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Effects of ionizing radiation on the properties of mono-crystalline Si solar cells

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ABSTRACT

Mono-crystalline Si solar cells were irradiated by cLINAC with electrons of 8 MeV and Bremsstrahlung photons obtained from electrons of 18 MeV. Systematic dose experiments were conducted with both irradiation types. The current-voltage, capacitance-voltage, conductance-voltage and external quantum efficiency analysis were carried out to investigate the overall effect of radiation on the crystalline Si solar cells. From these measurements, we summarized short-circuit currents, open-circuit voltage, fill factor and efficiency of prepared samples with respect to total applied dose and radiation types. All systematic experiments, measurements and calculations clearly indicate that solar cells are very sensitive to irradiation and nearly all parameters are seem to be decreased with respect to applied dose, regardless of radiation types. Moreover, overall efficiency of the solar cells are degraded by ~ 15 % due to the irradiation which requires more attention for radiation protection of photovoltaic devices in the radiation harsh environments.

1. Introduction

Solar cells (SCs) are the prominent renewable power sources converting lights to an electrical energy. Due to the its advantageous (Binetti et al., 2013), mono-crystalline Si wafers are used in commercial SCs (Shin et al., 2017). Recent studies showed that semiconductors are very sensitive to irradiation and they are very prone to changes in their optical and electrical properties (Srour and Palko, 2013; Kabacelik et al., 2017). The charged particles and high energy photons may produce very large number of lattice defects and ionization effects in semiconductor crystals (Tobnaghi et al., 2014). Since these defects in crystals limit transport properties and lifetime of minority charge carriers, electrical properties of SCs degrades significantly (Vasic et al., 2008). The main results of these defects are the new energy levels in semiconductor materials. These irradiation induced energy levels act as trap-energy levels. Minority carrier recombination centers cause coupling of electrons and holes in SCs by absorption of light. Since the minority charge carriers in base layer of p-n junction are reduced, the overall performance of SCs are also deteriorated. On the other hand, trapping of majority charge carriers by the new energy levels give rise to problems in electrical conductivity of material (Hauser and Kerns, 1990). As a result, electrical conductivity of SCs exposed to radiation is decreased and turned into highly resistant structure. Since SCs are employed in space applications consisting of highly energetic electrons and photons, a very large number of attempts have been performed to discover the effects of radiation on the properties of SCs.

High energy photons (Ashry and Fayek, 2001; Tuzmen et al., 2008; Radosavljevic and Vasic, 2012; Ali et al., 2013; Zhang et al., 2014; Stojanovic et al., 2015), neutrons (Radosavljevic and Vasic, 2012; Simic et al., 2013) and accelerated charged particles (electron, proton or ion) (Ashry and Fayek, 2001; Sato et al., 2009a, 2009b; Becker et al., 2014; Getman, 2014; Hamache et al., 2014; Yanhui et al., 2015; Sato et al., 2015) are used to observe the effect of irradiation on the electrical properties of SCs. Displacement damage dose calculations (Warner et al., 2005) allows one prediction of degradation of solar cell output parameters exposed to charged particles. Except for Radosavljevic and Vasic (2012), Zhang et al. (2014), and at relatively lower doses, almost all researchers found that regardless of the type of radiation and mono-energetic beams overall efficiency of the SCs showed a significant decrease. However, there are not many efforts to compare effects of electrons and poly-energetic photons on degradation behavior of Si solar cell. Therefore, the main purpose of this current work is to compare degradation of Si solar cell samples exposed to 8 MeV electrons and Bremsstrahlung photons.

Nowadays, clinical Linear Accelerators (cLINAC) modified for research applications are used to discover the effect of irradiation on semiconductors. cLINACs can generate both high energy electron (e^--) beams and photon beams via Bremsstrahlung effect. In this work,

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cLINAC was used to obtain 8 MeV e^-- and maximum energy of 18 MV photon beams. Complete analysis and systematic dose experiments were conducted on prepared mono-crystalline SCs before and after the irradiation process. Moreover, radiation hardness of mono-crystalline SCs were tested relatively for both e^-- and photon beams.

