [6]. Capacitance-voltage (C-V) measurements were used to calculate the built-in junction width. Absorption coefficients were taken from literature [6]-[8]. Ideally, the influence of interference waves between the top Si layer and substrate should be accounted for in the calculation of R. However, an exact calculation of R is difficult in this case and a first order estimation is made from the Si refractive index and extinction coefficient [7]. This assumption is valid for the near-infrared region for which the device was designed. There are several reasons for the marked difference below 500nm. The first, and most likely reason is that the anti-reflection (AR) coating on the surface attenuates wavelengths outside of those typically applied (i.e. near-infrared). The second possibility is that the very high-injection levels present below 450nm may decrease the Auger lifetime in the surface region, leading to a small reduction in the optical responsivity.

As a function of dose, the experimental data indicated in Fig. 1 are in good agreement with that predicted in the near-infrared region. As detailed above, the response in the low-wavelength region is not as well described. The increasing disagreement with dose may be due to several reasons. This may be explained by R that has increased with increasing dose, and/or, the

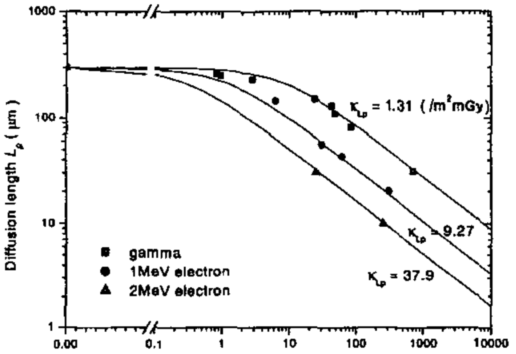

Fig. 3. The minority carrier diffusion length in base layer is shown as a function of absorbed dose. The diffusion length damage factors κ_{Lp}, which are estimated with (3), are also shown.

diffusion length in the p-layer has also decreased with dose. Previous reports in literature have stated that R is independent of dose for 1MeV electron irradiations up to 5×10^{15}cm^{-2} [9],[10]. Hence, it is more likely that the diffusion length in the p-layer is decreasing with increasing dose. However, since this device is primarily designed to operate within a narrow band around 960nm, we are not as concerned with modeling the degradation in the low-wavelength region of the spectrum. Any difference between the calculated and observed sensitivity in the low-wavelength region is of no significance here.

By fitting (1) to the experimental data, both L_p and the diffusion length damage factor, κ_{Lp}, were estimated. The degradation in L_p can be expressed by the following equation:

$$\frac{1}{L_p}=\sqrt{\left(\frac{1}{L_{p0}}\right)^2+\kappa_{L_p}\phi} \tag{3}$$

where L_{p0} and ϕ are the initial diffusion length and fluence, respectively [7],[11]. Fig. 3 shows L_p as a function of dose as well as a least-squares fit to the data. The calculated damage factors have also been included. Carrier removal at high doses can also influence the measurement of L_p. However, C-V measurements have shown little evidence of carrier removal up to fluences of 5×10^{15}cm^{-2} and 1×10^{15}cm^{-2} for 1MeV and 2MeV electrons, respectively. Hence, carrier removal effects have been ignored in this analysis.

B. Radiation damage in pin photodiode

The use of the Non-Ionizing Energy Loss (NIEL) for correlating radiation degradation with electrical performance has been successfully applied to a variety of devices, over a wide fluence range. In this section, we give a brief review of the NIEL concept and apply it to the collected data. NIEL values for charged particles and gamma rays are given in literatures [3],[12]-[14]. For this work we assumed NIEL values of 31.42, 50.69 and 13.08 eVcm^2/g for 1MeV, 2MeV electrons and gamma rays, respectively [12]. In the case for gamma rays, the NIEL value assumes a contribution from the entire compton spectrum. Another commonly used definition is that of the equivalent displacement damage dose (EDDD), D_{eq}. The NIEL and EDDD are related to one another by the following expression:

$$D_{eq}=\int_{E_{\min}}^{E_{\max}}\Phi(E)\cdot NIEL(E)\cdot Q(E)^{n-1}\,dE \tag{4}$$

where $\Phi(E)$, E_{min} and E_{max} are the differential electron fluence, minimum electron energy required for displacement and maximum incident electron energy, respectively [12]-[14]. The quality factor, $Q(E)$, is defined as:

$$Q(E)=\frac{NIEL(E)}{NIEL(E_{ref})} \tag{5}$$

where $NIEL(E)$ is the energy dependence of the NIEL values and $NIEL(E_{ref})$ is the NIEL value for a reference particle with a reference energy, E_{ref}, such as 1MeV electrons [12]. Values for n have been measured by Messenger et al. to be 1 and 2 in n- and p-type Si, respectively. However, reasons for the difference

