3.0 MeV proton-irradiation induced non-radiative recombination center in the GaAs middle cell and the GaInP top cell of triple-junction solar cells

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Abstract. 3.0 MeV proton-irradiation effects on the GaAs middle cell and the GaInP top cell of n⁺-p GaInP/GaAs/Ge triple-junction (3J) solar cells have been analyzed using temperature-dependent photoluminescence (PL) technique. The E5 (Eᵥ - 0.96 eV) electron trap in the GaAs middle cell, the H2 (Eᵥ + 0.55 eV) hole trap in the GaInP top cell are identified as the proton irradiation-induced non-radiative recombination centers, respectively, causing the performance degradation of the triple-junction solar cells. The GaAs middle cell is less resistant to proton irradiation than the GaInP top cell.

1. Introduction

Recently, GaInP/GaAs/Ge triple-junction (3J) solar cells are the main power generator used in space satellites [1]. It consists of three subcells, i.e, GaInP top cell, GaAs middle cell and Ge bottom cell, having the potential to provide high efficiency. For space applications, exposure to proton irradiation degrades the performance of solar cells, probably resulting in space emission failure [2]. Therefore, the understanding of the mechanisms responsible for the irradiation degradation is important for the use of solar cells in space. The radiation response of the 3J solar cells is complicated due to three subcells with different proton irradiation effects. Exactly, The proton effects of the Ge bottom cell are not considered here as the Ge bottom cell does not contribute to the voltage output or affect the current degradation of the 3J solar cells [3] and effects of the GaInP top cell and the GaAs middle cell are investigated.

In fact, the degradation of solar cells induced by proton irradiation has been found to be directly related to the concentrations of the defects which play the role of non-radiative recombination centers for low irradiation fluences (typically below 10¹⁶ cm⁻²) [4]. The proton-induced defects in solar cells have been analyzed by deep-level transient spectroscopy (DLTS) [5]. However, the defects acting as non-radiative recombination centers have not been identified among all the detected defects. Photoluminescence (PL) is a potential method used to analyze non-radiative recombination centers of each individual subcell in multi-junction solar cells independently of the others [6]. In particular, temperature-dependent photoluminescence could not only identify non-radiative recombination centers among all the proton irradiation induced defects, but also reveal their activation process in solar cells [7,8]. Therefore, in this work, to clarify the proton effects on GaInP/GaAs/Ge triple-junction solar cells, temperature-dependent photoluminescence was applied to recognizing the 3.0
MeV proton-irradiation induced non-radiative recombination centers in the GaAs middle cell and the GaInP top cell.

2. Experiments
The samples were n+–p GaInP/GaAs/Ge triple-junction solar cells grown by the metal-organic chemical vapor deposition (MOCVD) technique. The detailed structure of the solar cells is shown in [9]. The solar cells were irradiated with 3.0 MeV proton beams with fluence of $3 \times 10^{11} \text{cm}^{-2}$, avoiding significant sample heating during irradiation.

In the PL analysis of the GaAs middle cell and the GaInP top cell, a 730 nm (1.70 eV) red diode laser (100 mW) and a 532 nm (2.33 eV) green solid state laser (75 mW) were used as the excitation sources, respectively. The laser beam diameter were both about 3.0 mm. Photoluminescence in the GaAs middle cell was transferred to a grating monochromator with 600 grooves/mm grating blazed at 750 nm and that in the top cell was transferred to another grating monochromator with 600 grooves/mm grating blazed at 500 nm. The luminescence of the middle cell was detected by Si photodetector and that of the top cell was detected by photomultiplier with a lock-in amplifier.

The temperature range of 10 - 300 K was controlled by ARS - 4 HW closed-cycle cryogenic refrigerator equipped with a digital thermometer controller (Lake Shore, 355 temperature controller). The temperature step is 20 K for the regions of 10 - 100 K and 200 - 300 K, and 10 K for the region of 100 - 200 K. The temperature stability is 0.1 K or more.

3. Result and discussion
Figure 1 shows the PL spectrum of the GaAs middle cell and the GaInP top cell of unirradiated and 3.0 MeV proton-irradiated GaInP/GaAs/Ge triple-junction solar cells at room temperature. The band gap of GaInP top cell is approximately 1.88 eV at room temperature, and that of GaAs middle cell is approximately 1.39 eV, decreasing about 30 meV compared with the band gap of GaAs (1.42 eV), probably attributed to Indium doping in triple-junction solar cells [10]. It can also be observed from figure 1 that the PL intensity of both the middle cell and the top cell shows a great degradation after irradiation, but the PL intensity of the middle cell degrades much more obviously than that of the top cell. This indicates that the GaAs middle cell is less radiation-tolerant than the GaInP top cell.

![Figure 1](image.png)

**Figure 1.** Room temperature PL spectrum of the GaAs middle cell and the GaInP top cell of GaInP/GaAs/Ge triple-junction solar cells.

