RECOVERY OF ELECTRON / PROTON RADIATION-INDUCED DEFECTS IN n^+p AlInGaP SOLAR CELL BY MINORITY-CARRIER INJECTION ANNEALING

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1 INTRODUCTION

A high efficient $In_{0.48}Ga_{0.52}P/In_{0.01}Ga_{0.99}As/Ge$ triple junction solar cell has been developed for application in space and terrestrial concentrator PV system [1-3]. Recently, a high conversion efficiency of 31.5% (AM1.5G) has been obtained in InGaP/(In)GaAs/Ge triple junction solar cell, and as a new top cell material of triple junction cells, (Al)InGaP [1] has been proposed to improve the open-circuit voltage (*Voc*) because it shows a higher *Voc* of 1.5V while maintaining the same short-circuit current (I_{SC}) as a conventional InGaP top cell under AM1.5G conditions as seen in figure 1 (a). Moreover, the spectral response of 1.96eV AlInGaP cell with a thickness of 2.5μm shows a higher response in the long wavelength region, compared with that of 1.87eV InGaP cell with 0.6μm thickness, as shown in figure 1 (b). Its development will realize next generation multijunction (MJ) solar cells such as a lattice mismatched AlInGaP/InGaAs/Ge 3-junction and lattice matched AlInGaP/GaAs/InGaAsN/Ge 4-junction solar cells. Figure 2 shows the super high-efficiency MJ solar cell structures and wide band spectral response by MJ solar cells under AM1.5G conditions.

For realizing high efficient MJ space solar cells, the higher radiation-resistance under the electron or proton irradiation is required. The irradiation studies for a conventional top cell InGaP have been widely done [4-6], but little irradiation work has been performed on AlInGaP solar cells. Recently, we made the first reports of 1 MeV electron or 30 keV proton irradiation effects on AlInGaP solar cells, and evaluated the defects generated by the irradiation [7,8].

The present study describes the recovery of 1 MeV electron / 30 keV proton irradiation-induced defects in n^+p-AlInGaP solar cells by minority-carrier injection enhanced annealing or isochronal annealing. The origins of irradiation-induced defects observed by deep level transient spectroscopy (DLTS) measurements are discussed.

2 EXPERIMENTAL DETAILS

The n^+p-$(Al_{0.08}Ga_{0.92})_{0.52}In_{0.48}P$ single junction (SJ) solar cells (1.97eV) for 1 MeV electron irradiation

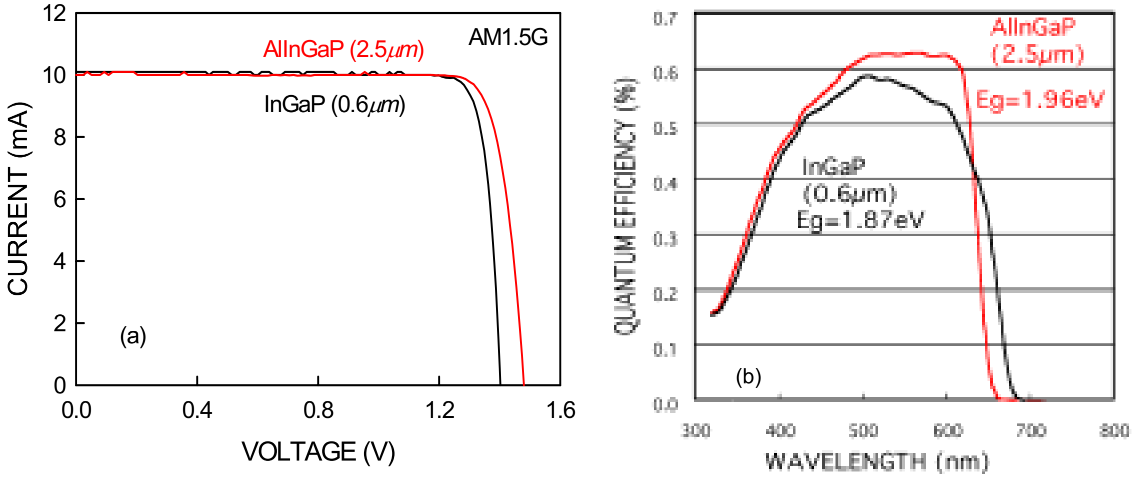

Fig. 1. Light *I-V* curves (a) and the spectral responses (b) for 1.96eV AlInGaP with a thickness of 2.5μm and 1.87eV InGaP cell with 0.6μm thickness under AM1.5G with no anti-reflective coating. (From Ref. [1])

