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Description	

Influence of light irradiation on the charge-accumulation-type potential-induced degradation of n-type front-emitter crystalline Si photovoltaic modules

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We investigated the influence of light irradiation on the charge-accumulation-type potential-induced degradation (PID) of n-type front-emitter (n-FE) crystalline silicon (c-Si) photovoltaic (PV) modules. A PID test under one-sun irradiation leads to faster reductions of short-circuit current density (J_{sc}) and open-circuit voltage (V_{oc}) compared to the case of a PID test in the dark. This indicates that light irradiation accelerates the charge-accumulation-type PID of the n-FE PV modules. The J_{sc} and V_{oc} reductions become slower under irradiation without ultraviolet (UV) light, showing almost the same time dependence as the PID test in the dark. The acceleration of PID by the addition of UV light may be explained by the excitation of electrons at K^0 centers in silicon nitride (SiN_x) and their faster drift to the surface by electric field applied to SiN_x.

Keywords: potential-induced degradation, n-type front-emitter module, silicon nitride

I. INTRODUCTION

Recently, the problem of global warming and depletion of energy resources become more and more serious. To solve these problems, the use of sustainable energy must become more widespread. Photovoltaics (PV) is one of the most promising technologies for the sustainable energy since it can directly convert sunlight into electricity. Increasing system voltage is important to reduce power transmission loss, and large-scale PV power plants operating at a high voltage have been recently increasing. In such PV power plants, potential-induced degradation (PID) has been one of the most serious reliability issues for PV modules. PID is a phenomenon in which a potential difference between an aluminum (Al) frame and cells leads to degradation in performance of PV modules.[1)]

Since p-type crystalline silicon (c-Si) wafer-based solar cells have been most commonly used, their PID has also been investigated in detail.[1–11)] n-type c-Si wafer-based solar cells generally have better performance than p-type ones, and their market share will increase in the future; however there have been less activities for the investigation of the PID of n-type c-Si PV modules.[12–28)] We have thus far investigated the PID of n-type c-Si PV modules with cells such as front-emitter (FE),[16–24)] rear-emitter,[25)] Si heterojunction,[26–27)] and interdigitated back-contact cells.[28)] In particular, n-type FE (n-FE) c-Si PV modules show three-stage degradations with different behaviors and mechanisms under a negative-bias stress. The first PID results from the accumulation of positive charges in silicon nitride (SiN_x) on the front side of an n-FE cell, also referred to as polarization-type PID or PID-p in other literatures. This leads to the accumulation of minority carriers, electrons, in the vicinity of the surface of a p^+ emitter and resulting enhancement of surface recombination, by which short-circuit current density (J_{sc}) and open-circuit voltage (V_{oc}) are reduced. We have proposed that the accumulated positive charges can be formed by the extraction of electrons from K centers present in the SiN_x films, which are dangling bonds back-bonded to three nitrogen atoms.[17,18)] The second PID is governed by sodium (Na) introduction into the depletion layer of the p^+–n junction and resulting an increase in a recombination current and a decrease in fill factor (FF).[23)] The third PID is due to the formation of Na-based dome-shaped structures on the surface of n-FE cells and the destroy of surface SiN_x, resulting in serious V_{oc} loss.[24)] Among the PID phenomena, the first PID is the most serious problem in the n-FE c-Si PV modules since it appears within a relatively short duration, induces a serious reduction in output power of the modules (~10% or more),[17,18] and can occur in outdoor environment.[21] We thus need more detailed understanding of the first, charge-accumulation-type PID of n-FE c-Si PV modules.

