External quantum efficiency artifacts in partial-irradiated GaInP/GaAs/Ge solar cells by protons and electrons

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Introduction

Nowadays, trijunction GaInP/GaAs/Ge becomes the main solar cells used in spacecraft, quantum efficiency (QE) or spectral response (SR) measurements are always applied to characterize the cell’s properties or quality and to evaluate the damage behaviors of the solar cells after particle irradiation. The series configuration of the MJ solar cells brings many specific phenomena, including QE artifacts. QE artifacts always exist during external QE (EQE) measurements and one should take some measurements to eliminate it [1–3]. The generation of artifacts requires series subcells structures and either low shunt resistance or high level of fluorescence coupling (FC). The low shunt resistance could cause a partial short circuit condition, producing a current leakage. High level of photon recycles may introduce extra signal from configurations above the detected layer, making the EQE results shift from where it should be. The two effects could be divided individually by the analytical method [4]. Li et al. analyzed both of the two effects and established mathematical models to explain them. Although mathematics analysis is relatively precise, it is complicated as well. One important thing should be pointed out is that the artifacts could be detected and analyzed using a typical measurement mode with a bias light and a pulse EQE excited spot. When the area of bias light is as large as it of the pulse EQE excited spot, the artifacts could be well expressed by one-dimension relations; however, when the area of bias light is much larger than that of the pulse EQE excited spot, one-dimension relations cannot describe the artifact behavior correctly. Some modifications are needed. In this paper, we develop a graphic explanation of artifacts and extend it to two-dimension (2D) condition, which is hard for previous mathematic analysis method.

Keywords
2D EQE artifacts, fluorescence coupling, GaInP/GaAs/Ge solar cells, lateral scanning, radiation degradation

Abstract

Artifact is a special kind of phenomenon related to fluorescence coupling and shunt resistance in external quantum efficiency (EQE) measurements in multi-junction (MJ) solar cells, and it is sensitive to the defects and damages. In this paper, the changes of artifacts were studied in partial irradiated MJ solar cells by common or two-dimension mapping Quantum Efficiency (QE) measurements. Simplified mathematical models and graphic analysis were applied to explain the mechanisms of changes of artifacts. Irradiation weakens the artifacts effects due to the decrease in relative fluorescence yield. Artifacts analysis results indicate that after 1 MeV electron irradiation, the open circuit voltage $V_{oc}$ of GaInP subcell decays from 1.40 V to 1.35 V, and the reverse saturation non-radiative recombination current $I_{02}$ increases 3.7 times. Correspondingly, after 70 keV protons irradiation, the open circuit voltage $V_{oc}$ decays to 0.90 V and $I_{02}$ increases 7550 times by EQE artifacts analysis. Lateral scanning of the partial damaged samples shows a smooth artifacts transition region that appears near the boundary of damaged region in MJ solar cells. This is found correlated with the difference in the lighted areas of bias light and EQE pulse spot. 2D artifacts analysis could properly explain the smoothness and shift of damage interface.
On the other hand, space particles radiation results in damage of MJ solar cells, changing the shunt resistance and also photoluminescence behaviors of the composed layers (such as GaInP, GaAs) [5, 6]. It should be noted that after irradiation, artifacts usually be weakened, leading to an abnormal increase in EQE in the underneath/bottom parts of MJ solar cells. The phenomenon was shown mainly in the GaAs/Ge [7, 8] packed cells, but no more literature was found to report this effect of the important GaInP/GaAs part in MJ solar cells to the author’s knowledge. Thus, in this paper, we would focus on the artifacts between GaInP and GaAs junction.

Radiation resistance is a crucial factor that would significantly influence the design of solar cells. Energetic particles cause defects which act as Shockley-Read-Hall (SRH) recombination centers shortening the carrier lifetime. Augment of SRH recombination weakens the counteracting radiative one, mainly from the results of electroluminescence (EL) [9, 10], thus decreasing the conversion efficiency further. Here, artifacts could reflect the radiative recombination in GaInP, becoming a potential method for radiation degradation analysis.

Quantum efficiency mapping is a developed technique to study the inhomogeneity of solar cells. Through scanning the pulse EQE excited spot-radiation on the cell surface, the contrast of QE signals could determine the macroscopic defects distributions and composition heterogeneity of the cells. In this paper QE mapping were applied to study the 2D artifacts of multi-junction solar cells affected by the charged particles, then exposing the mechanisms on the inhomogeneous defects or damage in MJ solar cells in both depth and lateral directions.