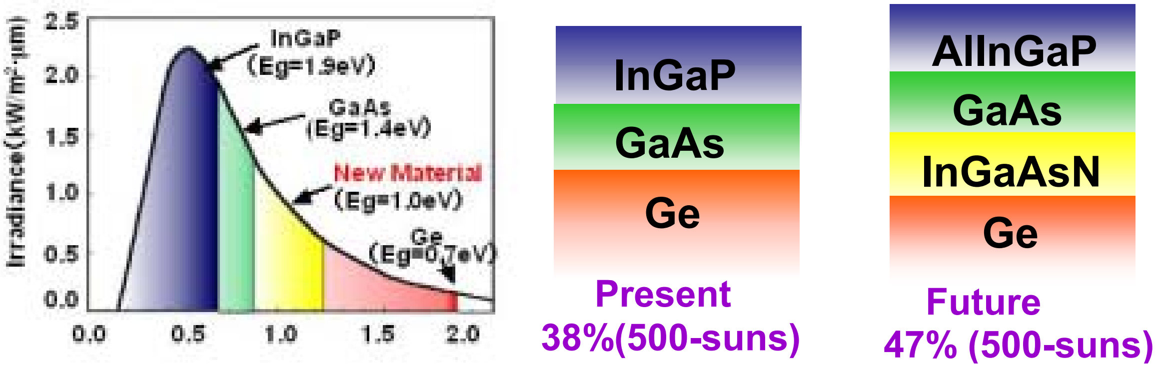

Fig. 2. Super high-efficiency MJ solar cell structures and wide band spectral response by MJ solar cells under AM1.5G conditions.

experiment and n^+p-$(Al_{0.20}Ga_{0.80})_{0.52}In_{0.48}P$ solar cells (2.08eV) for 30 keV proton irradiation were used in this study, respectively. The AlInGaP solar cells were grown on *p*-GaAs substrates by metal-organic chemical vapor deposition (MOCVD). The n^+ emitter layer (0.03μm) was Si-doped and *p* base layer (0.6~2μm) was Zn-doped with the concentrations of $2\times10^{18}cm^{-3}$ and $1\times10^{17}cm^{-3}$, respectively. The back-surface field layer and window layer of the AlInGaP solar cells were made with InGaP (0.03μm) and AlInP (0.03μm), respectively. An anti-reflective coating was not formed. Additionally, a number of mesa diodes with an area of $1.3\times10^{-3}cm^2$ were fabricated from the same wafer.

The irradiation was carried out at the Japan Atomic Energy Research Institute (JAERI), using fluences in the range of 1×10^{15}~$3\times10^{16}cm^{-2}$ for 1 MeV electron and 1×10^{10}~$1\times10^{12}cm^{-2}$ for 30 keV proton at room temperature, respectively. Capacitance-voltage (*C-V*) and deep level transient spectroscopy (DLTS) measurements were carried out to characterize the carrier concentration and deep level defects introduced with irradiation. The minority-carrier injection enhanced annealing of radiation-induced defects was investigated at temperatures of 25°C, 55°C and 70°C with applying a forward bias current $100mA/cm^2$ to the n^+-*p* junction to evaluate the origin of defects, and the resultant changes in the concentration of defects were monitored by DLTS measurements. In addition, isochronal annealing has been carried out on the irradiated samples at temperatures of 100~300°C for 20min under a nitrogen ambient.

