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Temperature-dependent photoluminescence analysis of 1-MeV electron irradiation-induced nonradiative recombination centers in GaAs/Ge space solar cells

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ABSTRACT

The effects of irradiation of 1-MeV electrons on p^+–n GaAs/Ge solar cells have been investigated by temperature-dependent photoluminescence (PL) measurements in the temperature range of 10–290 K. The temperature dependence of the PL peak energy agrees well with the Varnish relation, and the thermal quenching of the total integrated PL intensity is well explained by the thermal quenching theory. Meanwhile, the thermal quenching of temperature-dependent PL confirmed that there are two nonradiative recombination centers in the solar cells, and the thermal activation energies of these centers are determined by Arrhenius plots of the total integrated PL intensity. Furthermore, the nonradiative recombination center, as a primary defect, is identified as the H3 hole trap located at $E_v + 0.71$ eV at room temperature and the H2 hole trap located at $E_v + 0.41$ eV in the temperature range of 100–200 K, by comparing the thermal activation and ionization energies of the defects.

1. Introduction

In our recent work [1] that aimed to identify the nonradiative recombination center of the electron-irradiated GaAs/Ge solar cells among all irradiation-induced defects and recognize the causes of the electron irradiation-induced degradation of the GaAs/Ge solar cells, electron irradiation-induced defects produced in GaAs/Ge space solar cells have been analyzed with photoluminescence (PL) measurements at room temperature, whose results show that the nonradiative recombination center (or the minority carrier capture center) introduced by the electron irradiation probably corresponds to the H3 hole trap located at $E_v + 0.71$ eV.

In fact, temperature dependence of defect-related PL measurements better identify the nonradiative recombination center than the room-temperature PL measurements, because the temperature dependence of PL intensity and position can provide valuable information on the nonradiative recombination centers and help identify them among all irradiation-induced defects. With increasing temperature, the nonradiative recombination centers will be activated, thereby altering the intensity of the PL by few orders of magnitude [2]. Therefore, in this study, we used temperature-dependent PL measurements to recognize the nonradiative recombination centers introduced by 1-MeV-electron irradiation in GaAs/Ge space solar cells.

2. Experiments and results

The samples used for PL measurements are p^+–n GaAs/Ge solar cells fabricated by metal–organic chemical vapor deposition (MOCVD). The detailed structure of the solar cells is shown in Ref. [3]. The solar cells were irradiated with electron beams with energy of 1 MeV, with fluences ranging up to $3 \times 10^{15}\ \mathrm{cm}^{-2}$.

In PL measurements, a 532-nm (2.3-eV) emission laser line (power of $\sim$100 mW and beam diameter of $\sim$3.0 mm) is used as a typical excitation source. The excitation energy is significantly larger than the band gap of GaAs and is strongly absorbed (absorption coefficient, $\alpha \approx 10^5\ \mathrm{cm}^{-1}$) [4]. PL spectra from the *n*-type base layer of GaAs/Ge solar cells were collected by a lens and then transferred to a grating monochromator with 600-grooves/mm grating blazed at 750 nm. The output signal from the monochromator was detected by a Si photodetector and the luminescence was chopped to provide a reference frequency for the lock-in amplifier.

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In order to measure temperature dependence of the PL spectra, a closed-cycle cryogenic refrigerator (ARS-4HW) equipped with a digital thermometer controller (Lake Shore, 355 Temperature Controller) was used to control the temperature from 10 to 290 K, with a temperature stability of 0.1 K or more.

Fig. 1 shows the PL spectra of the 1-MeV-electron-irradiated and -nonirradiated GaAs/Ge solar cells at room temperature. It is evident from the figure that the emission band is the broad peak feature centered at 1.42 eV with the full-width at half-maximum of approximately 45 meV. Furthermore, as the band gap of GaAs is approximately 1.42 eV at room temperature, it is obvious that the GaAs PL spectra peak at 1.42 eV be attributed to near-band-edge emission and band-to-band recombination to dominate the spectra in this region at room temperature. It can also be observed from Fig. 1 that the PL intensity has a fast degradation after irradiation with 1-MeV electrons, and it further increases with increasing fluence. Essentially, the degradation of solar cells induced by electron irradiation is directly proportional to the concentration of the defects, which acts as nonradiative recombination centers for low-irradiation fluences (typically < 10^{16} cm^{-2}) [5].

Temperature-dependent PL spectra of GaAs/Ge solar cells irradiated with 1-MeV electrons with fluence of 3×10^{15} cm^{-2} are shown in Fig. 2. It is evident from the figure that, at temperatures <30 K, a near-band-edge emission consisting of the exciton emission at ~1.49 eV is present [6]. As the temperature increases to 100, 160, 230, and 290 K, the photon energy of the PL peak decreases by about 10, 20, 50, and 70 meV, respectively, compared with that at 30 K. It can also be observed from Fig. 2 that the position of the PL peak shifts toward the left-hand side and the PL intensity decreases with increasing temperature.

3. Analysis of the temperature dependence PL spectra

Fig. 3 shows the temperature dependence of the band-edge-related PL peak shift. The solid line in the figure shows that the measured data agree well with the Varnish equation [7]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T}, \tag{1}$$

where E_g (0) is 1.49 eV, the energy gap at T = 0 K and the parameters α and β equal 6.1×10^{-4} eV K^{-1} and 436 K, respectively. Obviously, the measured data agree well with the Varnish equation.

