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Change in the electrical performance of GaAs solar cells with InGaAs quantum dot layers by electron irradiation

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ABSTRACT

The radiation response of GaAs PiN solar cells with 50 stacked layers containing self-aligned $In_{0.4}Ga_{0.6}As$ quantum dots (QDs) was compared to that of GaAs PiN solar cells with non QD layers. Those solar cells were radiated with 1 MeV electrons up to $1 \times 10^{16}/cm^2$, and the change in their electrical characteristics under AM 0 was investigated using an *in-situ* measurement technique. After electron irradiation at $1 \times 10^{16}/cm^2$, the value of open circuit voltage (V_{OC}) for the $In_{0.4}Ga_{0.6}As$ 50 QD and the non QD solar cells remained 90 and 80% of the initial value, respectively. On the other hand, the values of short circuit current (I_{SC}) and maximum power (P_{MAX}) for the 50 QD solar cells became approximately 80 and 55% of the initial value by electron irradiation at $1 \times 10^{16}/cm^2$, respectively, although the non QD solar cells showed 95% for I_{SC} and 63% for P_{MAX} after the irradiation. The recovery of the electrical characteristics of both the InGaAs 50 QD and the non QD solar cells irradiated with electrons at $1 \times 10^{16}/cm^2$ were observed under AM0 light illumination at RT.

1. Introduction

Solar cells with highly stacked layers containing well-aligned Quantum Dots (QDs) are regarded as promising candidates for space applications as well as terrestrial applications owing to the potential as solar cells with the extremely high efficiency [1–6]. For example, it was estimated that the highest power conversion efficiency for QD solar cells is above 60%, if the intermediate band or miniband structures can be formed [1,2]. For the creation of the intermediate band or miniband structure, the realization of a well-aligned three dimensional (3D) QD lattice is required. However, the growth techniques for highly stacked QD layers have not yet been optimized. One of the issues is the generation of defects, such as misfit dislocations, during crystal growth due to the accumulation of internal lattice strain [7,8]. To overcome this issue, Okada et al. proposed the growth of space layers with GaNAs, and as a result, they could fabricate high quality InAs/GaNAs QD solar cells with a PiN structure [3,4]. Sugaya et al. also reported that self-organized InGaAs QDs with high uniformity can be grown on GaAs substrates using As_2 by Molecular Beam Epitaxy (MBE) [9,10], and InGaAs QD solar cells with up to 50 QD layers could be fabricated [5,6].

From the point of view of high efficiency, QD solar cells are attractive not only for terrestrial applications but also for space applications since the size of solar array panels of satellites is limited and/or the electric power required by solar array panels increases. For solar cells applied to space applications, their electrical performance at the end of mission (End-of-Life: EOL) as well as the Beginning-Of-Life (BOL) is very important because their electrical performance is degraded by irradiation of energetic particles such as electrons and protons in space. Thus, this indicates that we should know radiation response of solar cells before launch to predict their lifetime in space.

In a previous study, it was reported that the photo luminescence intensity of InGaAs/GaAs QDs irradiated with 1.5 MeV protons is two orders of magnitude higher than that for InGaAs/GaAs quantum wells irradiated under the same condition [11]. Cress et al. [12] also reported that GaAs solar cells with InAs QD layers showed higher radiation (alpha particle) resistance than GaAs solar cells with non QD layers. Furthermore, we reported that GaAs solar cells with up to 30 InGaAs QD layers, which were fabricated at AIST, showed better radiation resistance for V_{OC} than GaAs solar cells without QD layers [13]. We also observed no significant difference in the degradation of I_{SC} between solar cells with and without QD layers [13]. Those reported results suggest that QD solar cells might be suitable for space applications. However, on the other hand, the fabrication of solar cells with a larger number of stacked QD layers is required to achieve high efficiency solar cells, and the radiation response of such solar cells must be clarified to realize space applications.

In this article, we study change in their electrical characteristics of the GaAs solar cells with 50 QD layers by 1 MeV electron

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irradiation. Furthermore, we investigate the recovery of their degraded characteristics at room temperature (RT) by an *in-situ* measurement technique.