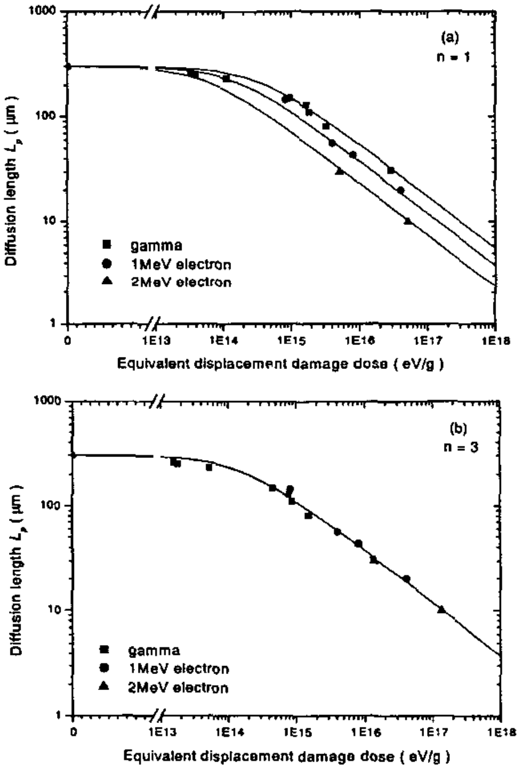

Fig. 4. The minority carrier diffusion length in base layer as a function of EDDD. The EDDD are calculated using n = 1 (a) and n = 3 (b). The diffusion length damage factor of 7.0×10^{-9}g/keVcm^2 is obtained from (b).

between n- and p-type materials are not fully understood as no concrete theoretical framework has been developed [14]. For an n value of 1, the calculated EDDD profiles do not fit the experimental data shown in Fig. 4(a). Best agreement between theory and data was obtained for an n value of 3. For an n value of 3, the degradation in L_p as a function of EDDD is displayed in Fig. 4(b). In certain situations, the normal NIEL parameters have been known not to fit observed device degradation. Ruzin et al. found that the presence of C and O in Si complicates NIEL analysis [15]. Furthermore, Khan et al. reported that the defect introduction rate changed in the presence of B and Ga [16]. Hence, the value of n depends on both the impurity type and concentration. A value of 3 is not out of the question given the different fabrication technologies for producing solar cells ($n = 1$ for n-type Si) and the photodiodes measured here ($n = 3$ for n-type Si). For an n value of 3 the diffusion length damage factor is estimated to be 7.0×10^{-9}g/keVcm^2. Fig. 5 shows the peak sensitivity and wavelength as a function of EDDD. With an n value of 3, the EDDD fits are in good agreement with the measured data.

To explain the degradation in peak sensitivity, a semi-empirical equation describing the degradation of solar cell performance is introduced. An equation describing the degradation of the short circuit current, I_{SC}, as a function of EDDD is given by:

$$I_{SC} = I_{SC0} - C\log\left(1+\frac{D_{eq}}{D_x}\right) \qquad (6)$$

where I_{SC0} is the initial short circuit current and C is a constant [7]. The displacement damage dose, D_x, is the knee point at which the logarithm of EDDD becomes linear, and is given by:

$$D_x = 1/\kappa_{Lp}L_{p0}^2\,. \qquad (7)$$

The estimated values κ_{Lp} of 7.0×10^{-9}g/keVcm^2 and L_{p0} of 300μm were used to calculate a D_x value of 1.6×10^8MeV/g. Since the optical response of pin photodiodes is expected to degrade in a similar manner to that of solar cells, we are justified in applying (6) to the results. The peak sensitivity and wavelength of C were calculated to be 0.06A/W and 60nm, respectively. The good fits shown in Fig. 5 suggest these parameter values satisfactorily describe the degradation process. Although the above equations are borrowed from solar cell degradation studies, it appears to be suitably general as to also describe degradation in pin photodiodes.

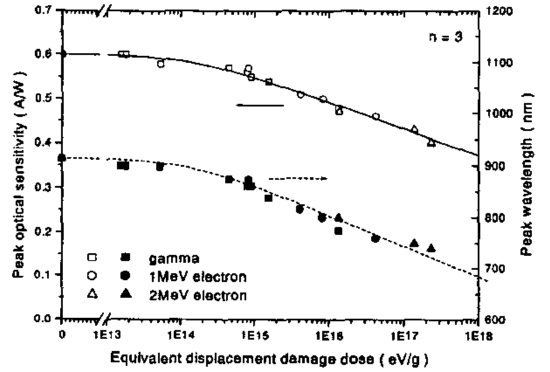

Fig. 5. The peak sensitivity and the peak wavelength of Si pin photodiode as a function of EDDD after gamma and electron irradiation. The blank symbols and solid symbols represent the peak sensitivity and the peak wavelength, respectively. The solid and dash lines are obtained by (6).