2. Experiments

A modified cLINAC (Elekta Systems) was employed for generation of an e^- and a photon beams. In cLINAC, a 50 keV potential difference was applied to an electron gun to allow emission of e^- s. Then emitted e^- s, accelerated by radio frequency at ~ 3 GHz, are collimated by magnetic and electrostatic components. While 8 MeV e^--beam from cLINAC were directly sent to the SCs, 18 MeV energy of e^--beam was sent to a tungsten target. The average beam current of LINAC is 30 μA and this collision causes production of photons in the range of 0–18 MV through Bremsstrahlung effect which was then forwarded to the SCs. All irradiation facilities were conducted under ambient conditions at room temperature. The dose rate was also guaranteed to be constant at 7.5 Gy/min providing that the distance between SC sample and the radiation source unchanged. The electron fluence is 16×10^{10} electron/cm^2 for 1 Gy irradiation dose in 8 MeV e^--beam case. Since we use poly-energetic photons for another irradiation type, energy distribution, photon energy and electron flux can be estimated from Boztosun et al. (2015) for our case. The photon fluence is estimated as 4×10^6 photons/cm^2 at E = 6 MeV for 1 Gy irradiation dose.

Before irradiation experiments, we first prepared the SC samples (named Set 1 and Set 2). Czochralski-grown, 160- μm-thick, p-type Si wafers in (100) crystallographic direction doped with Boron concentration of $5 \times 10^{16}\ cm^{-3}$, with a resistivity of 1–3 Ω.cm and with dimensions of 156 mm × 156 mm, were used for SC fabrication. Surface damages resulted from the mechanical cutting were removed by an isotropic etching technique with a concentrated alkaline potassium hydroxide (KOH) solution. Then, not only residues and debris but also the thin SiO_2 layer that naturally present on the surface of Si wafers were cleaned by exposing the Si samples to an ultrasonic cleaner of hydrochloric acid (HCl), hydrofluoric acid (HF) and deionized water solutions for a duration of 10 min. Surface texturing keeps reflected light away from the substrate and improves the light absorption that yields enhanced amount of light converted into photocurrent in Si SC. Therefore, p-Si surfaces were textured by wet anisotropic KOH (chemical) etching technique. The pyramid structures created on the surface of the SC lead to multi-reflection of incident light from the surface. After pyramidal texturing and nanowire formation were obtained, the emitter layer was formed by phosphorus diffusion with a thickness of 500 nm and concentration of $5 \times 10^{20}\ cm^{-3}$, resulting in a sheet resistance of 50 Ω/sq on a standard wafer. Following the removal of phosphorus glass through dipping the substrates into a 5% HF solution, a 80-nm-thick silicon nitride (Si_3N_4) layer was deposited via plasma-enhanced chemical vapor deposition for surface passivation. The silicon nitride layer also acts as an anti-reflective (AR) coating. Deposition of back aluminum (Al) and front silver (Ag) contacts through screen printing of ~30 μm thickness was followed by a co-firing process at 875 °C. Finally, edge isolation was performed by a laser scribing. The structure of fabricated SCs is shown in Fig. 1.

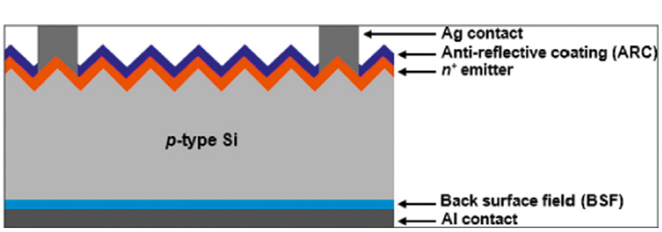

Fig. 1. Structure of fabricated Si Solar Cells.