Typical PL spectrum of the GaAs middle cell and the GaInP top cell of the triple-junction solar cells irradiated with 3.0 MeV protons with fluence of $3 \times 10^{11} \text{cm}^{-2}$ at 10 K, 160 K, 210 K and 290 K
are presented in figures 2 and 3. There are two peak emissions with peak energy of 2.00 eV and 1.96 eV at 10 K in the spectrum of the top cell. The peak emission at 2.00 eV is probably attributed to band-to-band transition. The spectrum of the middle cell also consists of two peak emissions, i.e., 1.49 eV (exciton emission) and 1.47 eV (donor-to-acceptor pair emission) at 10 K [11]. The photon energy of the band-edge-related PL peak decreases with increasing temperature for the two subcells, following Varnish equation [12].

![Figure 2](image1.png)

**Figure 2.** Typical PL spectrum of the GaAs middle cell of the triple-junction solar cells irradiated by a 3.0 MeV protons fluence of $3 \times 10^{11}$ cm$^{-2}$ at 10 K, 160 K, 210 K and 290 K.

![Figure 3](image2.png)

**Figure 3.** Typical PL spectrum of the GaInP top cell of the triple-junction solar cells after irradiated with 3.0 MeV protons with a fluence of $3 \times 10^{11}$ cm$^{-2}$ at 10 K, 160 K, 210 K and 290 K.

As the temperature increases, the PL intensity of the GaAs middle cell and the GaInP top cell
The PL emission efficiency $\eta(T)$ has the following dependence on temperature:

$$\eta(T) = \left[1 + \kappa \exp\left(-\frac{E}{k_B T}\right)\right]^{-1} \tag{1}$$

Figure 4. Arrhenius plot of temperature-dependent PL intensities of the GaAs middle cell of the triple-junction solar cells irradiated by a 3.0 MeV protons fluence of $3 \times 10^{11}$ cm$^{-2}$.

Figure 5. Arrhenius plot of temperature-dependent PL intensities of GaInP top cell of the triple-junction solar cells after irradiated with 3.0 MeV protons with a fluence of $3 \times 10^{11}$ cm$^{-2}$.
where $\kappa$ is the ratio of the non-radiative to radiative probability for non-radiative recombination mechanism at room temperature, $E$ is the thermal activation energy, and $k_B$ is the Boltzmann constant. The data in Arrhenius plots shown in figures 4 and 5 seem to exhibit an exponential region, both suggesting that a thermally activated non-radiative recombination mechanism is presented. The solid lines represent the fits of the measured data of the two subcells to equation (1) and the fitting parameters are $\kappa_{GaAs} = 10^{17}$, $E_{GaAs} = 0.96$ eV, $\kappa_{GaInP} = 10^{6}$, $E_{GaInP} = 1.33$ eV, respectively.

The PL quenching behaviors take place with the thermal activation of the defects in the p-type base layers [14,15]. For electron trap, the thermal activation energy ($E_d$) equals to its ionization energy ($E_v$), that is, $E_d = E_v$. For hole trap, the thermal activation energy ($E_d$) equals to the difference between band gap energy ($E_g$) and the ionization energy ($E_v$), i.e., $E_d = E_g - E_v$. Therefore, in the GaAs middle cell, we yield a defect level near 0.96 eV below the conduction band from the Arrhenius plot. It has been suggested that the defect could be consistent with E5 (0.96 - 0.6 eV) electron trap, an effective nonradiation recombination center, probably related to an As vacancy-interstitial pair [16]. Furthermore, in the GaInP top cell, a defect level near 1.33 eV below the conduction band is yielded, corresponding to H2 (E_v + 0.55 eV) defect, located at 0.55 eV above valence band. This is consistent with the results of Nethaji Dharmarasu et al [5] that H2 hole trap (0.51 ± 0.09 eV) was identified as recombination centers in the 3.0 MeV proton-irradiated p-type GaInP, playing an important role in determining the minority carrier lifetime.

The large value of $\kappa_{GaAs}$ indicates that the E5 electron trap in GaAs middle cell is a highly efficient non-radiative recombination center. Meanwhile, $\kappa_{GaAs}$ is eleven orders of magnitude higher than $\kappa_{GaInP}$, showing that the GaAs middle cell is less resistant to proton irradiation than the GaInP top cell, which is thought to be due to higher migration energies of Ga- and As-related defects than that of In- and P-related defects [17].

4. Conclusion

Temperature-dependent PL measurements for studying non-radiative recombination center induced by 3.0 MeV proton irradiation in the GaAs middle cell and the GaInP top cell of GaInP/GaAs/Ge triple-junction cells at the temperature range of 10 - 300 K is demonstrated. E5 electron trap in the GaAs middle cell, located at 0.96 eV below the conduction band, and H2 hole trap in the GaInP top cell, located at 0.55 eV above valence band are identified as the non-radiative recombination centers, respectively. The E5 electron trap in the GaAs middle cell is a highly efficient non-radiative recombination center, and the GaAs middle cell shows less proton radiation resistance than the GaInP top cell.

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