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1-MeV electron irradiation effects on InGaAsP/InGaAs double-junction solar cell and its component subcells

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Solar cells (SCs) are used as the primary source of power in satellites and other space missions, and operate in a harsh radiation environment in orbit. The demand for power has been increasing in various space tasks. Space applications require high radiation hardness and power-to-mass ratio for SCs. In the past decade, high efficiency (30% at AM0, 1 sun), lattice-matched, GaInP/GaAs/Ge triple-junction solar cells (3JSC) were chosen for the main power source in spacecrafts and satellites. The key to improving the radiation hardness of the triple-junction GaInP/GaAs/Ge solar cell is reducing the damage of the base-zone of GaAs subcell as much as possible. A four-junction SC fabricated by wafer bonding technique and with a higher efficiency has been reported (46% at AM1.5, 508 suns) [1]. It is a promising candidate for future space solar cells which can meet the requirements of heavy payloads in space missions, however, research on radiation performance of four-junction SCs is still in its early stage. Although extensive literature is available on radiation damage of multi-junction structures [2,3], the analysis of cell degradation remains a topic of keen scientific interest and debate due to the extreme complexity of cell configuration. Besides, most of the previous studies focused on the analysis of irradiation damage either in single-junction solar cells or in multi-junction solar cells as a whole. It has been recently reported that the degradation of the bottom dual-junction subcell (InGaAsP/InGaAs) within a wafer-bonded four-junction SC is more serious than that of the top dual-junction subcell (GaInP/GaAs) [4]. Our study focused on the damage mechanism mainly in the InGaAsP single-junction SC, InGaAs single-junction SC and in the InGaAsP/InGaAs double-junction SC.

In the present work, InGaAsP/InGaAs double-junction SC and its two component subcells (InGaAsP single-junction SC and InGaAs single-junction SC) were grown by MOCVD technique and integrated into four-junction SC, and were irradiated by 1-MeV electrons. External quantum efficiency (EQE), light I-V and dark I-V charac-

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teristics of the fabricated cell were studied in order to evaluate the cell performance before and after irradiation. In addition, the trajectory of the electron beam across the material was simulated by CASINO software.

Experiment. The schematic of the device structure is shown in Figure 1(a) (see Supporting information online). The compositions of $In_{0.78}Ga_{0.22}As_{0.48}P_{0.52}$ and $In_{0.53}Ga_{0.47}As$ were lattice-matched to the InP substrate. Each cell is comprised of a p-type base layer, an n-type emitter layer, and hetero-junctions that serve as back-surface field (BSF) layer and window layer so as to reduce surface recombination. Silicon and Beryllium were used as the n- and p-type doping sources, respectively.

The InGaAsP/InGaAs double-junction solar cell and its component subcells were irradiated with a 1-MeV electron beam derived from an ELV-8 II vertical electron accelerator. Referring to ISO 23038-2006, the flux was adjusted to obtain the desired total fluence in a specific interval of time, and the electron flux obtained was typically in the range of 10^9–10^{12} electrons/cm^2/s[1]. In our experiment, the electron fluence varied from 1×10^{14} to 1.5×10^{15} e/cm^2. To observe the solar cell degradation with increasing radiation dose, the electron beam was interrupted at four different stages (at intervals of 80 min approximately) for each solar cell and ex-situ measurement of I-V, dark I-V and EQE were conducted. This is considering that the displacement damage is an accumulative process and that the radiation-induced defects in GaAs material cannot be annealed out at room temperature and in such a short span of time. Therefore, the time interval for the ex-situ measurement will not affect the radiation effects in the SCs.

Results and discussion. Figure 1(b) shows the simulated trajectory of electron beam across the material using CASINO software. Different colors represent different electron energies. When electrons of 1-MeV energy move across the active zone of a solar cell, the beam trajectory is indicated as yellow, here, there is almost no energy loss, as we assume that the same amount of energy is needed to produce displacement damage at different depths in the material.

As in a power device, maximum power (Pm) of a solar cell is a crucial parameter for evaluating the performance. Figure 1(c) shows the variation of normalized Pmax values which decrease with increase in electron fluence. The InGaAsP (on InP) and InGaAs (on InP) subcells showed power losses of 35% and 47%, respectively, due to irradiation with electron beam fluence of 1.5×10^{15} e/cm^2 while the InGaAsP/InGaAs double-junction solar cell degraded by 37%. The degradation of maximum power is a combined effect of the reduction in open-circuit voltage (Voc) and short-circuit current (Isc). The marked increase in degradation of Voc and Isc with increase in electron fluence is due to creation of radiation-induced displacement damages in the cells which reduces the carrier diffusion length. This effect is pronounced in the InGaAs subcell compared to that in the InGaAsP subcell.

The single-junction solar cell can be regarded as a special P-N junction diode. In the absence of light, the I-V characteristic of a solar cell is similar to that of a conventional diode. The multi-junction cell is formed by connecting multiple diodes in series through a tunnel junction. In order to analyze the effect of displacement damage produced by high-energy charged particles on the electrical properties of solar cells and, at the same time, to avoid the influence of uneven illumination, we measured the dark I-V curves of the three cell structures. These are plotted in Figure 1(d). It is clearly seen that the dark current increases significantly after irradiation in all three cells for the same voltage. As the photo-generated current and dark current are in opposite directions, the output current eventually decreases.