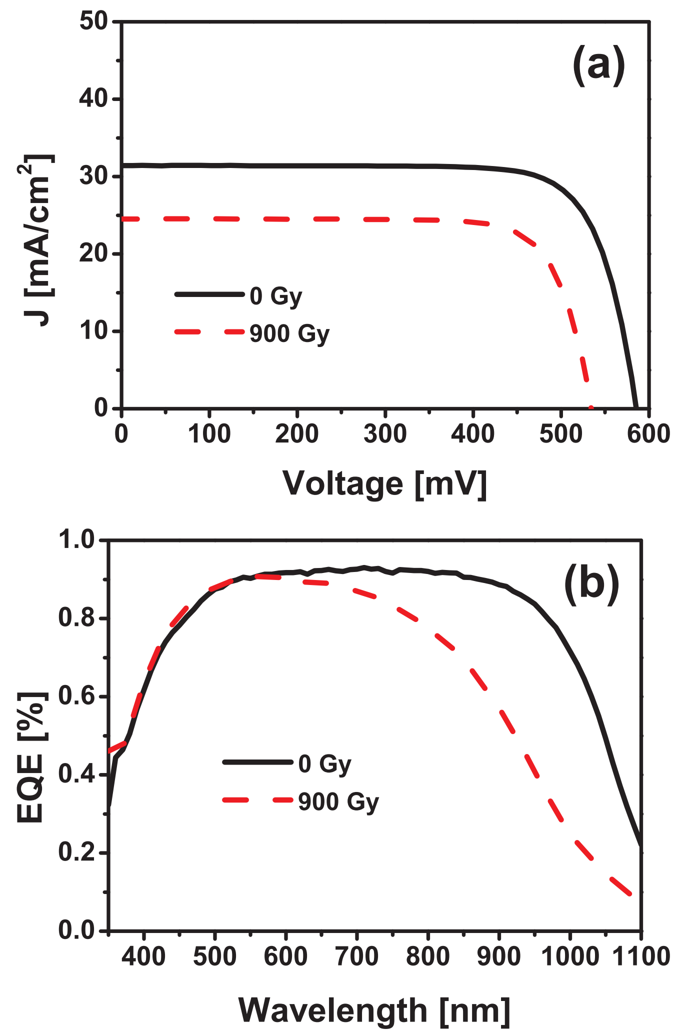

Fig. 2. (a) Current density and (b) External Quantum Efficiency (EQE) measurements of un-irradiated (0 Gy) and irradiated (900 Gy) samples with an electron beam of 8 MeV peak energy.

After edge isolation, the large area fabricated SC (from Set 1 and Set 2) was divided into small SCs pieces in which the process ensure the equality of SCs in our experiments. Small SCs obtained from Set 1 were exposed to electron irradiation while the other small SCs from Set 2 were exposed to photon beam. After the sample preparation, different c-Si SCs were exposed to two types of irradiation (electron and photon beams) at different doses with a constant dose rate. In order to see the effect of irradiation, following characterizations and calculations were performed before and after irradiation process for each sample.

The current-voltage (I-V), capacitance-voltage (C-V), conductance-voltage (G/ω-V) and external quantum efficiency (EQE) characteristics of all c-Si SCs were measured before and after irradiation. Measurement of I-V character of the Si SCs were conducted under illumination conditions. For an illumination, the AM 1.5 G solar simulator (power density 800 W/m^2) controlled with Newport I-V test software was utilized. C-V and G/ω-V measurements were performed at a constant frequency of 100 kHz by using an HP 4192A LF impedance analyzer. EQE measurements were performed using an apparatus equipped with a monochromator, an optical chopper, a lock-in amplifier and a calibrated light detector. All characterizations were conducted in ambient conditions at room temperature.