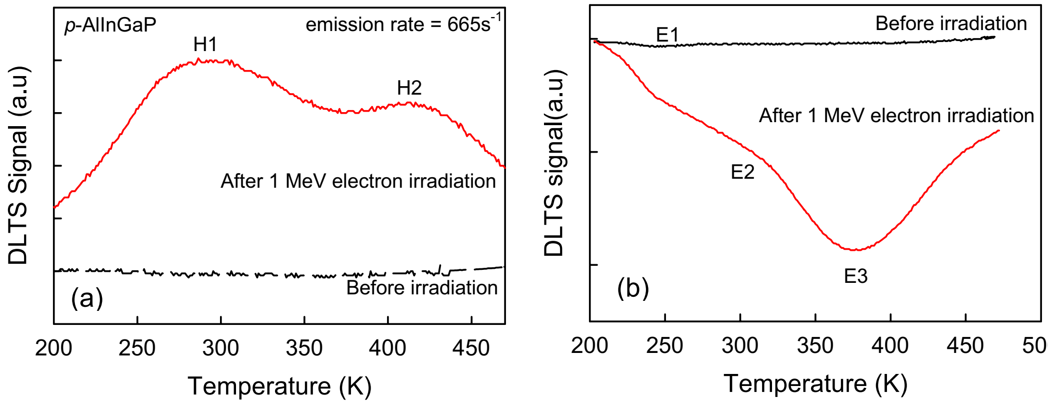

Fig. 3. Majority- (a) and minority-carrier (b) DLTS spectra in *p*-AlInGaP before and after 1 MeV electron irradiation with a fluence of $1\times10^{16}cm^{-2}$. (From Ref. [9])

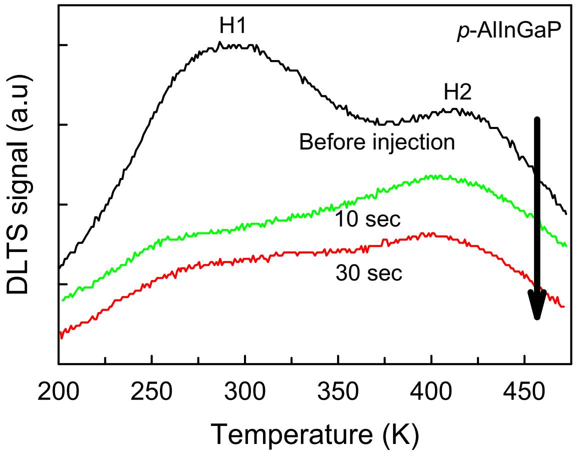

Fig. 4. Change in DLTS signal of H1 and H2 defects in *p*-AlInGaP irradiated with a fluence of $1x10^{16}cm^{-2}$ as a function of injection time. (From Ref. [9])

3 RECOVERY OF 1 MeV ELECTRON IRRADIATION-INDUCED DEFECTS IN AlInGaP

We have observed the defects generated in AlInGaP solar cells under 1 MeV electron irradiation, and reported them in previous reports [8,9]. As shown in figure 3, two dominant traps for majority-carriers (hole) (a) H1 (E_v+0.50±0.05eV, N_T=$2.2\times10^{15}cm^{-3}$), H2 (E_v+0.90±0.05eV, N_T=$1.7\times10^{15}cm^{-3}$) and minority-carrier (electron) traps (b) E2 (E_c-0.70eV, N_T=$4.3\times10^{15}cm^{-3}$), E3 (E_c-0.85eV, N_T=$9.8\times10^{15}cm^{-3}$) are observed in *p*-AlInGaP under 1 MeV electron irradiation with a fluence of $1\times10^{16}cm^{-2}$ from DLTS measurements.

In order to clarify the origin of defects, irradiated samples were subjected to forward bias injection at various temperatures. In this study, we focus on the majority-carrier traps H1 and H2 because the minority-carrier traps E2 and E3 are stable against the minority-carrier injection. Figure 4 shows the recovery of defects H1 and H2 in *p*-AlInGaP samples irradiated with a fluence of $1x10^{16}cm^{-2}$ by a forward bias injection ($100mA/cm^2$). As seen in figure 4, DLTS signal of H1 and H2 decreases with increasing the injection time. These results imply that H1 and H2 defects, which act as recombination centers, are annealed out due to nonradiative electron-hole recombination enhanced process, so called Bourgoin mechanism [10]. A similar behavior has been observed with 1 MeV electron irradiated *p*-InGaP [11] and *p*-InP [12]. The energy release mechanism has been understood to underlie the recovery of radiation damage.