2. Experiments

The solar cells used in this study were GaAs PiN structures, of which i-layers contain self-organized $In_{0.4}Ga_{0.6}As$ QD layers, grown on Si-doped GaAs (001) by MBE. The active area of the solar cells was 0.38×0.38 cm^2. As_2 source was applied to the growth of 2 nm thick InGaAs QD layers at 520 °C at 4.5×10^{-6} Torr, and a GaAs buffer layer with 20 nm thick was grown on each InGaAs QD layer. Since 50 stacked QD layers were grown, the thickness of the i-layer for the 50 QD solar cell was 1.1 μm. Ti/Au front and AuGa/Ni/Au back electrodes were formed using photolithography and lift-off techniques. No anti-reflector coating was employed on the surface of the solar cells in this study. The efficiency for the 50 QD layer solar cells is 7.6% under AM1.5 at 25 °C. The details of crystal growth and the electrical characteristics of solar cells are described in Ref. [5,6]For comparison, non QD contained GaAs solar cells with an i-layer at a thickness of 660 nm fabricated under the same process without the fabrication of QD layers.

The both 50 QD and non QD solar cells were irradiated with 1 MeV electrons up to 1×10^{16}/cm^2 under AM0 illumination conditions in vacuum simultaneously using an *in-situ* measurement technique at JAEA, Takasaki [14,15]. The fluence rate used in this study was 5×10^{11} or 1×10^{12}/cm^2/sec. During the electron irradiation, the samples were placed on a water cooled copper plate to avoid heating up by electron beams. The temperature which was monitored using a dummy solar cell placed on the water cooled plate was between 17 and 60 °C under irradiation. The sample temperatures increased with irradiation time and became above 55 °C last 2 h of the irradiation. It can be mentioned that even if the electrical characteristics of those solar cells show annealing behavior at such a temperature, the effect of temperature on the recovery of the electrical performance of both solar cells should be the same, since the electron irradiation into both solar cells were carried out in almost the same condition. After irradiation at 1×10^{16}/cm^2, the annealing behavior of the electrical characteristics was also investigated. In the annealing experiment, the samples were kept under AM 0 illumination conditions at temperatures between 23 and 26 °C.

3. Results and discussion

3.1. Electron irradiation effects

The typical current density (*J*)–voltage (*V*) characteristics of an InGaAs 50 QD and a non QD GaAs solar cell under AM 0 light illumination before and after irradiation at 1×10^{16}/cm^2 are shown in Fig. 1(a). The value of J_{SC} obtained from the InGaAs 50 QD solar cell is larger than that for the GaAs solar cell. This suggests that the quantum efficiency in long wavelength regions (above 890 nm) increases due to the light absorption by InGaAs QD layers [13], and also the longer i-layer of the 50 QD solar cell can generate larger current than that of the non QD solar cell. To clarify this, the external quantum efficiency (EQE) for both solar cells was measured. The results of EQE for 50 QD and non QD solar cells are shown in Fig. 1(b). The value of EQE for the 50 QD solar cell obviously increases at wavelength regions above 890 nm although no significant increase in EQE for the non QD solar cell is observed above 890 nm. The current density generated by the 50 QD solar cell above 890 nm is estimated to be 1.8 mA/cm^2 from the EQE result. Since the *J*sc for the 50 QD and non QD solar cells are 22.0 and 18.7 mA/cm^2, respectively, it is concluded that can remaining 1.5 mA/cm^2 is effects of the longer i-layer of the 50 QD cell. On the other hand, the value of V_{OC} for the InGaAs 50 QD solar cell is smaller, as shown in the figure. This means that the issue of surface recombination still remains. However, we can say that the quality of the InGaAs QD layers might be high enough to study radiation effects in QD solar cells because the increase in I_{SC} and EQE above 890 nm obviously observed by introducing 50 QD layers.

