

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

H.S. Lee, M. Yamaguchi
Toyota Technological Institute, Nagoya 468-8511, Japan

N.J. Ekins-Daukes
University of Sydney, NSW 2006, Australia

A. Khan
University of South Alabama, Mobile 36688, USA

T. Takamoto
Sharp Corporation, Nara 639-2198, Japan

M. Imaizumi
Japan Aerospace Exploration Agency, Tsukuba 305-8505, Japan

T. Ohshima, H. Itoh
Japan Atomic Energy Research Institute, Takasaki 370-1292, Japan

1 INTRODUCTION

A high efficient $\text{In}_{0.48}\text{Ga}_{0.52}\text{P}/\text{In}_{0.01}\text{Ga}_{0.99}\text{As}/\text{Ge}$ 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 $\text{InGaP}/(\text{In})\text{GaAs}/\text{Ge}$ triple junction solar cell, and as a new top cell material of triple junction cells, $(\text{Al})\text{InGaP}$ [1] has been proposed to improve the open-circuit voltage (V_{oc}) because it shows a higher V_{oc} 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 AllnGaP cell with a thickness of $2.5\mu\text{m}$ shows a higher response in the long wavelength region, compared with that of 1.87eV InGaP cell with $0.6\mu\text{m}$ thickness, as shown in figure 1 (b). Its development will realize next generation multijunction (MJ) solar cells such as a lattice mismatched $\text{AllnGaP}/\text{InGaAs}/\text{Ge}$ 3-junction and lattice matched $\text{AllnGaP}/\text{GaAs}/\text{InGaAsN}/\text{Ge}$ 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 AllnGaP solar cells. Recently, we made the first reports of 1 MeV electron or 30 keV proton irradiation effects on AllnGaP 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 - AllnGaP 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 - $(\text{Al}_{0.08}\text{Ga}_{0.92})_{0.52}\text{In}_{0.48}\text{P}$ single junction (SJ) solar cells (1.97eV) for 1 MeV electron irradiation

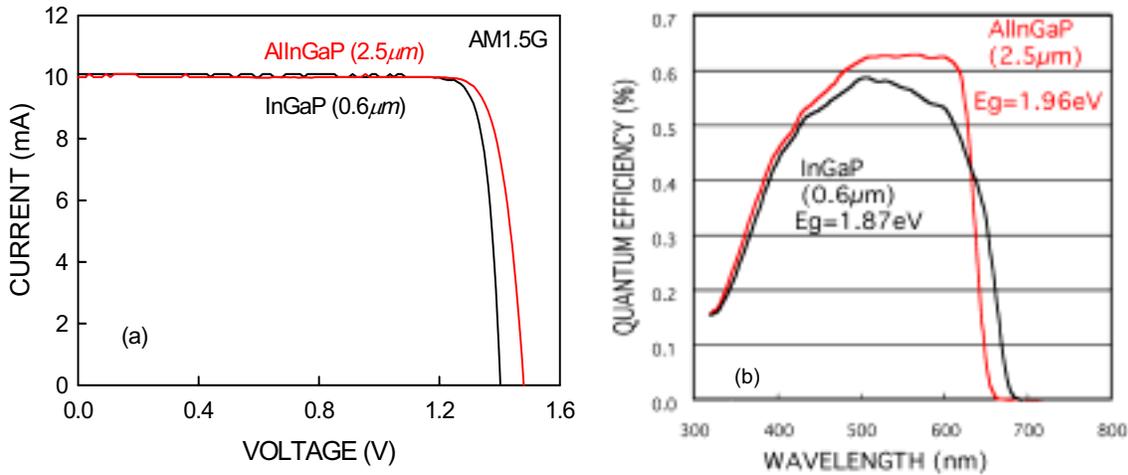


Fig. 1. Light I - V curves (a) and the spectral responses (b) for 1.96eV AlInGaP with a thickness of $2.5\mu\text{m}$ and 1.87eV InGaP cell with $0.6\mu\text{m}$ thickness under AM1.5G with no anti-reflective coating. (From Ref. [1])