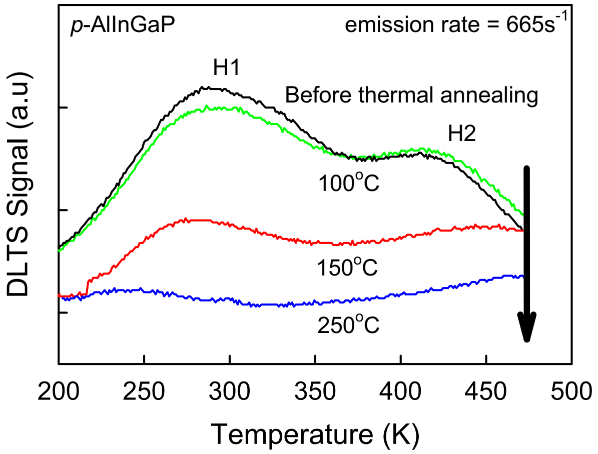

Fig. 5. Change in DLTS signal of H1 and H2 defects in *p*-AlInGaP irradiated with a fluence of 1x10^{16}cm^{-2} as a function of isochronal annealing temperature.

The minority-carrier injection annealing causes the annihilation of some recombination centers introduced by electron irradiation. The irradiation-induced defects are annihilated as follows [11]:

$$N_T = N_{T0}\exp(-A^*t), \tag{1}$$

where N_T and N_{T0} are the concentrations of irradiation-induced defect centers after and before injection annealing, respectively, A^* the annealing rate, and t the injection time. The annealing activation energy of irradiation-induced defect centers is expressed as follows:

$$A^* = A(J)\exp(-\Delta E/kT)\ (\mathrm{s}^{-1}) \tag{2}$$

where $A(J)$ is the pre-exponential factor, ΔE the annealing activation energy, and k the Boltzmann constant. An analogous investigation such as isochronal annealing was also performed for the H1 and H2 defects. Figure 5 shows the isochronal annealed DLTS signal of defects H1 and H2 in *p*-AlInGaP irradiated with a fluence of 1x10^{16}cm^{-2}. As seen in figure 5, the concentration of the defect H1 decreases gradually at temperatures above 100°C, and anneals out at about 250°C. On the other hand, the concentration of H2 defect remains almost unchanged up to 100°C, and its concentration decreases above 100°C.

Figure 6 shows the temperature dependence of thermal and injection annealing rates for H1 and H2 defects in the 1 MeV electron irradiated *p*-AlInGaP. By using Eqs. (1) and (2), the activation energy of injection annealing was estimated as ΔE=0.50eV for H1 defect and ΔE=0.60eV for H2 defect, respectively. Moreover, the thermal activation energy was determined as ΔE=1.51eV for H1 defect, but that for H2 defect could not be obtained accurately.

In previous reports, *p*-InP [12] and *p*-InGaP [11,13] irradiated with 1 MeV electrons have shown a major majority-carrier trap labeled H4 (E_v+0.32eV) and H2 (E_v+0.50-0.55eV), respectively. The activation energy of injection (ΔE=0.51eV) and thermal (ΔE=1.68eV) annealing for H2 defect in *p*-InGaP suggests a vacancy-phosphorus Frenkel pair (V_p-P_i) as a possible origin of H2 defect. In the present study, we observe H1 (E_v+0.50±0.05eV) and H2 (E_v+0.90±0.05eV) defects in the 1 MeV electron irradiated *p*-AlInGaP, and they are likely to be associated with vacancy-phosphorus Frenkel pair (V_p-P_i) due to the similar annealing characteristics between H1 (ΔE=0.50eV for injection anneal, ΔE=1.51eV for thermal anneal), H2 (ΔE=0.60eV for injection anneal) defects in *p*-AlInGaP and H2 defect (ΔE=0.51eV for injection anneal, ΔE=1.68eV for thermal anneal) in *p*-InGaP.