**Experiments**

**Multi-junction solar cells and radiation experiments**

GaInP/GaAs/Ge solar cells with a dimension of 20 × 40 mm and with surface Anti-Reflection Coating (ARC) were fabricated in CETC18 (18th China Electronics Technology Group Corporation) in Tianjin, China. The configuration was shown in Figure 1. In order to determine the damage effects from different subcells on the artifacts behaviors, 70 keV protons and 1 MeV electron beams were selected as the irradiation sources. Hence, the range of 70 keV protons is within GaInP layer in the solar cells verified by SRIM [11] code, while 1 MeV electrons could penetrate thoroughly through the solar cells, causing damage in GaInP, GaAs and Ge layer by Casino [12] code. On the other hand, half surface of solar cells was irradiated by 70 keV protons and 1 MeV electron beams by using 5 mm thick iron sheet as a shielding layer (as showed in Fig. 2), in order to demonstrate the effects of local irradiated damage on the artifacts behaviors. In our tests, the protons fluence was set up to 2 × 10^{12} cm^{-2} and the electron fluence was determined as 2 × 10^{15} cm^{-2}, both of which are high enough to cause the damage for our study.

**EQE measurement of FC effect**

External quantum efficiency of GaInP/GaAs/Ge was tested on QE10X system made in USA. The bias light with a spot radius of 12 mm was chosen blue in the wavelength of 450–550 nm for top subcell, red (650–750 nm) for the middle and IR (1200+ nm) for the bottom ones, respectively. The intensity of bias light should be controlled high enough to saturate the corresponding subcells reaching the condition of quasi-open circuit in each subcell. Unless specially mentioned, the intensity of bias light is unchanged.

In order to make two-dimensional EQE mapping measurements, the samples on the holder could be controlled and moved along X and Y directions near the center line of the tested cells. EQE lateral mapping was along the middle line of the solar cells and the moving step is 0.2 mm, while the width of the test spot is 1.5 mm (Fig. 2). The bias light and test light are fixed while the solar cell holder is controlled movably to realize the scanning mode.

For artifacts measurement, we focus on the middle GaAs subcell. Artifacts refer to the EQE signal of EQE of the GaAs cells appearing abnormally at shorter wavelength which should not have appeared, namely the artifacts of middle cell is influenced by top one. 400 nm photons...
are totally absorbed by top GaInP for their higher absorption coefficients, thus the EQE for GaAs at 400 nm should be zero. However, EQE for GaAs at 400 nm is not zero. On the other hand, artifact effects also result in that the real EQE of GaAs at $\lambda = 750$ nm should be larger than the measured one. In this cases, EQE of GaAs at $\lambda_1 = 400$ nm and $\lambda_2 = 750$ nm was selected for 2D artifact analysis in our study.

**Explanation of Artifacts between GaInP and GaAs in EQE Measurement**

Most researches about artifacts concern between GaAs and Ge because of the high fluorescence yield of GaAs and low shunt resistance of Ge. Although the artifacts between GaInP and GaAs are weaker than that between GaAs and Ge, artifacts behaviors between GaInP and GaAs include some information about top cell and the middle one, which is important for the irradiation degradation analysis for GaInP/GaAs/Ge solar cells applied in space. Generally speaking, the top GaInP and middle GaAs cells of the space tri-junction cells are far more important to precisely evaluate the orbital behavior for their sensitivities to the irradiation environments. Thus, it is necessary to clearly explain the artifacts of GaAs coupled with GaInP top cells. Besides, the addition bias voltage of solar cells when EQE of Ge were measured could make the problem much complex. Thus we simplified somehow the physical artifact models to perfectly explain the phenomena as well.

It is known that the source of artifacts comes in two ways: the fluorescence coupling and shunt resistance effect, simplified models of the artifacts will be presented as the followings.