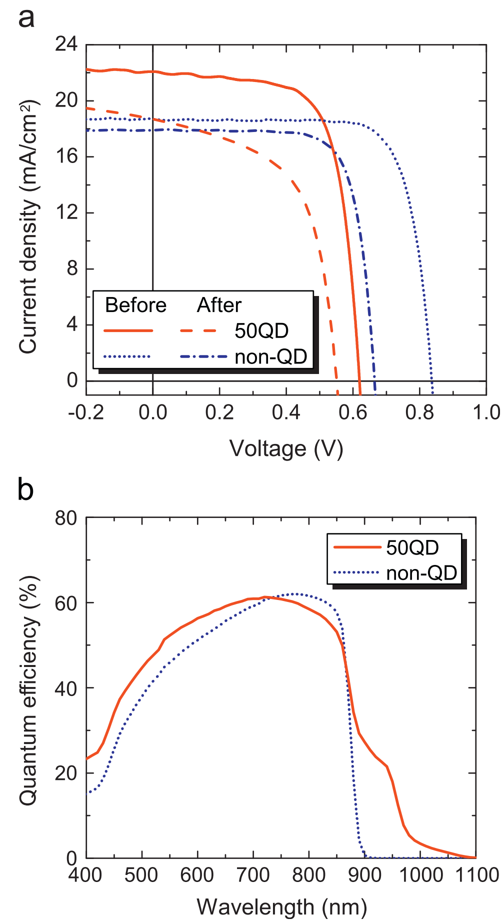

Fig. 1. (a) Current density (J)–voltage (V) characteristics of an InGaAs 50 QD solar cell and a non QD GaAs solar cell under AM 0 light illumination. The solid line and broken lines represent results obtained from the InGaAs 50 QD solar cells before and after irradiation at 1×10^{16}/cm^2, respectively. The results obtained from the non QD solar cells before and after irradiation at 1×10^{16}/cm^2 are depicted as dotted and dotted-broken lines, respectively. (b) EQE for 50 QD (Solid line) and non QD (dotted line) solar cells before irradiation.

These samples were irradiated with 1 MeV electrons up to 1×10^{16}/cm^2. By the irradiation, the *J*–*V* curves for both solar cells are degraded. Although the decrease in J_{SC} for the 50 QD solar cell is larger than that for the non QD solar cell, the 50 QD solar cell still keep higher J_{SC} value than the non QD solar cell after irradiation at 1×10^{16}/cm^2, as shown in Fig. 1(a). In order to observe the degradation behavior of both solar cells, the typical results of remaining factors of I_{SC}, V_{OC} and P_{MAX} for InGaAs 50 QD and for non QD solar cells are plotted in Fig. 2(a)–(c). After 1 MeV electron irradiation at 1×10^{16}/cm^2, the remaining factor of I_{SC}, V_{OC} and P_{MAX} for the InGaAs 50 QD solar cell becomes 80, 90 and 55% of the initial values, respectively. On the other hand, those values for non QD GaAs solar cells decrease to approximately 95, 80 and 63% of the initial values after electron irradiation at 1×10^{16}/cm^2, respectively. The diffusion length of minority