Previous studies for the first PID of n-FE c-Si PV modules have been performed in the dark. The actual PV modules, however, receive sunlight during their operation in PV power plants. We should thus investigate the influence of sunlight irradiation on the PID of PV modules. There have been prior studies for the influence of light irradiation on the PID of PV modules. It has been clarified that the Na-related PID of p-type wafer-based c-Si PV modules can be delayed with the addition of sunlight irradiation.[9–11] Since the degree of delay depends on the bandgap of SiN_x,[10] the delay of the PID is probably due to carrier excitation in SiN_x and resulting weakening of electric field there, which decelerates Na drift toward c-Si. On the other hand, the influence of light irradiation on the charge-accumulation-type PID has not yet been fully clarified. In this study, we investigate how light irradiation affects the charge-accumulation-type PID behaviors of n-FE c-Si PV modules. We also elucidate the wavelength dependence of incident light on the PID, from which we discuss the mechanism of the influence of light irradiation.

II. EXPERIMENTAL DETAILS

156×156 mm^2-sized n-FE c-Si solar cells with SiN_x/Si dioxide (SiO_2) passivation stacks and a diffused p^+ front emitter were cleaved into 20×20-mm^2-sized pieces. The SiO_2 films in the n-FE c-Si PV cells were so thick that charge exchange between SiN_x and the p^+ emitter was completely prevented.[17] Interconnector ribbons were soldered onto the busbars of the front and rear silver electrodes. Then the n-FE cells were laminated to fabricate one-cell modules with a cover glass (45×45 mm^2)/ethylene vinyl acetate copolymer (EVA)/cell/EVA/backsheet (polyvinyl fluoride sheet/ethylene terephthalate sheet/polyvinyl fluoride sheet) structure. The lamination process was performed in a solar cell module laminator (LM-50X50-S, NPC) through a degassing process at 135 °C in vacuum for 5 min and a successive pressing process at 135 °C for 15 min. A PID test was performed at a temperature of 85 °C with no intentional humidity stress. To observe the time dependence of charge-accumulation-type PID clearly, we chose a negative voltage of −600 V for the PID test, which was smaller than our previous experimental condition of −1000 V.[17,18] The bias voltage was applied to the cells with respect to a grounded Al plate with a cell-sized hole using an insulation tester (TOS7210S, KIKUSUI). The PID test was performed under different irradiation conditions in addition to the dark PID test: under one-sun irradiation through no filter, through an ultraviolet (UV)-cut filter (<430 nm) (LV0430, Asahi Spectra), and through a long-wavelength- (LW-) cut filter (> 650 nm) (SV0650, Asahi Spectra). To divide the effect of light irradiation alone, we also performed one-sun irradiation test for an n-FE c-Si PV module without bias stress at 85 °C. The n-FE c-Si PV modules before and after the PID tests were evaluated by measuring current-density–voltage (*J*–*V*) characteristics under one-sun irradiation and external quantum efficiency (EQE) spectra (CEP-25, Bunkoukeiki). The modules after the PID tests were sufficiently cooled down before the *J*–*V* and EQE measurements, and these measurements were performed at 25 °C.

III. RESULTS

Figure 1 shows the photo *J*–*V* curves of n-FE c-Si PV modules before and after the PID test in the dark and under one-sun irradiation. We see simultaneous decrease in J_{sc} and V_{oc}, independent of the irradiation conditions during the PID test. These are triggered by the accumulation of positive charges in SiN_x and resulting enhancement in the surface recombination of minority carriers on the surface of the p^+ emitter and can be typically observed in the charge-accumulation-type PID of n-FE c-Si PV modules.[15–18] The *J*–*V* curve of the module after the PID test under one-sun irradiation for 180 s shows larger reduction in maximum power (P_{max}) compared to that after the PID test in the dark. This indicates that one-sun irradiation accelerates the charge-accumulation-type PID of n-FE c-Si PV modules.

Figure 2 shows the EQE spectra of n-FE c-Si PV modules before and after the PID test in the dark and under one-sun irradiation. Regardless of the light irradiation, a decrease of EQE in the short wavelength region appears. This results from the enhanced recombination of photo-excited minority carriers on the surface of the p^+ emitter due to accumulated positive charges in SiN_x and is also a typical behavior of the charge-accumulation-type PID of n-FE c-Si PV modules.[17,18] The n-FE c-Si PV modules receiving the PID stress under one-sun irradiation show a faster reduction in the EQE compared to the module which underwent the PID test in the dark. This is consistent with the results of *J*–*V* characteristics.