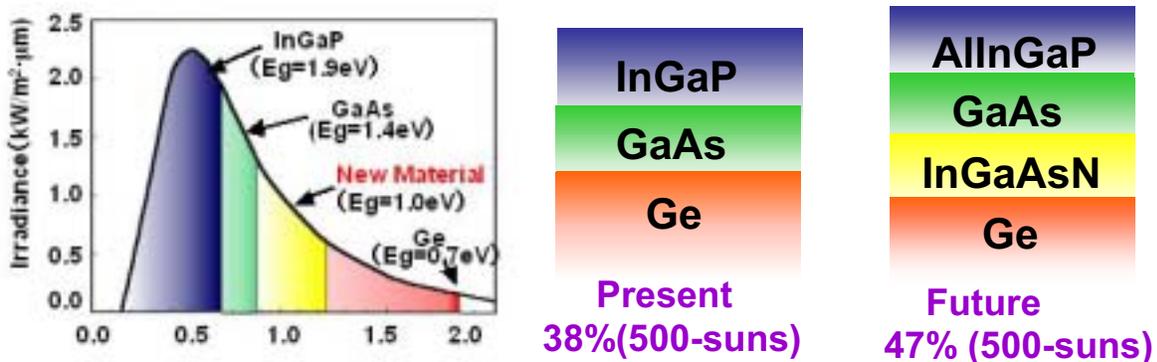


Fig. 2. Super high-efficiency MJ solar cell structures and wide band spectral response by MJ solar cells under AM1.5G conditions.

experiment and n^+p -($\text{Al}_{0.20}\text{Ga}_{0.80}$) $_{0.52}\text{In}_{0.48}\text{P}$ 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 ($0.03\mu\text{m}$) was Si-doped and p base layer ($0.6\sim 2\mu\text{m}$) was Zn-doped with the concentrations of $2\times 10^{18}\text{cm}^{-3}$ and $1\times 10^{17}\text{cm}^{-3}$, respectively. The back-surface field layer and window layer of the AlInGaP solar cells were made with InGaP ($0.03\mu\text{m}$) and AlInP ($0.03\mu\text{m}$), respectively. An anti-reflective coating was not formed. Additionally, a number of mesa diodes with an area of $1.3\times 10^{-3}\text{cm}^2$ 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 $1\times 10^{15}\sim 3\times 10^{16}\text{cm}^{-2}$ for 1 MeV electron and $1\times 10^{10}\sim 1\times 10^{12}\text{cm}^{-2}$ 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 $100\text{mA}/\text{cm}^2$ 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 $100\sim 300^\circ\text{C}$ for 20min under a nitrogen ambient.

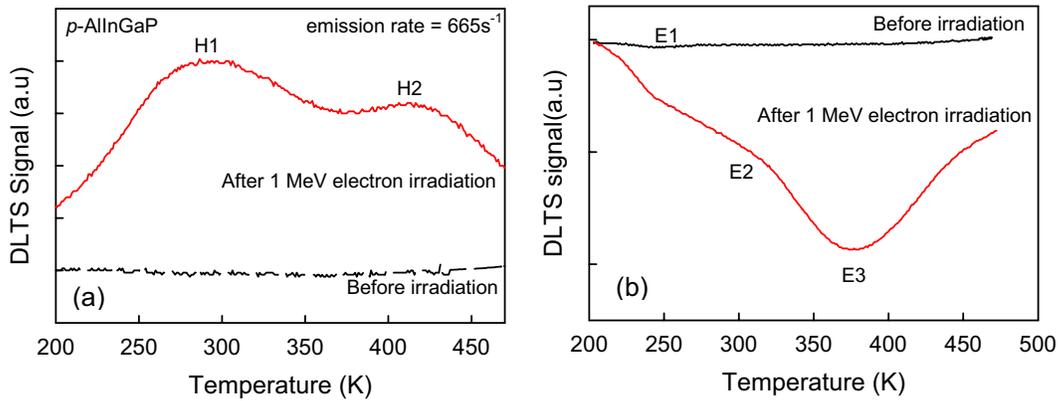


Fig. 3. Majority- (a) and minority-carrier (b) DLTS spectra in p -AlInGaP before and after 1 MeV electron irradiation with a fluence of $1 \times 10^{16} \text{ cm}^{-2}$. (From Ref. [9])