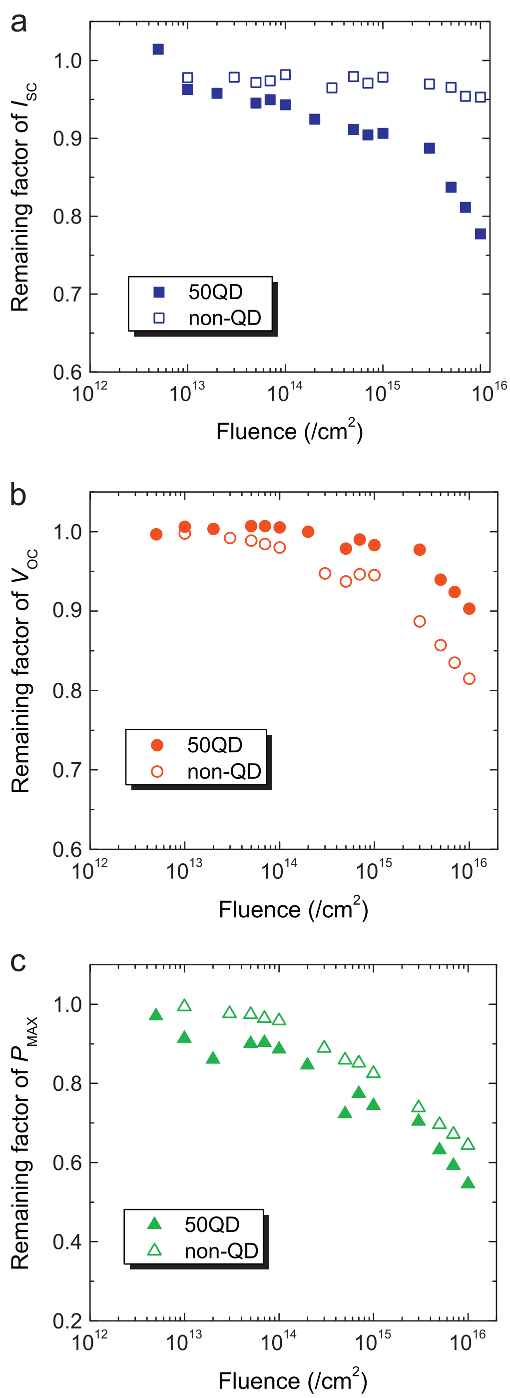

Fig. 2. Typical results of remaining factors of (a) I_{SC} (Squares), (b) V_{OC} (Circles) and (c) P_{MAX} (Triangles) for InGaAs 50 QD (Closed symbols) and non-QD solar cells (Open symbols).

carriers (holes) in the non QD solar cell is estimated to be approximately 5 μm before irradiation by fitting of J–V characteristics using the simulation code PC1D [16]. Although the damage coefficient of the diffusion length (K_L) for the solar cells used in this study is not clear, if the reported value of K_L (10^{-9} cm^2) is applied [17], the minority carrier diffusion length after irradiation at 1×10^{16}/cm^2 can be estimated to be 2.7 μm. This suggests that the minority carrier diffusion length still keeps an enough value for current generation even after irradiation at 1×10^{16}/cm^2. The result of I_{SC} obtained from the non QD solar cell supports this estimation. However, the 50 QD solar cell shows the significant degradation in I_{SC} after the irradiation, as shown in Fig. 2(a). Since the substrates for both 50 QD and non QD solar cells have the same spec and quality, the origin of the decrease in I_{SC} for the 50 QD solar cell might be different from the decrease in the minority carrier diffusion length. In this case, carrier recombination and/traps in the drift region (i-layer) is thought to be one of the reasons for the decrease in I_{SC}. The drift length ($\mu E\tau$) is an important parameter to understand the decrease in I_{SC} due to irradiation, where μ, E and τ are minority carrier mobility, electric field and minority carrier lifetime, respectively [18]. Since the drift length is much longer than the drift region in general, the decrease in I_{SC} due to carrier recombination and/traps is not dominant effects in the drift region. However, the value of μ and τ in the i-layer with QDs might be smaller than the i-layer with non-QDs owing to the existence of QDs. In addition, the length of the i-layer (total thickness of QD-layers) for the 50 QD solar cell (1.1 μm) is thicker than that for the non QD solar cell (660 nm), and as a result, the electric field in the 50 QD solar cell is weaker than that in the non QD solar cell. Thus, the number of carriers recombined in the i-layer for the 50 QD solar cell might be larger than that for the GaAs solar cell, and as a result, the decrease in I_{SC} for the 50 QD solar cell is larger than that for the GaAs solar cell. To clarify the mechanism of the degradation in I_{SC} for QD solar cells, further investigations are necessary.

In contrast to the behavior of I_{SC}, the V_{OC} for the 50 QD solar cell shows higher radiation resistance than that for the non QD solar cell. No significant decrease in V_{OC} is observed for the 50 QD solar cell at fluence ranges up to 2×10^{14}/cm^2. Then, the V_{OC} decreases with increasing fluence above 2×10^{14}/cm^2, and the value becomes 90% of the initial value after irradiation at 1×10^{16}/cm^2. For the non QD GaAs solar cell, the value of V_{OC} decreases with increasing fluence, and the value is approximately 80% of the initial value after irradiation at 1×10^{16}/cm^2. Since the non QD solar cell shows high radiation resistance in I_{SC}, the decrease in V_{OC} might come from the increase in the surface recombination. For the 50 QD solar cell, although the detailed mechanism of the degradation of V_{OC} has not yet been clarified, following two possibilities can be proposed. Firstly, the 50 QD solar cell is less sensitive to the surface recombination created by irradiation. Thus, the initial value of the surface recombination for the 50 QD solar cell must be larger than that for the non QD solar cell due to layer-by-layer structures of QD layers. This means that the V_{OC} is subjected to the surface recombination effects even before irradiation. Although the surface recombination increases by irradiation, the value of the surface recombination created by irradiation might be still low compared to the initial value of the surface recombination. As a result, less degradation in V_{OC} for the 50 QD solar cell is observed. For another possibility, since the QD layers consist of two materials (InGaAs and GaAs) with different bandgap energy, the value of V_{OC} might not be explained by the mechanism based on the simple p-i-n structure with one material. Thus, even if the surface recombination at the interface between GaAs layers increases by irradiation, if the saturated currents (leakage currents) are limited by the existent of InGaAs which has a narrower bandgap than GaAs, the value of V_{OC} for the 50 QD solar cell is not strongly affected by the surface recombination generated by irradiation. Although the decrease in the initial value of V_{OC} for QD solar cells is disadvantage to non QD solar cells, the less degradation of V_{OC} by irradiation can be said to advantage from the point of view of radiation hardness. Thus, the result obtained in this study suggests that QD has a potential to be applied to radiation hardness technologies for space solar cells. It was reported that GaAs solar cells with 20 and 30 InGaAs QD layers showed better radiation resistance than GaAs solar cells without QD layers from the point of view of V_{OC} [13]. Therefore, the result obtained in this study is consistent with the report. The value of P_{MAX} for both the 50 QD and the GaAs solar cells