The major defects H1 and H2 in *p*-AlInGaP introduced by 1 MeV electron irradiation act as recombination centers, which cause mainly the degradation of solar cell property. However, to understand which defects play an important role in the degradation of solar cell property, the correlation between the recovery of solar cell property and radiation-induced defects by injection and thermal annealing should be investigated, and is open to future discussion.

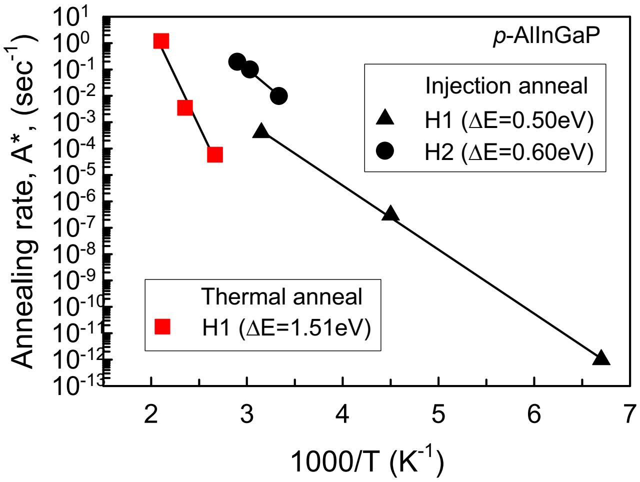

Fig. 6. The temperature dependence of thermal and injection annealing rates for H1 and H2 defects in the 1 MeV electron irradiated *p*-AlInGaP. (Injection anneal H1 from Ref. [8])

4 RECOVERY OF 30 keV PROTON IRRADIATION-INDUCED DEFECTS IN AlInGaP

We have investigated the 30 keV proton irradiation-induced defects in AlInGaP solar cells, and consequently two majority-carrier (hole) traps (a) HP1 (E_v+0.98eV, N_T=3.8×10^{14}cm^{-3}), HP2 and minority-carrier (electron) traps (b) EP1 (E_c-0.71eV, N_T=2.0×10^{15}cm^{-3}), EP2 are observed in *p*-AlInGaP after 30 keV proton irradiation with a fluence of 1×10^{12}cm^{-2}, as shown in figure 7 [14]. However, the energy level of HP2 and EP2 defects could not be evaluated accurately due to little change of DLTS spectra as a function of emission rate.

The minority-carrier injection annealing was performed in order to characterize the origin of HP1 defect. The concentration of HP1 defect decreases with increasing the injection (100mA/cm^2) time, as shown in figure 8. This result implies that HP1 defect acts as recombination center. From the temperature dependence of injection annealing rate for HP1 defect in *p*-AlInGaP after the 30 keV proton irradiation, the activation energy was estimated as ΔE=0.46eV for HP1 defect, as shown in figure 9. This activation energy is in agreement with that (ΔE=0.44eV) in the 3 MeV proton irradiated InGaP solar cell [5]. HP1 defect observed in *p*-AlInGaP is likely to be

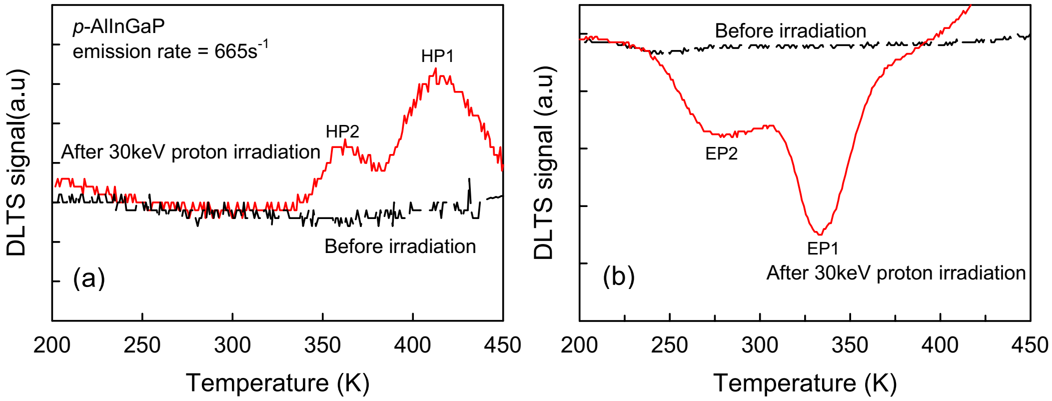

Fig. 7. Majority- (a) and minority-carrier (b) DLTS spectra in *p*-AlInGaP before and after 30 keV proton irradiation with a fluence of 1×10^{12}cm^{-2}. (From Ref. [14])