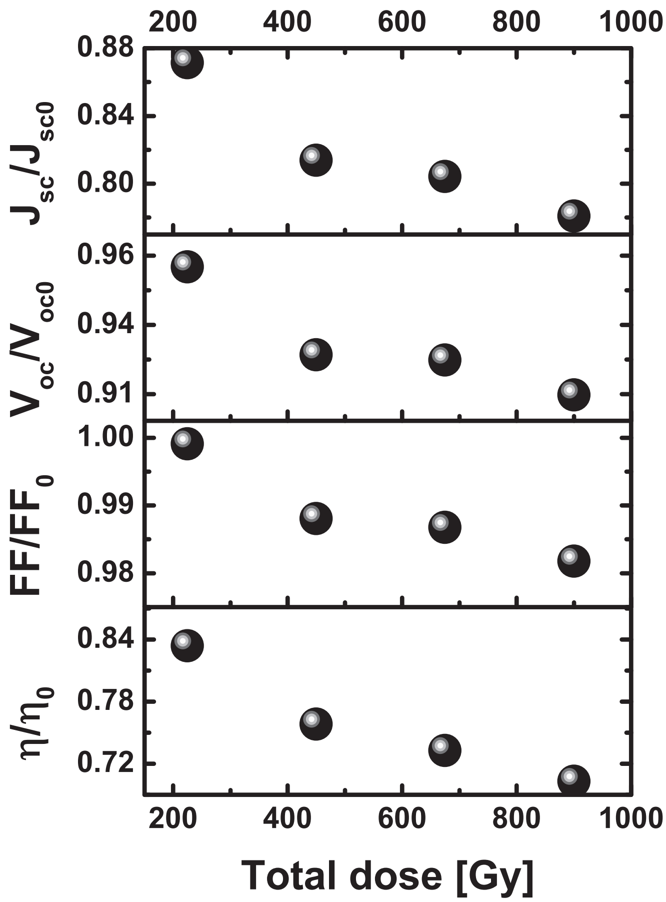

Fig. 3. Calculated Solar-Cell parameters from electron beam irradiated samples with respect to total applied dose.

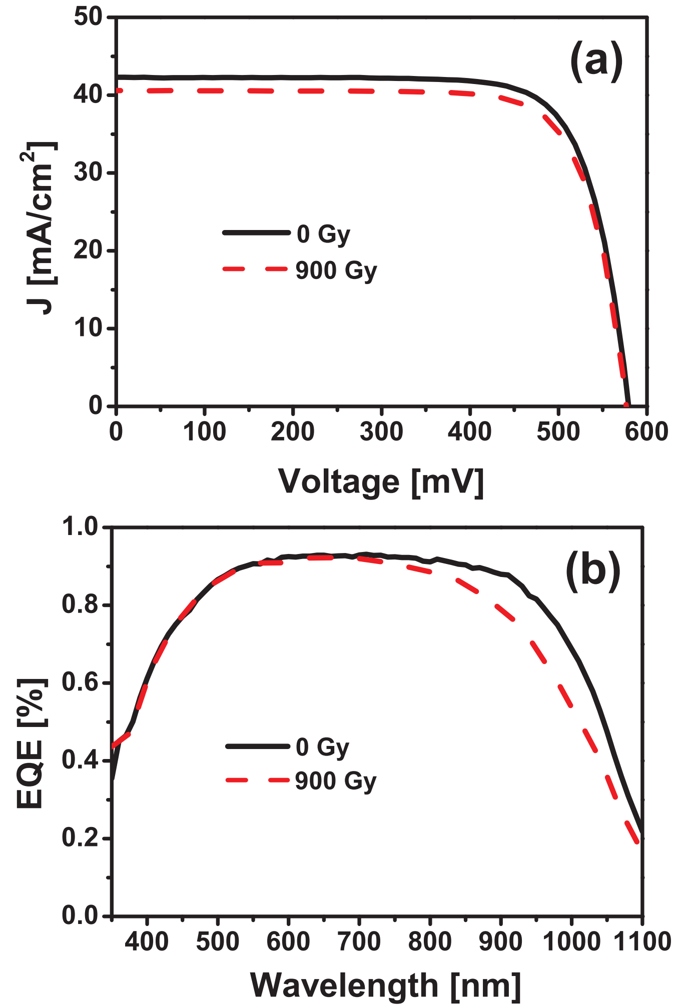

Fig. 4. (a) Current density and (b) External Quantum Efficiency (EQE) measurements of un-irradiated (0 Gy) and irradiated (900 Gy) samples with photon beam of 18 MV peak energy.