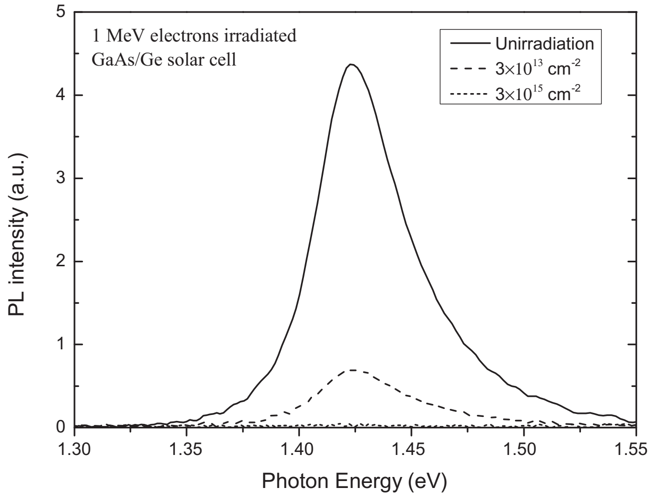

Fig. 1. Room-temperature PL spectra of GaAs/Ge solar cells irradiated with 1-MeV electrons with fluence ranging from 0 to 3×10^{15} cm^{-2}.

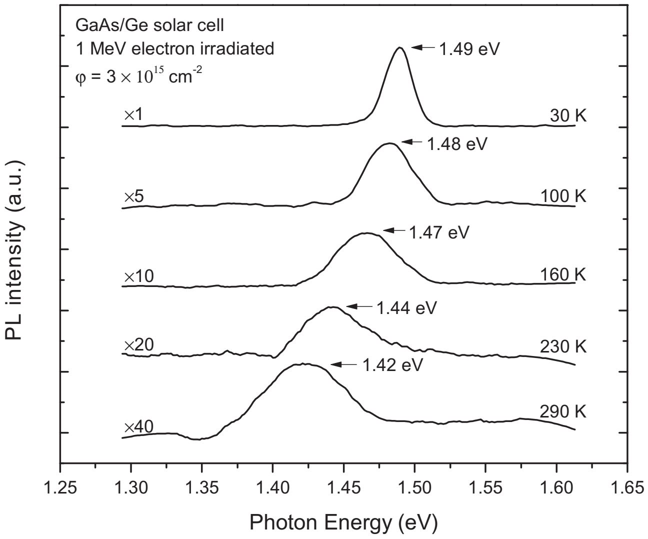

Fig. 2. Temperature dependence of PL spectra of GaAs/Ge solar cells irradiated with 1-MeV electrons with fluence of 3×10^{15} cm^{-2} and temperature in the range of 10–290 K. The peak positions are marked by arrows.

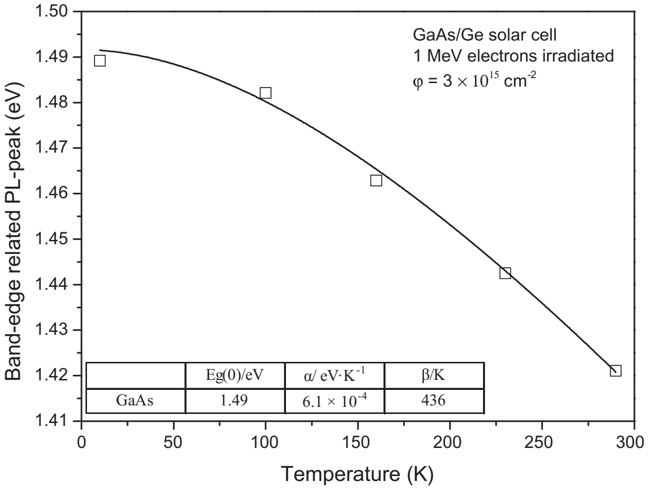

Fig. 3. Temperature dependence of the band-edge-related PL peak shift. The solid line shows the good agreement of the measured data (squares) with the Varnish equation Eq. (1).

Measured PL intensity of GaAs/Ge solar cells irradiated with 1-MeV electrons with fluence of 3×10^{15} cm^{-2} is plotted against inverse temperature, that is, an Arrhenius plot, in Fig. 4. As shown in the figure, the data seem to exhibit three different exponential regions, indicating three different thermally activated, nonradiative recombination levels. Obviously, the data below the temperature of 50 K correspond to the shallowest defect. However, such a defect is not expected to play a significant role in the operation of the cell, as the defects closer to mid-gap are expected to control the solar cell performance. Thus, the shallowest defect level was ignored and the data were analyzed in terms of two thermally activated processes a and b. The efficiency of emission (η) was approximated by [8]:

$$\eta = \left[1 + \kappa_a \exp\left(-\frac{E_a}{k_B T}\right) + \kappa_b \exp\left(-\frac{E_b}{k_B T}\right)\right]^{-1}, \tag{2}$$

where κ is the ratio of the radiative to nonradiative recombination lifetimes at T = 300 K and E is the thermal activation energy