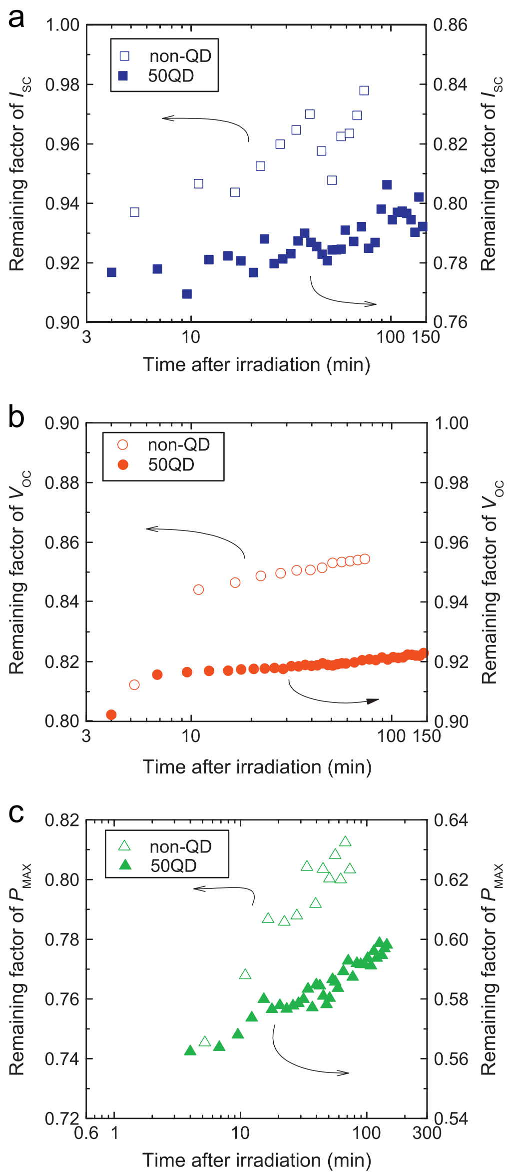

Fig. 3. Change in (a) I_{SC} (Squares), (b) V_{OC} (Circles) and (c) P_{MAX} (Triangles) for 50 QD (Closed symbols, right axis) and non-QD solar cells (Open symbols, left axis) irradiated with 1 MeV electrons at $1\times10^{16}/cm^2$ as a function of time immediately after electron irradiation. The values are normalized by the values before irradiation.

decreases with increasing fluence. The decrease in P_{MAX} for the 50 QD solar cell shows slightly larger than that for the GaAs solar cell. It should be noticed that solar cells with p-i-n structure were used in this study, and the radiation resistance of solar cells might depend on the polarity of solar cells (p/n or n/p). Since solar cells fabricated on p substrates show stronger radiation resistance in general, the higher radiation resistance might be obtained from QD solar cells with n-i-p structure. To clarify this, further investigations are required.