**Fluorescence coupling**

Fluorescence coupling is related to carrier recombination behaviors within a solar cell. Hence, carrier recombination $R$ is composed of two parts: radiative recombination $R_r$ and nonradiative one $R_{nr}$ as expressed in equation (1).

$$ R = R_r + R_{nr} $$

One radiative recombination generates a new photon with energy near the bandgap. For radiative recombination current, it is usually described as equation (2), where $J_r$ refers to the radiative recombination current as the two-diode model of solar cells, $V$ is the applied voltage, $k_B$ is the Boltzmann constant, $T$ is the temperature and $J_0$ is the corresponding inverse saturation current. Equation (2) is also similar with the light emitting equation in light-emitting diode (LED).

$$ J_r = J_0 \left[ \exp \left( \frac{qV}{k_B T} \right) - 1 \right] $$

Thus the number of the photons generated by radiative recombination is proportional to radiative recombination current $J_r$. The photons would be isotropic emitted and reabsorbed by materials. A part of these photons could penetrate the GaInP layer and be incident down into the middle GaAs layer, where they are reabsorbed, leading to an extra LC current $J_{mid,LC}$ and this current is in direct proportion to recombination current of top subcell $J_{r,top}$ [2, 3]. Thus one could get $J_{mid,LC} = \alpha J_{r,top}$ where $\alpha$ is the absorption rate of fluorescence in the top cells.

The primary part of nonradiative recombination is SRH recombination, which happens mainly in SCR region. The SRH recombination current could be expressed as equation (3), where $J_0'$ is the corresponding dark current at $V = 0$.

$$ J_{nr} = J_0' \left[ \exp \left( \frac{qV}{2k_B T} \right) - 1 \right] $$

Both of the recombination current is influenced by configuration of solar cells, for example, doping level and lifetime of minorities could affect $J_0$ and $J_0'$. High level of doping could decrease the width of SCR, thus influence the recombination current. In our research, the doping level hardly changes, and $J_0'$ is considered a constant. To estimate the fluorescence coupling, one could define relative internal fluorescence yield $e$, representing the percent of radiative recombination current $J_r$ to the total one ($J_r + J_{nr}$). Yield $e$ is related to electrical field $V$ across
the junction, as presented in equation (4). During EQE measurement for the middle cell, top GaInP cell is in quasi-open circuit state, which means \( V \approx V_{oc} \), \( qV \gg k_B T \). Thus, one could obtain the following equation (4):

\[
e^\approx \frac{J_0}{J_0 + J}\approx \frac{J_0}{J_0 + J_0 \exp\left(-\frac{qV}{2k_B T}\right)}
\]

(4)

The heavy doped p++/n++ InGaP tunneling junction is such thin that its absorption could be ignored and it is considered transparent for photons. As the main conduction mechanism in tunneling junction is tunneling effect, the bias voltage is small and no photons is generated, thus the effect of tunneling junction could be ignored.

In EQE measurements, the test mode is AC mode. The total current is the sum of the DC component \( J \) and AC component \( j \). The AC current induced by EQE pulse is \( j \), and the DC current induced by bias light is \( J \). Taking fluorescence coupling effect into consideration, the current of middle subcell is \( \alpha(J_{r,top} - j_{r,top}) \), and the balance relation of current in GaInP is equation (5), where the \( j_{r,top} \), \( j_{sc} \), \( J_{sc,mid} \) refer to the corresponding AC component of radiative recombination current, nonradiative recombination (SRH recombination) current and short-circuit current, \( \alpha \) is the fluorescence coupling coefficient. The mark top or mid refer to the current in top GaInP or mid GaAs subcell respectively. For artifacts at \( \lambda = 400 \) nm, the EQE pulse generates an AC signal \( j_{sc,top} \).

\[
J_{sc,top} + j_{sc,top} - J_{r,top} - j_{r,top} - j_{sc,top} = \alpha(J_{r,top} + j_{r,top})
\]

(5)

Only the AC component is meaningful in EQE measurement. EQE is the ratio of number of hole-electron pair generated by EQE pulse and the flux of the pulse. Applying (4) to AC current, we could get equation (6), where \( EQE_x^\lambda \) refers to the EQE of the \( x \) subcells (\( x = \text{GaInP or GaAs} \)) at the wavelength of \( \lambda \).

\[
EQE_{400nm}^\lambda = \frac{\alpha J_{sc,top}}{q\phi_{400nm}} = \frac{1}{1 + (ae)^{-1}} \left| \frac{J_{sc,top}}{q\phi_{400nm}} \right|
\]

(6)

By the same way, for the EQE measurement at \( \lambda = 750 \) nm, AC current in middle junction \( j_{sc,mid} \) is generated. The balance of current in GaInP changes to equation (7):

\[
J_{sc,top} - J_{r,top} - j_{r,top} - j_{sc,top} - j_{sc,mid} = \alpha(J_{r,top} + j_{r,top})
\]

(7)

And one could get equation (8) further.

\[
EQE_{750nm}^\lambda = \frac{j_{sc,mid} + \alpha j_{sc,top}}{q\phi_{750nm}} = \frac{1}{ae + 1} \left| \frac{j_{sc,mid}}{q\phi_{750nm}} \right|
\]

(8)

Although mathematic analysis could describe the origin of artifacts well, but it is less clear and much complicated. Graphic analysis could be helpful to understand these complicated relations and simplified the problem as well.