3. Results and discussions

All prepared SCs were characterized prior to irradiation to ensure that they presented equal output parameters under the same conditions. Then, SCs were exposed to 2-types of radiation at different doses to observe both the effect of total dose and type of radiation. Even after the irradiation, the current-voltage (I-V), capacitance-voltage (C-V), conductance-voltage (G/ω-V) and external quantum efficiency (EQE) measurements were carried out.

From I-V measurements, fundamental parameters of solar cells such as short circuit current (I_{SC}), open circuit voltage (V_{OC}), fill factor (FF) and efficiency (η) could be extracted by using the following expressions.

$$I_{SC} \approx I_L \tag{1}$$

$$V_{OC} \approx \left(\frac{kT}{q}\right) \times ln\left(\frac{I_L}{I_0} + 1\right) \tag{2}$$

$$FF = (V_{max} \times J_{max})/(V_{OC} \times J_{SC}) \tag{3}$$

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{OC} \times J_{SC} \times FF}{P_{in}} \tag{4}$$

In these expressions, k is the Boltzmann constant and T is the temperature where q is the charge of the e^-. I_L and I_0 are the light generated and dark saturation currents, respectively. In addition, V_{max} and J_{max} are the Voltage and Current density at a point of P_{max}. Moreover, P_{max} and P_{in} define the maximum power and the power of incident light, respectively.

We, first, started our experiment with 8 MeV energy of e^- beam then gradually increased the total applied dose by changing the exposure time with 30 min intervals while measuring the I-V curve of irradiated SCs. EQE of the irradiated samples was also measured after each I-V measurements. Fig. 2 indicates results of I-V and EQE measurements acquired from 2-hour irradiation of 8 MeV e^--beam and unirradiated SCs samples. Fig. 2 (a) clearly shows that irradiation with electron beam causes decrease in I-V curve. Effects of irradiation on I_{SC} and V_{OC} values of SCs are also obvious. Moreover, in the EQE measurement shown in Fig. 2 (b), there appears to be a significant decrease in long wavelength ($\lambda \geq$ 600 nm) region. This indicates that the crystal defects resulting from exposure of the c-Si SC to electron beam are deeper than the surface of the SC (Imaizumi et al., 1997). Since minority charge carriers formed in the inner part of the SC are short-lived, they merge at the re-junction centers before they are collected by the electrodes, reducing the SC performance. From I-V measurements at different doses, fundamental SC parameters are calculated by using above equations. Fig. 3 shows calculated SC parameters with respect to total applied dose. All results obtained from irradiated SCs are divided by calculated values from I-V measurements acquired from unirradiated SCs for normalization. It can be clearly seen from Fig. 3 that as the total applied dose increases, all the output parameters of SCs decrease. The source of changes in electrical properties of SCs is gradual decrease in lifetime of minority charge carriers via generating new energy levels inside the band-gap due to irradiation. Moreover, this decrease in minority charge carrier concentration causes decrease of short-circuit current (I_{SC}) by the photon absorption. On the other hand, dark saturation current increases with respect to total applied dose due to the increase in amount