Figure 3 shows the J_{sc}, V_{oc}, FF, and P_{max} of n-FE c-Si PV modules, normalized by their initial values, as a function of the duration of PID stress under various irradiation conditions. J_{sc} and V_{oc} decrease rapidly, and are then saturated. These tendencies reproduce the behavior of previous studies[17,18]. The saturation of J_{sc} and V_{oc} indicates the existence of the upper limit of positive charges. Since the origin of the positive charges in SiN_x is considered to be K^+ centers, i.e. K centers whose electrons are lost, positive charges in SiN_x reach maximum if all the K centers become K^+ centers. FF does not change significantly within the PID-stress duration in this experiment (1200 s). Note that FF starts to drop at a PID stress duration of ~1 h in our previous experiments at a negative bias of −1000 V.[23] It should be emphasized that the saturation values of J_{sc}, V_{oc}, and P_{max} are almost the same, independent of the irradiation conditions during the PID test. Comparing the PID progresses in the dark and under one-sun irradiation, the duration for the saturation of J_{sc} and V_{oc} is reduced by one-sun irradiation by a factor of >2. These clearly indicate that one-sun irradiation accelerates the charge-accumulation-type PID of the n-FE c-Si PV modules.

Figure 3 also contains the PID progresses of n-FE c-Si PV modules under UV-cut and LW-cut irradiation. The PID progress of the n-FE c-Si PV modules under UV-cut irradiation is similar to the PID progress in the dark. On the contrary, the modules that were subjected to the PID stress under LW-cut irradiation show faster J_{sc} and V_{oc} reductions, similar to the case of the modules receiving PID stress under one-sun irradiation. These clearly indicate that the cause of the acceleration of the charge-accumulation-type PID is the irradiation of UV light.

To distinguish the effect of light irradiation alone, we performed light-soaking test without negative bias application. Figure 4 shows the P_{max} of an n-FE c-Si PV module, normalized by their initial values, as a function of one-sun irradiation duration. We see no significant change in P_{max} for >20 days, which is much longer than the duration of the PID tests. We thus confirmed that the light irradiation alone does not affect the P_{max} of n-FE c-Si PV modules and the acceleration of the charge-accumulation-type PID takes place under the coexistence of negative bias and light irradiation.

IV. DISCUSSION

According to a series of experimental results, we have found that UV irradiation accelerates charge-accumulation-type PID. As mentioned above, the charge-accumulation-type PID of n-FE c-Si PV modules is known to be due to an increase in the surface recombination rate of minority carriers, caused by the accumulation of positive charges in SiN_x. The origin of the positive charges is K^+ centers formed by electron extraction from neutral and negatively-charged K centers (K^0 and K^- centers, respectively) in SiN_x.[29–37] It is therefore suggested that UV irradiation affects the electron extraction from K^0 centers. Figure 5 shows the schematics of the possible effect of the UV irradiation on the acceleration of electron extraction from K^0 centers. An electric field exists in SiN_x due to the negative bias stress, and electrons at K^0 centers may drift toward the SiN_x surface by hopping conduction through discrete states during the dark PID test. On the other hand, under UV irradiation, electrons at K^0 centers may be excited to the conduction band of SiN_x and can drift therein toward the SiN_x surface. The difference of the carrier drift mechanism, slow hopping conduction or fast band conduction, can be the reason for the faster accumulation of positive charges, i.e. K^+ center formation, and resulting acceleration of the reductions of J_{sc} and V_{oc}. The excitation of electrons at K^0 centers to the conduction band by UV light is possible since the energy difference between the conduction band edge of SiN_x and the energy level of K^0 center is smaller than the energy of UV light in this study (>2.88 eV).[29]

Note that there have been seemingly opposite results in which the charge-accumulation-type PID of n-FE c-Si PV modules decelerates or is suppressed under light irradiation.[14] The suppression of the PID is found to occur only when encapsulant with sufficiently high volume resistivity is used in the modules, and no deceleration of the PID has been observed in the EVA-based modules.[14] The experimental results obtained in this study thus do not conflict with those of Ref. 14.