3.2. RT annealing effects

After irradiation at $1\times10^{16}/cm^2$, the annealing behavior of the electrical characteristics for samples was investigated under AM 0 illumination. Fig. 3(a)–(c) show the change in I_{SC}, V_{OC} and P_{MAX} for 50 QD and non QD solar cells irradiated with 1 MeV electrons at $1\times10^{16}/cm^2$ as a function of time immediately after electron irradiation. The recovery of all characteristics (I_{SC}, V_{OC} and P_{MAX}) is observed for both solar cells, and the recovery of the non QD GaAs solar cell is relatively larger than that of the 50 QD solar cell. Since the electrical characteristics of irradiated samples are usually measured at a different facility from an irradiation facility, this recovery cannot be found by conventional evaluation methods. Thus, we can conclude that the *in-situ* measurement method used in this study is useful to find out the annealing effects immediately occurring after irradiation at RT. Although the mechanism of this recovery has not yet been clarified, the origin of this recovery is thought not to come from the existence of QDs because the GaAs solar cell without QD layers also shows the recovery. The degradation of I_{SC} due to irradiation occurs by shortening minority carrier lifetime due to the creation of defects which act as minority carrier traps or/and recombination centers. Therefore, at least, the recovery of I_{SC} might be caused by the reduction of defects introduced by irradiation.

As for the annealing of defects in non-doped/n-type GaAs irradiated with 1 MeV electrons at RT, it was reported from Deep Level Transient Spectroscopy (DLTS) studies that defect centers which act as electron traps called E1 and E2, showed recombination-enhanced annealing at relatively low temperatures (around 165 °C) [19,20]. The annealing of E2 increased with increasing injected current density as well as temperature. DLTS studies by Pons et al. [21] also revealed that other defect centers (E3, E4 and E5) generated in n-type GaAs by 1 MeV electron irradiation at RT decrease by annealing at 190 °C, and the annealing behavior of E3 and E5 was the same as E2. They also proposed that vacancy-interstitial pairs or vacancy-antisite defects affect the annealing behavior of these defect centers. These reports suggest that some radiation-induced defects in GaAs can be mobile at temperatures around RT, especially during carrier injection. However, the RT annealing of defects in GaAs irradiated with electrons at RT has not yet been reported to our knowledge. On the other hand, the annealing behavior of defects created in GaAs by irradiation of 1.3 MeV-electrons at low temperatures (5 or 77 K) was studied, and a small recovery of the conductivity was observed at annealing temperature ranges between 200 and 300 K [22]. Since defects were created by low temperature irradiation, the annealing behavior of such defects might not be the exact same as defects created by RT-irradiation. However, this reported result suggests that some residual defects in GaAs have a possibility to be mobile even at RT. Since vacancy type defects are stable at RT in general, it seems that interstitial-related defects and/or defects located near the interface of each layer might play a role in annealing at RT. To clarify this, further investigations are necessary.

According to Yamaguchi et al. [23], the diffusion length (L_{diff}) of minority carriers decreases with increasing defect density, and the degradation of J_{SC} is related to a decrease of L. Then, these relationships are expressed as

$$1/J^2{}_{SC\Phi}-1/J^2{}_{SC0}\propto 1/L^2_{diff\Phi}-1/L^2_{diff\ 0}=\mathrm{BN}_{T0}, \tag{1}$$

$$1/J^2{}_{SCA}-1/J^2{}_{SC0}\propto 1/L_{diffA}{}^2-1/L_{diff}{}^2 0=BN_{TA}, \tag{2}$$

where the suffix 0 indicates before proton irradiation, Φ indicates after irradiation, and A indicates after annealing. N_{T0} are defect density after irradiation, and N_{TA} are defect densities after annealing. B is a constant. Since solar cells used in this study have PiN structures, the drift length ($L_{drift}=\mu E\tau$) of minority carriers affects J_{SC}, instead of L_{diff},. Where μ, E and τ are mobility of minority carriers, electric field and minority carrier lifetime, respectively. Therefore, Eqs. (1) and (2) are described as

$$1/J^2_{SC\Phi}-1/J^2_{SC0}\propto 1/L^2_{drift\Phi}-1/L^2_{drift0}=\mathrm{BN}_{T0}, \tag{1′}$$

$$1/J^2_{SCA}-1/J^2_{SC0}\propto 1/L^2_{drift}\mathrm{A}-1/L^2_{drift}0=\mathrm{BN}_{TA}, \tag{2′}$$