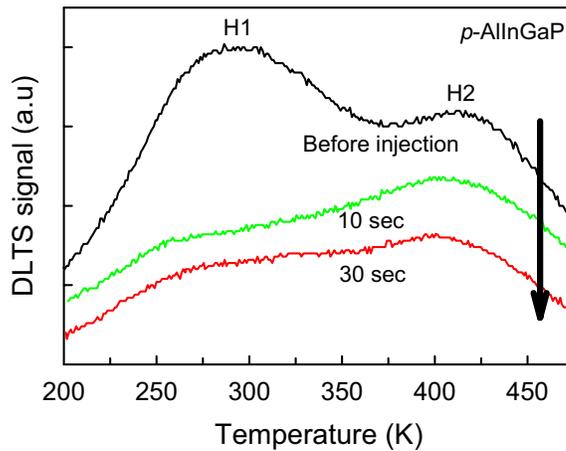


Fig. 4. Change in DLTS signal of H1 and H2 defects in p -AlInGaP irradiated with a fluence of $1 \times 10^{16} \text{ cm}^{-2}$ as a function of injection time. (From Ref. [9])

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 ($E_v+0.50 \pm 0.05 \text{ eV}$, $N_T=2.2 \times 10^{15} \text{ cm}^{-3}$), H2 ($E_v+0.90 \pm 0.05 \text{ eV}$, $N_T=1.7 \times 10^{15} \text{ cm}^{-3}$) and minority-carrier (electron) traps (b) E2 ($E_c-0.70 \text{ eV}$, $N_T=4.3 \times 10^{15} \text{ cm}^{-3}$), E3 ($E_c-0.85 \text{ eV}$, $N_T=9.8 \times 10^{15} \text{ cm}^{-3}$) are observed in p -AlInGaP under 1 MeV electron irradiation with a fluence of $1 \times 10^{16} \text{ cm}^{-2}$ 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 $1 \times 10^{16} \text{ cm}^{-2}$ by a forward bias injection (100 mA/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.

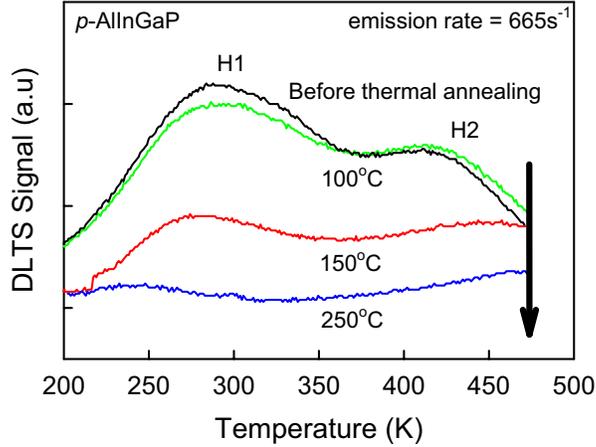


Fig. 5. Change in DLTS signal of H1 and H2 defects in p -AlInGaP irradiated with a fluence of $1 \times 10^{16} \text{ cm}^{-2}$ as a function of isochronal annealing temperature.

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]:

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

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:

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

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 $1 \times 10^{16} \text{ cm}^{-2}$. 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 $\Delta E = 0.50 \text{ eV}$ for H1 defect and $\Delta E = 0.60 \text{ eV}$ for H2 defect, respectively. Moreover, the thermal activation energy was determined as $\Delta E = 1.51 \text{ eV}$ 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 ($E_v + 0.32 \text{ eV}$) and H2 ($E_v + 0.50\text{--}0.55 \text{ eV}$), respectively. The activation energy of injection ($\Delta E = 0.51 \text{ eV}$) and thermal ($\Delta E = 1.68 \text{ eV}$) annealing for H2 defect in p -InGaP suggests a vacancy-phosphorus Frenkel pair ($V_p\text{-}P_i$) as a possible origin of H2 defect. In the present study, we observe H1 ($E_v + 0.50 \pm 0.05 \text{ eV}$) and H2 ($E_v + 0.90 \pm 0.05 \text{ eV}$) defects in the 1 MeV electron irradiated p -AlInGaP, and they are likely to be associated with vacancy-phosphorus Frenkel pair ($V_p\text{-}P_i$) due to the similar annealing characteristics between H1 ($\Delta E = 0.50 \text{ eV}$ for injection anneal, $\Delta E = 1.51 \text{ eV}$ for thermal anneal), H2 ($\Delta E = 0.60 \text{ eV}$ for injection anneal) defects in p -AlInGaP and H2 defect ($\Delta E = 0.51 \text{ eV}$ for injection anneal, $\Delta E = 1.68 \text{ eV}$ 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.