Photo-generated carriers are separated by the built-in potential which relates to the threshold voltage directly. Semiconductor diodes begin to conduct electricity only when the applied voltage exceeds a threshold voltage or cut-in voltage in the forward direction. In Figure 1(d), the red line is marked to show the threshold voltage levels in the three SCs which are significantly reduced by irradiation. The experimental results show that the built-in potential is reduced. Deep-level defect centers are created in the semiconductor band gap by 1-MeV electron collisions which lower majority carrier density through charge compensation.

$$\phi_{\mathrm{bi}} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right). \tag{1}$$

Eq. (1) shows the relationship between carrier concentration and built-in potential. Reduction of majority carrier density can lower the built-in potential, which has an adverse effect on separation of light-generated carriers. The mechanism that leads to the decrease in majority carrier density is called carrier removal effect which is the most active at high radiation fluence levels [5]. The

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1) ISO 23038-2006. Space systems-space solar cells-electron and proton irradiation test methods. 2006. https://www.iso.org/standard/36600.html.

electron fluence used in our work yielded only a weak carrier removal effect. If the fluence level was increased much further, one would expect that carrier removal effect would be the main cause of degradation of cell performance.

$$V_{\mathrm{OC}} \propto \ln\left(\frac{I_L I_S}{n_i^2} - 1\right). \qquad (2)$$

Eq. (2) shows the relationship between open-circuit voltage and short-circuit current. Open-circuit voltage is affected by the short-circuit current. The reduction in photo-generated current and the increase in reverse saturation current (caused by displacement damage) result in open-circuit voltage degradation, this, in turn, influences the solar cell efficiency.

EQE does not depend on the solar spectrum. From a certain perspective, EQE can more objectively describe the absorption of light of different wavelengths. Figures 1(e) and (f) show the degradation of EQE spectra of InGaAsP/InGaAs double-junction solar cell and the corresponding InGaAs subcell at various fluence levels up to 1.5×10^{15} e/cm^2. It is seen that as the radiation fluence increases, the degradation in EQE is more severe. Besides, the base and emitter regions contribute differently to the EQE spectra. At low photon energies (long wavelengths), most carriers are generated in the base region [6]. As Figures 1(e) and (f) show, the degradation in the long wavelength region is more pronounced than at short wavelengths which validates the assumption that the photo-generated carriers within the base region find it difficult to move to the depletion region The large thickness of the base region also allows a lot of displacement of the target atoms through non-ionizing events. Therefore, the degradation occurring in the base region is more severe than that in the emitter region.

Figure 1(c) shows the normalized maximum power output of three-junction solar cells as a function of displacement damage dose and electron fluence. Maximum power densities of GaAsP/InGaAs double-junction SC, InGaAsP single-junction SC and InGaAs single-junction SC are 18.46, 19.59, and 16.19 mW/cm^2, respectively, before irradiation. After irradiation, the magnitude of loss estimated are 6.87, 6.54, and 7.53 mW/cm^2, respectively. As seen from Figures 1(e) and (f), the degradation in the three SC structures appear more or less the same, which is consistent with Pmax losses of similar magnitude. However, maximum power density of InGaAs subcell is relatively lower than that of others, the normalized degradation of InGaAs subcell is more serious although the amount of loss is almost the same.

Conclusion. The degradation behavior of an InGaAsP/InGaAs double-junction SC and its component subcells when irradiated with 1-MeV electron beam of fluence levels ranging from 1×10^{14} to 1.5×10^{15} e/cm^2 was investigated. The light I-V result showed that the degradation of cell performance was mainly attributable to the damage on the InGaAs subcell. With increase in electron fluence level, the displacement damage dose accumulates, and this leads to serious performance degradation. Short-circuit current and open-circuit voltage degradation occurs due to carrier lifetime reduction and radiation-induced defects caused by the carrier removal effect. In summary, the current-limiting component of the InGaAsP/InGaAs double-junction SC (used for the integration of four-junction SC by wafer bonding) is identified as the InGaAs subcell in both cases of pre- and post-irradiation. Therefore, the radiation resistance of InGaAsP/InGaAs double-junction solar cells can be enhanced most effectively by improving the InGaAs subcell design.

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Supporting information Figure 1. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Green M A, Emery K A, Hishikawa Y, et al. Solar cell efficiency tables (version 45). Prog Photovolt Res Appl, 2015, 23: 1–9
2 Stan M A, Aiken D, Sharps P R, et al. The development of > 28% efficient triple-junction space solar cells at Emcore photovoltaics. In: Proceedings of the 3rd World Conference on Photovolroic Energy Conversion, Osaka, 2003. 662–665
3 Cornfeld A B, Aiken D, Cho B, et al. Development of a four sub-cell inverted metamorphic multi-junction (IMM) highly efficient AM0 solar cell. In: Proceedings of the 35th IEEE Photovoltaic Specialists Conference, Honolulu, 2010
4 Dai P, Ji L, Tan M, et al. Electron irradiation study of room-temperature wafer-bonded four-junction solar cell grown by MBE. Sol Energ Mater Sol Cells, 2017, 171: 118–122
5 Maximenko S I, Messenger S R, Hoheisel R, et al. Characterization of high fluence irradiations on advanced triple junction solar cells. In: Proceedings of the 39th IEEE Photovoltaic Specialists Conference, Tampa, 2013. 2797–2800
6 Sze S M, Ng K K. Physics of Semiconductor Devices. 3rd ed. Hoboken: John Wiley & Sons, 2006. 728–729