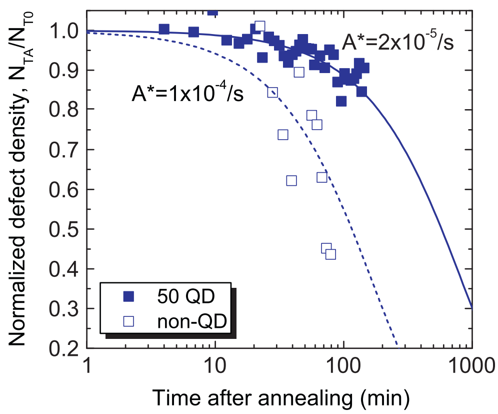

Fig.4. Normalized defect density (N_{TA}/N_{T0}) in 50 QD (Closed squares) and non-QD solar cells (Open squares) irradiated with electrons as a function of injected charge. The values of N_{TA}/N_{T0} estimated using eq. 3 are also plotted in the figure. Broken and solid lines represent the value of N_{TA}/N_{T0} where $A*$ is 1×10^{-4} and 2×10^{-5}/s, respectively.

From Eqs. (1′) and (2′), the normalized defect density (N_{TA}/N_{T0}) is obtained as

$$N_{TA}/N_{T0} = \left(1/J^2_{SCA} - 1/J^2_{SC0}\right)/\left(1/J^2{}_{SC}F - 1/J^2{}_{SC0}\right) \quad (3)$$

Furthermore, the relationship between N_{T0} and N_{TA} is expressed as

$$N_{TA} = N_{T0}\exp(-A{*}t), \quad (4)$$

where A^* is defect annealing rate and t is current injection time (in this case light illumination time).

Fig. 4 shows the Normalized defect density (N_{TA}/N_{T0}) in 50 QD (Closed squares) and non QD solar cells (Open squares) irradiated with electrons as a function of injected charge. The values of N_{TA}/N_{T0} estimated using Eq. (3) are also plotted in the figure. Broken and solid lines represent the value of N_{TA}/N_{T0} where A^* is 1×10^{-4} and 2×10^{-5}/s, respectively. The reported values of A^* at RT are at the orders below 10^{-6}/s for III–V compounds such as GaAs, InGaP. The A^* for only InP under current injection conditions was reported to be of the orders at 10^{-3}/s even at -30 °C [24]. Thus, the value of A^* obtained in this study is higher than the values reported for other III–V materials except InP under current injection conditions. The origin of such high A^* value obtained in this study has not yet been revealed. However, such a rapid recovery cannot be detected by general sequential techniques (measurement of the characteristics are carried out at the different place from irradiation facilities). Thus, only the *in-situ* measurement technique can detect such a rapid recovery. Therefore, we can say that the *in-situ* measurement technique is very useful to study such a rapid recovery effects.

4. Summary

GaAs PiN solar cells with 50 stacked layers containing self-aligned $In_{0.4}Ga_{0.6}As$ QDs and GaAs PiN solar cells with non QD layers were irradiated with 1 MeV electrons up to $1\times10^{16}/cm^2$. The radiation response of their electrical characteristics under AM 0 was investigated using an *in-situ* measurement technique. The value of V_{OC} for the InGaAs 50 QD solar cell remains 90% of the initial value after electron irradiation at $1\times10^{16}/cm^2$, and this value is larger than that for the GaAs solar cell with non QD layers. On the other hand, the values of I_{SC} and P_{MAX} for the 50 QD solar cells decrease to approximately 80 and 55% of the initial value after electron irradiation at $1\times10^{16}/cm^2$, respectively. The degradation of I_{SC} and P_{MAX} for the GaAs solar cells with non QD layers is smaller than those for the 50 QD solar cells.

After electron irradiation at $1\times10^{16}/cm^2$, the recovery of the electrical characteristics of the InGaAs 50 QD solar cells as well as the GaAs PiN solar cells with non QD layers is observed under AM0 light illumination at RT. The GaAs solar cells with non QD layers show larger recovery than that for the InGaAs 50 QD solar cells. Since such a rapid recovery cannot be detected by the conventional evaluation method, the *in-situ* measurements used in this study are useful to investigate recovery effects occurring immediately after irradiation.

Acknowledgments

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