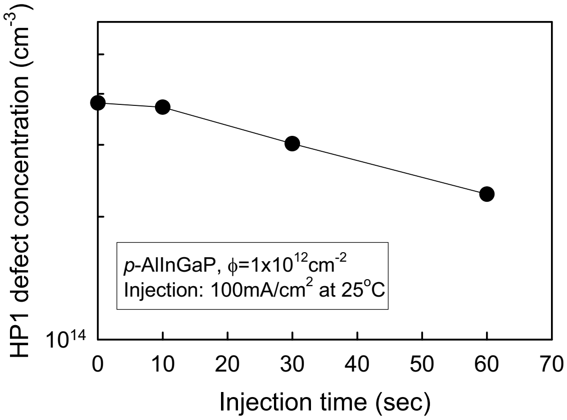

Fig. 8. Change of HP1 defect concentration as a function of injection time. (From Ref. [14])

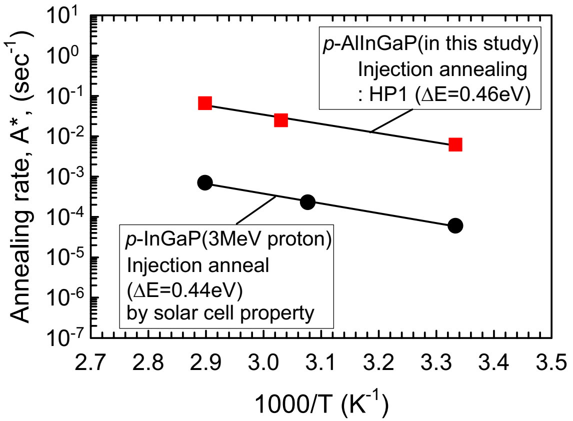

Fig. 9. The temperature dependence of injection annealing rate for HP1 defect in the 30 keV proton irradiated *p*-AlInGaP. (*p*-InGaP from Ref. [5])

associated with phosphorus-related vacancy complexes, and a similar defect HP1 (E_v+0.90eV) has been observed in 0.1, 0.38, 1 and 3 MeV proton irradiated *p*-InGaP [15,16]. In that paper, the HP1 defect is annealed out by the thermal annealing at a temperature above 300°C, and this annealing temperature is higher than that of H2 defect observed in the 1 MeV electron irradiated *p*-InGaP to anneal out. However, in order to clarify the origin of HP1 defect observed in the 30 keV proton irradiated *p*-AlInGaP, further study of isochronal annealing is necessary, and will be presented later.

5 SUMMARY

The minority-carrier injection enhanced annealing or isochronal annealing of radiation-induced defects in wide-band-gap (1.97~2.08eV) $n^{+}p$- AlInGaP solar cells under 1 MeV electron / 30 keV proton irradiation were investigated using DLTS measurements. The activation energy of injection annealing for H1 (E_v+0.50eV) and H2 (E_v+0.90eV) defects observed in *p*-AlInGaP under 1 MeV electron irradiation, which act as recombination centers, is ΔE=0.50eV and ΔE=0.60eV, respectively. In addition, the thermal activation energy for H1 defect is ΔE=1.51eV. They are likely to be associated with vacancy-phosphorus Frenkel pair (V_p-P_i). After 30 keV proton irradiation, HP1 (E_v+0.98eV) defect was observed, and the injection annealing activation energy is ΔE=0.46eV. This defect, which also acts as a recombination center, is associated with phosphorus-related vacancy complexes.

AlInGaP is expected as a new top cell material for high-efficient multijunction solar cells for space application due to a higher open circuit-voltage as well as radiation-resistance.

ACKNOWLEDGMENTS

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