In order to graphically represent the artifacts phenomena, one of the basic assumptions should be made is that the top and middle solar cells have the same current due to current-limitation rule, and total voltage is zero (because EQE are measured under short circuit condition) during measurements. Another assumption is that the fluorescence emission is much fast so that the transition time could be ignored compared with pulse period (several milliseconds). Under the current-limit and voltage-zero assumption, only point A (that is “working point”) could satisfy these requirements (shown in Fig. 3). The light I-V of top and middle cell is the black curves in Figure 3. The short circuit current of middle solar cell is not zero because of the FC effects. Thus, in the case of 400 nm wavelength, the EQE artifact phenomena in the middle sub-cell could be graphically shown with the following five steps:

1. The increase in excitation current \( I_{exc} \) because of the EQE pulse;
2. The addition of \( I_{exc} \) leads to a lift of I-V curve, increasing the voltage at the “working point” of top cells (from point A to B);
3. The increase in working point voltage of top cells enlarge radiative recombination, leading to an increase in \( I_{sc} \) in middle cells.
4. Under the current-limit requirement, the output current increases (from the current of A to current of B), and the increased current is the origin of artifacts.
5. The increase in \( I_{sc} \) in the middle cells could further move “working point” to a new place with higher current and lower voltage. The decrease in voltage of top cells could further decrease the \( I_{sc} \) of middle cells, but the change is relatively small. We call them “high order feedbacks”, which is small enough to affect the output current.

For 750 nm, there are similar five steps:

1. The increase in \( I_{sc} \) of middle solar cell \( I_{sc} \) because of the EQE pulse (form “0” state to “1+” state);
2. The addition of \( I_{exc} \) leads to decrease in the voltage of the working point of top solar cells (from point A to B);
3. The shift of working point from A to B leads the decrease in voltage of top GaInP cells. Radiative recombination decreases because of the drop of voltage.
4. The decrease in radiative recombination in top cells cause the decrease in \( I_{sc} \) in middle GaAs cell (changing the state from “1+” to “1−”). The decreased current is the origin of artifacts.
5. The decrease in current move the working point to larger voltage, and high order feedbacks are ignored.

**Shunt resistance**

Shunt resistance also affects the artifacts. As mathematic analysis is much more complicated, graphic analysis was used instead. Solar cells could be equivalent to a circuit consisting of diodes, resistors and current source. For artifacts at $\lambda = 400$ nm, the equivalent circuit of multi-junction solar cells could be rearranged by considering middle GaAs as a load and GaInP and Ge as sources connected in series (Fig. 4A). For artifacts at $\lambda = 750$ nm, the equivalent circuit is shown in Figure 4B.

Considering GaInP and Ge as a tandem solar cell, the abovementioned relation could be summarized in Figures 4 and 5, where the EQE test spot could raise the current $j_{sc}$. In Figure 5, the black curve is the I-V of the tandem solar cell (the left part of Fig. 4A and B), and the red one is the I-V curve of loads (the right part of Fig. 4A and B). The dash line refers to the I-V of solar cells when EQE pulse is on. The cross point of two curves is the working point, and the change in the working point is $\Delta j_{sc}$. For $\lambda = 400$ nm, $j_{sc}$ appears in left part in Fig. 4A, leading to a lift of blue curve. The increase in $I_{sc}$ of top cells could be transferred to $\Delta j_{sc}$. $\Delta j_{sc,1}$ is the EQE under high shunt resistance and $\Delta j_{sc,2}$ under low shunt resistance. We could see that $\Delta j_{sc,2}$ is larger than $\Delta j_{sc,1}$ at $\lambda = 400$ nm. The $\Delta j_{sc,2}$ leads to the artifacts signal. Artifacts at $\lambda = 750$ nm could be explained by a similar way.

In conclusion, the resource of artifacts could be divided into two kinds: fluorescence coupling and low shunt resistance effect. Both of them result in artifacts at $\lambda = 400$ and $\lambda = 750$ nm. For epitaxy grown GaAs with high crystal quality, the shunt resistance is so large and its effect could be ignored.