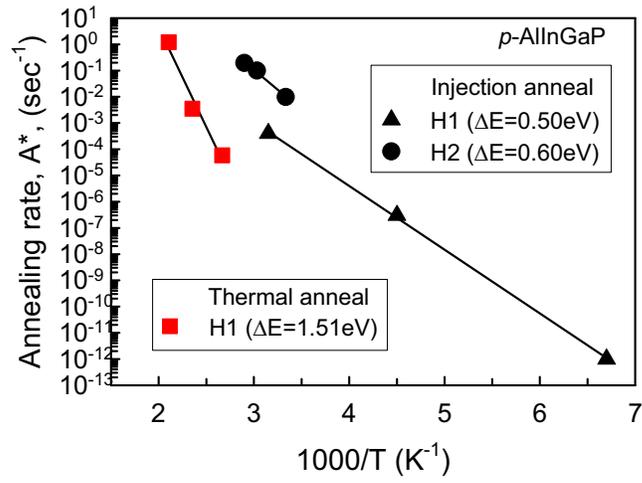


Fig. 6. The temperature dependence of thermal and injection annealing rates for H1 and H2 defects in the 1 MeV electron irradiated *p*-AlInGaP. (Injection anneal H1 from Ref. [8])

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 ($E_v+0.98\text{eV}$, $N_T=3.8\times 10^{14}\text{cm}^{-3}$), HP2 and minority-carrier (electron) traps (b) EP1 ($E_c-0.71\text{eV}$, $N_T=2.0\times 10^{15}\text{cm}^{-3}$), EP2 are observed in *p*-AlInGaP after 30 keV proton irradiation with a fluence of $1\times 10^{12}\text{cm}^{-2}$, 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 $\Delta E=0.46\text{eV}$ for HP1 defect, as shown in figure 9. This activation energy is in agreement with that ($\Delta E=0.44\text{eV}$) in the 3 MeV proton irradiated InGaP solar cell [5]. HP1 defect observed in *p*-AlInGaP is likely to be

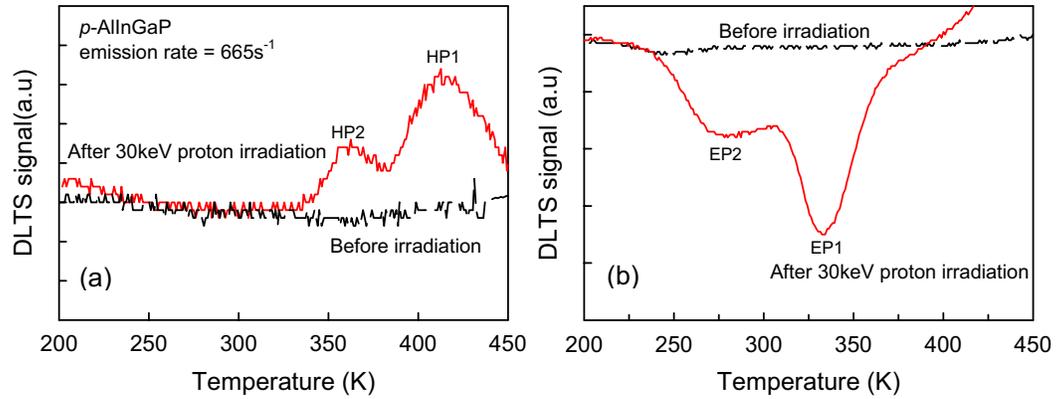


Fig. 7. Majority- (a) and minority-carrier (b) DLTS spectra in *p*-AlInGaP before and after 30 keV proton irradiation with a fluence of $1\times 10^{12}\text{cm}^{-2}$. (From Ref. [14])

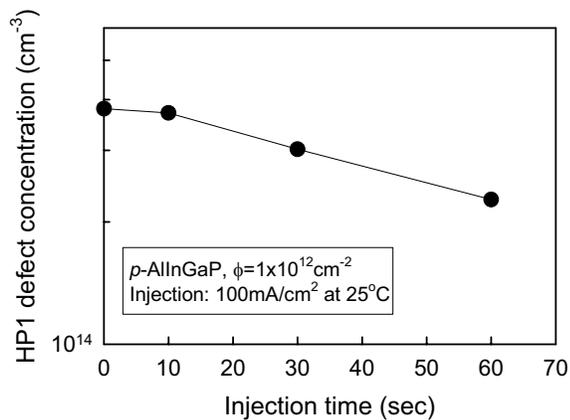


Fig. 8. Change of HP1 defect concentration as a function of injection time. (From Ref. [14])