One may expect that UV irradiation rather neutralizes K^+ centers to K^0 centers, according to the previous literatures.[30–37] The photon energy needed for the neutralization of K^0 centers is known to be 4–5 eV.[30,31] Photons with such high energies are not sufficiently contained in the one-sun light. Thus, the neutralization of K centers by light irradiation does not have to be considered in the experiments of this study.

In this study, we have demonstrated that the charge accumulation-type PID of n-FE c-Si PV modules is accelerated by one-sun irradiation. This fact is important particularly when the PID in out-door conditions is expected based on the in-door test results. Note that the n-FE c-Si PV cells have a thick SiO_2 film by which charge exchange between SiN_x and the p^+ emitter is suppressed, as mentioned above. It has been clarified that the modules with n-FE cells with very thin SiO_2 can show different PID behaviors,[22] and one might see different effect of light irradiation on the PID of these modules.

V. CONCLUSION

We have investigated how light irradiation affects the charge-accumulation-type PID behaviors of n-FE c-Si PV modules. The charge-accumulation-type PID is accelerated by one-sun irradiation, but is not accelerated by UV-cut irradiation. Based on these results, UV irradiation is found to accelerate the charge-accumulation-type PID of the n-FE c-Si PV modules. Since no change in P_{max} is observed under the one-sun irradiation alone, the degradation and its acceleration are due to the coexistence of negative bias voltage application and light irradiation. A possible mechanism of the acceleration of the charge-accumulation-type PID is the excitation of electrons in K^0 center to the conduction band and successive fast drift therein toward the surface of SiN_x by the electric field.

Acknowledgment

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Figure Captions

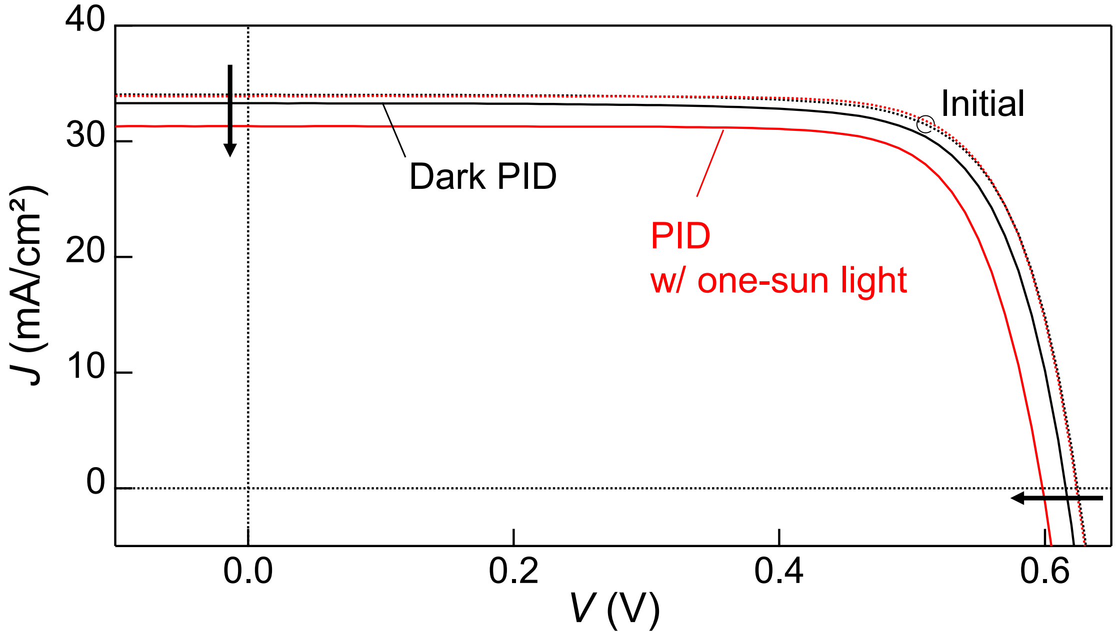
Fig. 1 (Color online) Photo *J*–*V* curves of n-FE c-Si PV modules before and after the PID tests in the dark and under one-sun irradiation for 180 s.