**Artifacts in Damaged Solar Cells by 1 MeV Electrons and 70 keV Protons Radiation**

External quantum efficiencies of solar cells before and after 1 MeV electrons radiation are shown in Figure 6A. After irradiation, the EQE of middle subcell decreases...
seriously to zero at $\lambda = 400$ nm while remains 87% at $\lambda = 800$ nm. It implies that artifacts may have different degradation laws compared with normal real signals at different wavelengths. It also reminds us that the EQE degradation of solar cells appears a mixture of artifacts degradation and real quantum efficiency one.

It is widely accepted that irradiation-induced defects enhance the nonradiative recombination (mainly through the introduction of SRH recombination centers) $R_{nr}$, which shorten the lifetime of the minorities carriers and decrease the relative internal fluorescence yield $e$ [13–15]. Given that the shunt resistance of GaAs does not change too much during electron irradiation, one could attribute the change in artifacts to FC effects.

After 1 MeV electron radiation, that $e$ decrease 93% after radiation (from eq. 6, as the change in $\alpha$ is little).

Equation (4) could further be simplified to equation (9) under quasi-open circuit condition assumption. High energy electrons enhance nonradiative recombination (SRH recombination) current by a factor of $k$ (from $J_0'$ to $kJ_0'$). Assuming $V_{oc} = 1.40$ V, $J_{sc} = 13.0$ mA/cm$^2$ (by integral of EQE), $J_0 = 5.36 \times 10^{-26}$ mA/cm$^2$ and $J_0' = 2.64 \times 10^{-11}$ mA/cm$^2$ before radiation (calculated by $e = 0.001$ from EL data [16, 17]. Common luminescence efficiency [14, 15] of GaInP is 0.0001–0.01, so $e = 0.001$ was used). By equations (10) and (11) we could estimate the $V_{oc}$ after radiation.

The relative internal fluorescence yield $e$ before irradiation and after irradiation are equations (9) and (10) respectively.

$$e = \frac{J_0'}{J_0} \exp \left( \frac{qV_{oc}}{2k_BT} \right)$$

**Figure 5.** The artifacts of external quantum efficiency at $\lambda = 400$ nm induced by low shunt resistance of GaAs. (A) $\lambda = 400$ nm; (B) $\lambda = 750$ nm.

**Figure 6.** External quantum efficiency of top and middle junction of GaInP/GaAs/Ge solar cells pre and post–radiation. (A) $3 \times 10^{15}$ cm$^{-2}$ 1 MeV electrons; (B) $2 \times 10^{12}$ cm$^{-2}$ 70 keV protons.
that all the degradation of top cells after radiation is 0.9 V (by the assumption of top GaInP subcells). We could calculate $k = 7550 \pm 50$, which is much larger than $k = 2.12 \pm 0.02$ for electron radiation because of higher level of displacement damages. The corresponding fluorescence yield $e$ decreases to 1/10,000 of the original one, indicating the disappearance of artifacts.

**EQE Lateral Scanning**

Spatially resolved EQE could be applied to characterize the homogeneity of solar cells and also to detect macroscopic defects such as cracks and composition float. Whether artifacts could affect the EQE lateral scanning results has not been reported yet. In our research, a partial intentionally damaged solar cell was used to study the 2D response of artifacts phenomena. Part of the solar cell was irradiated by 70 keV protons to a fluence of $1 \times 10^{12}$ cm$^{-2}$ as shown in Figure 7. The EQE lateral mapping results at the wavelength of 400 nm in GaInP, 400 nm and 750 nm in GaAs were presented in Figure 8, where the definition of X axis is shown in Figure 7. The sharp decrease in EQE in Figure 8A shows a sharp boundary of damaged regions for the EQE mapping of GaInP, but the boundary is much less clear and broadens for those of GaAs shown in Figure 8B. There appear transition regions, which extends into undamaged region up to 12 mm from the point of $X = 0$. This phenomenon has not been reported yet. It is seen that the broader interface is larger than the radius of EQE bias light of 8 mm. This may be due to that the bias light could be scattered and then enlarged as it penetrate through GaInP top layer into the GaAs subcell. This result implies that the inhomogeneous damage would exert special effects on artifacts behaviors, thus affecting the precise evaluation and characterization of properties and quality of multi-junction solar cells.