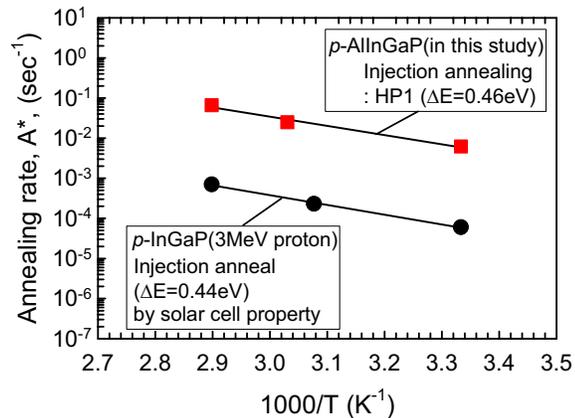


Fig. 9. The temperature dependence of injection annealing rate for HP1 defect in the 30 keV proton irradiated p-AllnGaP. (p-InGaP from Ref. [5])

associated with phosphorus-related vacancy complexes, and a similar defect HP1 ($E_v+0.90\text{eV}$) 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-AllnGaP, 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 - AllnGaP solar cells under 1 MeV electron / 30 keV proton irradiation were investigated using DLTS measurements. The activation energy of injection annealing for H1 ($E_v+0.50\text{eV}$) and H2 ($E_v+0.90\text{eV}$) defects observed in p-AllnGaP under 1 MeV electron irradiation, which act as recombination centers, is $\Delta E=0.50\text{eV}$ and $\Delta E=0.60\text{eV}$, respectively. In addition, the thermal activation energy for H1 defect is $\Delta E=1.51\text{eV}$. They are likely to be associated with vacancy-phosphorus Frenkel pair (V_p-P_i). After 30 keV proton irradiation, HP1 ($E_v+0.98\text{eV}$) defect was observed, and the injection annealing activation energy is $\Delta E=0.46\text{eV}$. This defect, which also acts as a recombination center, is associated with phosphorus-related vacancy complexes.

AllnGaP 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

This work was supported in part by the Ministry of Education, Culture, Sports, Science and Technology as a Private University Academic Frontier Center Program in Japan.

REFERENCES

- [1] Tatsuya Takamoto, Takaaki Agui, Kunio Kamimura, Minoru Kaneiwa, Mitsuru Imaizumi, Sumio Matsuda and Masafumi Yamaguchi, "Multijunction solar cell technologies – high efficiency, radiation resistance, and concentrator applications," Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion, pp.581-586, Osaka., May 11-18, 2003.
- [2] Masafumi Yamaguchi, "III-V compound multi-junction solar cells: present and future," Solar Energy Materials & Solar Cells, 75: 261-269, 2003.
- [3] Kenji Araki, Hisafumi Uozumi, Michio Kondo, Tatsuya Takamoto, Takaaki Agui, Minoru Kaneiwa, Toshio Egami, Masao Hiramatsu, Yoshinori Miyazaki, Yoshishige Kemmoku, Atsushi Akisawa, Hae-Seok Lee, N.J. Ekins-Daukes and Masafumi Yamaguchi, "Development of a new 550X concentrator module with 3J cells –