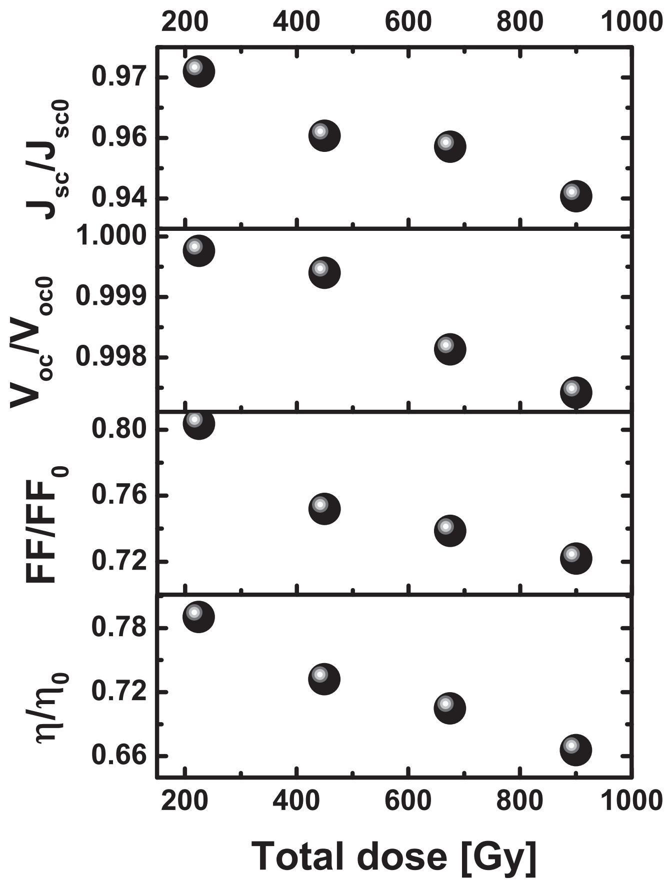

Fig. 5. Calculated Solar-Cell parameters from photon beam irradiated samples with respect to total applied dose.

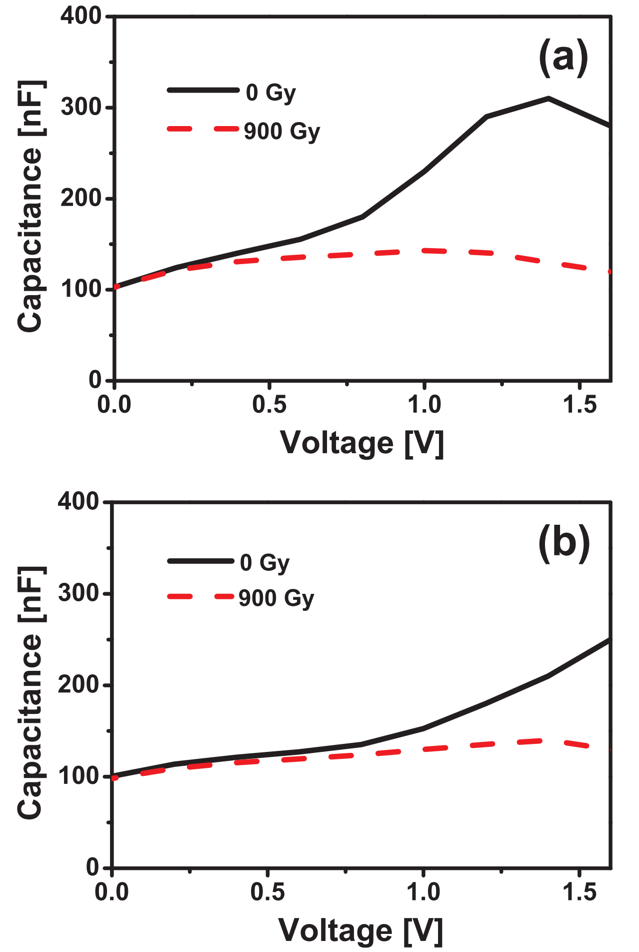

Fig. 6. Comparison of C-V characteristic behavior of (a) electron and (b) photon beam irradiated samples at 100 kHz.

of recombination centers (Zhang et al., 2014) while the open-circuit voltage (V_{OC}) shows a decrease in opposite direction (see Eq. (2)). As a result, FF and η are also reduced proportional to the degradations of I_{SC} and V_{OC}.

For a comparison, we repeated all the experiments mentioned above with the photon beam. Fig. 4 indicates I-V and EQE measurements from unirradiated and 2-hour irradiated SCs with Bremsstrahlung photon beam. Although we observed similar results, the degradation in J_{SC} and V_{OC} was much smaller than the degradation of SCs irradiated with 8 MeV of e^--beam for our setup.