In fact, the bias light is usually much larger than EQE pulse spot. The area of bias light is nearly 100 times larger than EQE pulse spot. A simplified mathematical model is built as follows:

From equations (6) and (8), the most important parameter is $e$, which is related to inverse saturation current and open circuit voltage. We define $\beta$ as the area ratio of undamaged area to the total area of bias light spot. Assuming the bias-light illuminating regions has the same voltage $V$, the short circuit current of GaInP could be expressed as equation (12). We should keep in mind that $V$ is a function of $\beta$, if $\beta = 1$, $V = 1.40$ V, and if $\beta = 0$, $V = 0.90$ V.

$$J_{sc} = J_0 \exp \left( \frac{qV_{oc}}{kT} \right) + \beta J_0 \exp \left( \frac{qV_{oc}}{2kT} \right)$$

(12)
And we could get the fluorescence efficiency in equation (13).

\[ e = \frac{I_s \exp \left( \frac{qV_g}{k_B T} \right)}{I_q} = \frac{I_s \exp \left( -\frac{qV_g}{k_B T} \right) \exp \left( \frac{qV_g}{k_B T} \right)}{I_q} \]

(13)

By calculation in “Artifacts in Damaged Solar Cells by 1 MeV Electrons and 70 keV Protons Radiation”, we have gotten \( k = 7550 \). Thus, a smallest change in \( \beta \) could lead to large change in artifacts. Thus the artifacts start to decrease at the boundary of the bias light.

In order to further study the phenomenon, supplementary tests were performed. Using different intensity of bias light (by varying the voltage of Xe lamps with filter), we get that 2D artifacts is related to the voltage applied to lamps as showed in Figure 9. The stronger the bias light is, the more obvious the artifacts are. The difference among the curves of Figure 9 lies in the difference of \( V(\beta) \). When the voltage of Xe lamp is larger, the \( V(\beta) \) is larger too.

For 1 MeV electrons radiated solar cells, lateral scanning results of EQE in GaAs at \( \lambda = 750 \) nm and \( \lambda = 400 \) nm are in Figure 10. It should be reminded that 1 MeV electrons damage much the middle GaAs cells. Thus the final result is the combination of smooth changing caused by relative fluorescence yield and steep changing caused by electrons damage. EQE at \( \lambda = 400 \) nm shows similar regularity as Figure 8B. The decrease in EQE at \( \lambda = 400 \) nm is due to the radiation damage and disappear of FC effect. Transition region decreases to 6 mm, because of the smaller \( k \) value. If \( e \) decreases 10%, \( k = 2.12, \beta = 0.9 \). The decrease in EQE at \( \lambda = 750 \) nm is mainly due to irradiation damage. This is similar with the change in \( \lambda = 400 \) nm in proton-irradiated GaInP subcells. Artifacts could partly compensate the damages of irradiation. Considering the effect, the irradiation resistance of GaAs could be overestimated.

**Conclusions**

Artifacts in EQE exist in MJ solar cells and they are related to fluorescence coupling and shunt resistance. Mathematic and graphic models were built to discuss the artifacts between GaAs and GaInP. We successfully described the artifacts between GaInP and GaAs at \( \lambda = 750 \) nm and \( \lambda = 400 \) nm. Artifacts are sensitive to irradiation damage. 70 keV protons decrease the EQE of top GaInP seriously, decreasing the artifacts at the same time. After 1 MeV electrons radiation, artifacts decrease 93%. These decreases in artifacts is due to the increase in SRH recombination. In our model, we could estimate the Voc of top cell changes from 1.4 V to 1.355 V and \( k = 2.12 \pm 0.02 \) by 1 MeV electrons irradiation, which is hardly to gain by other methods. We also estimate \( k = 7550 \pm 50 \) after 70 keV protons radiation.

In order to clarify the 2D behavior of artifacts, specially-designed partial irradiation tests were performed. EQE mappings near the interface between damaged and undamaged regions were measured and a slow-changing transition area appears. During EQE lateral scanning, the EQE of \( \lambda = 400 \) nm and \( \lambda = 750 \) nm varies in front of the boundary of damaged regions. And the transition regions are much larger than the width of EQE pulse spot. By decreasing the voltage applied to the Xe light, the transition region becomes larger but weaker, shifting...
away from the interface. This 2D behavior could be described using modified-2D-artifacts model. Artifacts are useful phenomena that could be used to detect properties of MJ solar cells as well as coupling effects between subcells in a MJ solar cell system.

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Conflict of Interest

None declared.

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