IV. SUMMARY

These results illustrate the optical response degradation of Si pin photodiodes subjected to irradiation with Co^{60} gamma rays, 1MeV and 2MeV electrons. We observed a marked change in the optical response curve with increasing total absorbed dose. This degradation was attributed to radiation induced degradation of the minority carrier diffusion length in the base layer. Diffusion length damage factors were estimated and analyzed in terms of NIEL and EDDD. The EDDD completely described the experimental data for an n value of 3. The difference between the estimated value of n and that reported previously in literature is postulated to be due to a difference of impurities presented in Si pin diodes as opposed to those found in other samples used in literature. A revised diffusion length damage factor of 7.0×10^{-9}g/keVcm^2 was obtained by the relevant equation to the experimental data. The estimated κ_{Lp} and L_{p0} values were used to obtain D_x value of 1.6×10^8MeV/g and C values of 0.06A/W and 60nm for the respective peak sensitivity and wavelength.

V. CONCLUSION

We have successfully applied the NIEL concept to the study of radiation induced degradation in Si pin photodiodes. For the case of n-type material used in these photodiodes a revised n factor of 3 was determined.

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REFERENCES

[1] J. E. Gover, and J. R. Srour, *Basic radiation effects in nuclear power electronics technology.* SAND85-0776, Unlimited Release Reprinted April 1986.

[2] IEEE Nuclear and Space Radiation Effects Conference (NSREC) 1997 Short Course, Section I, Dec 1997

[3] S. R. Messenger, E. A. Burke, G. P. Summers, M. A. Xapsos, R. J. Walters, E. M. Jackson, and B. D. Weaver, "Nonionizing energy loss for heavy ions," *IEEE Trans. Nucl. Sci., Vol. 46, No. 6, 1999, pp. 1595-1602.*

[4] P. W. Marshall, and C. J. Dale, "Space radiation effects on optoelectronic materials and components for a 1300 nm fiber optic data bus," *IEEE Trans. Nucl. Sci., Vol. 39, No. 6, 1992, pp. 1982-1989.*

[5] S. R. Messenger, E. M. Jackson, E. A. Burke, R. J. Walters, M. A. Xapsos, and G. P. Summers, "Structural changes in InP/Si solar cells following irradiation with protons to very high fluences," *J. App. Phys., Vol. 86, No. 3,1, 1999, pp. 1230-1235.*

[6] S. M. Sze, *Physics of semiconductor devices, 2^{nd} Edition.* John Wiley & Sons, Inc., 1981.

[7] B. E. Anspaugh, *GaAs solar cell radiation handbook.* JPL Publication 96-9, July 1996.

[8] E. D. Palik, *Handbook of optical constants of solids.* Academic Press, Inc., 1985.

[9] H. L. Cotal, S. R. Messenger, R. J. Walters, and G. P. Summers, "Spectral response of electron-irradiated homoepitaxial InP solar cells," *Photovoltaic Specialists Conference, 1996, pp. 219 –222.*

[10] R. J. Walters, S. R. Messenger, H. L. Cotal, M. A. Xapsos, S. J. Wojtczuk, H. B. Serreze, and G. P. Summers, "Radiation response of heteroepitaxial n^+p InP/Si solar cells," *J. App. Phys., Vol. 82, No. 5,1, 1997, pp. 2164-2175.*

[11] Y. Morita, T. Ohshima, I. Nashiyama, Y. Yamamoto, O. Kawasaki, and S. Matuda, "Anomalous degradation in silicon solar cells subjected to high-fluence proton and electrons," *J. App. Phys., Vol. 81, No. 9, 1997, pp. 6491-6493.*

[12] G. P. Summers, E. A. Burke, P. Shapiro, S. R. Messenger, and R. J. Walters, " Damage correlations in semiconductors exposed to gamma, electron and proton radiations," *IEEE Trans. Nucl. Sci., Vol. 40, No. 6, 1993, pp. 1372-11379.*

[13] Xapsos, G. P. Summers, C.C. Blatchley, C. W. Colerico, E. A. Burke, S. R. Messenger, and P. Shapiro, " Co^{60} gamma ray and electron displacement damage studies of semiconductors," *IEEE Trans. Nucl. Sci., Vol. 41, No. 6, 1994, pp. 1945-1949.*

[14] S. R. Messenger, M. A. Xapsos, G. P. Summers, and E. A. Burke, " Co^{60} gamma ray irradiations of solar cells: a new way to predict space radiation damage," *IEEE First World Conference on Photovoltaic Energy Conversion, Vol. 2, 1994, pp. 2153 -2156.*

[15] A. Ruzin, G. Casse, M. Glaser, A. Zanet, F. Lemeilleur, and S. Watts, " Comparison of radiation damage in silicon induced by proton and neutron irradiation," *IEEE Trans. Nucl. Sci., Vol. 46, No. 5, 1999, pp. 1310-1313.*

[16] A. Khan, M. Yamaguchi, Y. Ohshita, N. Dharmarasu, K. Araki, T. Abe, H. Itho, T. Ohshima, M. Imaizumi, and S. Matsuda, "Role of the impurities in production rates of radiation-induced defect in silicon materials and solar cells," *J. App. Phys., Vol. 90, No. 3, 2001, pp. 1170-1178.*