- performance and reliability," Proceedings of the 31st IEEE Photovoltaic Specialists Conference, pp.631-634, Lake Buena Vista, January 3-7, 2005.
- [4] Robert J. Walters, M.A. Xapsos, H.L. Cotal, S.R. Messenger, G.P. Summers, P.R. Sharps, M.L. Timmons, "Radiation response and injection annealing of p^+n InGaP solar cells," *Solid-State Electronics*, 42: 1747-1756, 1998.
- [5] Nethaji Dharmarasu, Masafumi Yamaguchi, Aurangzeb Khan, Takashi Yamada, Tatsuya Tanabe, Shigenori Takagishi, Tatsuya Takamoto, Takeshi Ohshima, Hisayoshi Itoh, Mitsuru Imaizumi and Sumio Matsuda, "High γ -radiation-resistant InGaP, InGaAsP, and InGaAs solar cells for multijunction solar cells," *Applied Physics Letters*, 79: 2399-2401, 2001.
- [6] N.J. Ekins-Daukes, Hae-Seok Lee, Takuo Sasaki, Aurangzeb Khan, Tatsuya Takamoto, Takaaki Agui, Kunio Kamimura, Minoru Kaneiwa, Mitsuru Imaizumi, Takeshi Ohshima, T. Kamiya and Masafumi Yamaguchi, "Carrier removal in lattice-mismatched InGaP solar cells under 1MeV electron irradiation," *Applied Physics Letters*, 85: 2511-2513, 2004.
- [7] Hae-Seok Lee, N.J. Ekins-Daukes, Takuo Sasaki, Aurangzeb Khan, Tatsuya Takamoto, Takaaki Agui, Kunio Kamimura, Minoru Kaneiwa, Mitsuru Imaizumi, Takeshi Ohshima, Hisayoshi Itoh and Masafumi Yamaguchi, "Defect observation of AlInGaP irradiated with 30keV protons for multi-junction space solar cells," Proceedings of the 31st IEEE Photovoltaic Specialists Conference, pp.556-558, Lake Buena Vista, January 3-7, 2005.
- [8] Aurangzeb Khan, S. Marupaduga, S.S. Anandkrishnan, M. Alam, N.J. Ekins-Daukes, H.S. Lee, T. Sasaki, M. Yamaguchi, T. Takamoto, T. Agui, K. Kamimura, M. Kaneiwa, M. Imaizumi, "Radiation response analysis of wide-gap p-AlInGaP for super high-efficiency space photovoltaics," *Applied Physics Letters*, 85: 5218-5220, 2004.
- [9] Hae-Seok Lee, Masafumi Yamaguchi, N.J. Ekins-Daukes, Aurangzeb Khan, Tatsuya Takamoto, Takaaki Agui, Kunio Kamimura, Minoru Kaneiwa, Mitsuru Imaizumi, Takeshi Ohshima and Hisayoshi Itoh, "Deep level defects introduced by 1 MeV electron irradiation in AlInGaP for multijunction space solar cells," *Journal of Applied Physics*, in press, 2005.
- [10] J.C. Bourgoin, J.W. Corbett, "Ionization effect on impurity and defect migration in semiconductors," *Inst. Phys. Conf. Ser.* 23: 149-163, 1975.
- [11] Aurangzeb Khan, Masafumi Yamaguchi, Jacques C. Bourgoin, Koshi Ando and Tatsuya Takamoto, "Recombination enhanced defect reactions in 1 MeV electron irradiated p-InGaP," *Journal of Applied Physics*, 89: 4263-4268, 2001.
- [12] Masafumi Yamaguchi, Tatsuya Takamoto, Stephen J. Taylor, Robert J. Walters, Geoffrey P. Summers, Dennis J. Flood, Masamichi Ohmori, "Correlations for damage in diffused-junction InP solar cells induced by electron and proton irradiation," *Journal of Applied Physics*, 81: 6013-6018, 1997.
- [13] Aurangzeb Khan, Jacques C. Bourgoin, Tatsuya Takamoto and Masafumi Yamaguchi, "Thermal annealing study of 1 MeV electron-irradiation-induced defects in n^+p InGaP diodes and solar cells," *Journal of Applied Physics*, 91: 2391-2397, 2002.
- [14] Hae-Seok Lee, Masafumi Yamaguchi, N.J. Ekins-Daukes, Aurangzeb Khan, Tatsuya Takamoto, Mitsuru Imaizumi, Takeshi Ohshima and Hisayoshi Itoh, "Effects of a low energy proton irradiation on n^+/p -AlInGaP solar cells," *PHYSICA B*, in press, 2005.
- [15] Nethaji Dharmarasu, Masafumi Yamaguchi, Aurangzeb Khan, Tatsuya Takamoto, Takeshi Ohshima, Hisayoshi Itoh, Mitsuru Imaizumi and Sumio Matsuda, "Deep-level transient spectroscopy analysis of proton-irradiated n^+/p InGaP solar cells," *PHYSICA B*, 308-310: 1181-1184, 2001.
- [16] Nethaji Dharmarasu, Masafumi Yamaguchi, Jacques C. Bourgoin, Tatsuya Takamoto, Takeshi Ohshima, Hisayoshi Itoh, Mitsuru Imaizumi and Sumio Matsuda, "Majority- and minority-carrier deep level traps in proton irradiated n^+/p -InGaP space solar cells," *Applied Physics Letters*, 81: 64-66, 2002.