We also calculated whole SC parameters for photon beam irradiated samples. Fig. 5 shows calculated values at different doses. We observed similar trend with our previous results on SC samples exposed to e^- beam radiation. When I_{SC} and V_{OC} values are compared for both type radiation, it can be seen that the variation in SC parameters exposed to e^- beam are higher. Thus, one can think that accelerated charged particles are much harmful for SCs. In other words, the life-time of minority charge carriers in SC exposed to photon beam is longer than that of SC damaged by charged particles.

C-V measurements were also conducted on unirradiated and irradiated samples. C-V measurements of SC samples exposed to 8 MeV e^- beam and 18 MV peak energy of photon beam under dark conditions are presented in Fig. 6. C-V measurements are conducted at 100 kHz and explicit decreases are observed for both irradiation types. Moreover, the change in C value was relatively higher when the SC was exposed to e^- beam radiation. This reduction stems from decrease in number of minority charge carriers due to the damage by irradiation on SCs. Since we measured C values at low frequency regime, we could not observe an explicit change in C values at the negative voltages as observed in Bhat et al. (2015).

The G/ω-V measurements of the SCs were also performed before and after various e^- and photon beam irradiation at 100 kHz and results are presented in Fig. 7. Although the conductance of irradiated SCs decreases, reduction in conductance in e^- beam irradiated SC is much higher for our setup. This can be explained by trapping of majority charge carriers by crystal defects becoming much higher for charged particle irradiated SC case. These crystal defects make the SC resistant to electrical current and reduce the conductance.

4. Conclusion

In conclusion, irradiation hardness, effects of different types of irradiation and total applied dose on the output parameters of monocrystalline SCs were systematically analyzed through experiments and subsequent calculations. Measurements show that both C-V and G/ω-V were effected by irradiation. Calculated parameters from I-V measurements were clearly reduced by the amount of applied radiation dose. Although output parameters were much degraded in e^--beam case, overall decrease in the η was nearly the same for both radiation types. These results presented here emphasize the importance of radiation protection for SCs used in space applications.

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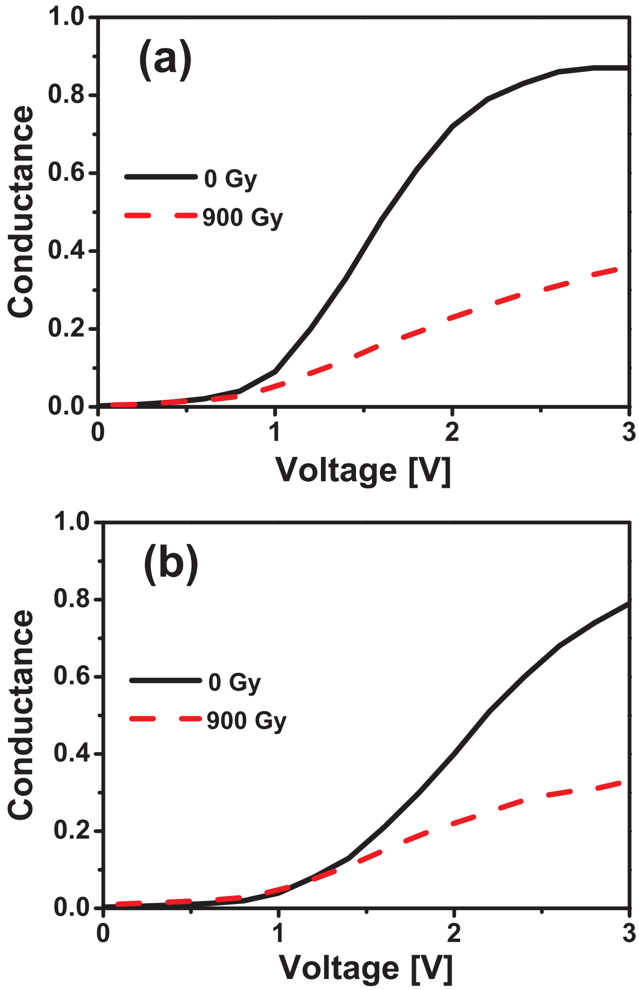

Fig. 7. Comparison of conductance properties of (a) electron and (b) photon beam irradiated samples.

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