Fig. 2 (Color online) EQE spectra of n-FE c-Si PV modules before and after the PID tests in the dark and under one-sun irradiation for 180 s.

Fig. 3 (Color online) J_{sc}, V_{oc}, FF, and P_{max}, normalized by their initial values, of n-FE c-Si PV modules as a function of PID-stress duration. Each data point shows the mean value for two modules, and each error bar corresponds to the standard deviation of the mean.

Fig. 4 (Color online) P_{max}, normalized by its initial value, of n-FE c-Si PV modules as a function of one-sun irradiation duration.

Fig. 5 (Color online) Schematics of electron movement under the PID stress without and with UV irradiation. E_c and E_v in the figures represent the conduction band minimum and the valence band maximum, respectively.



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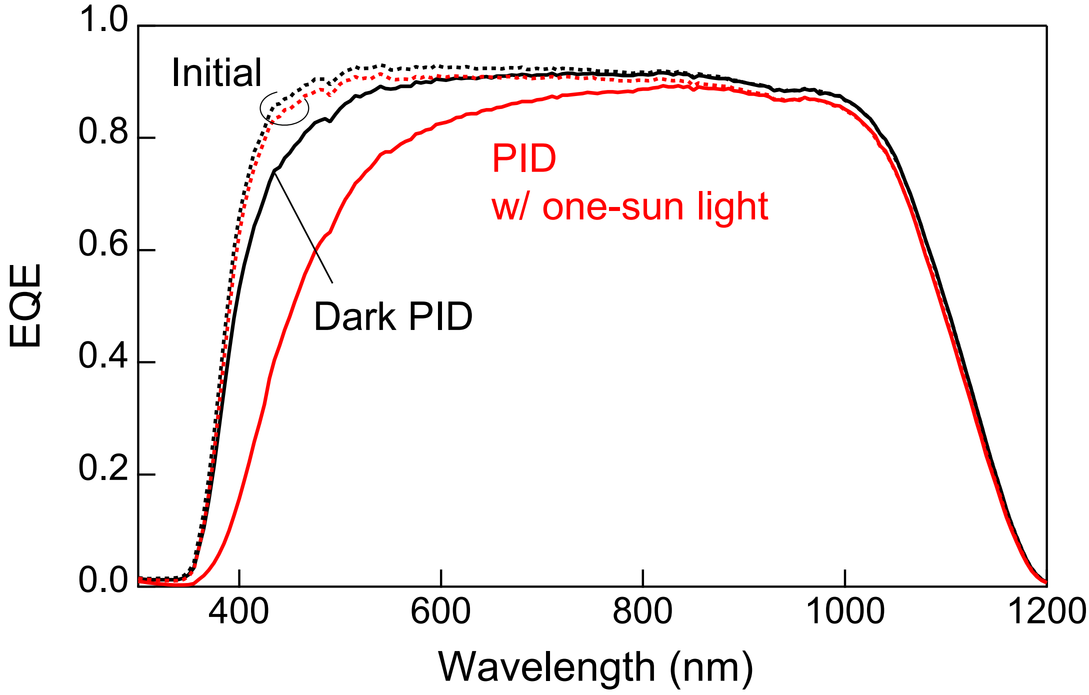

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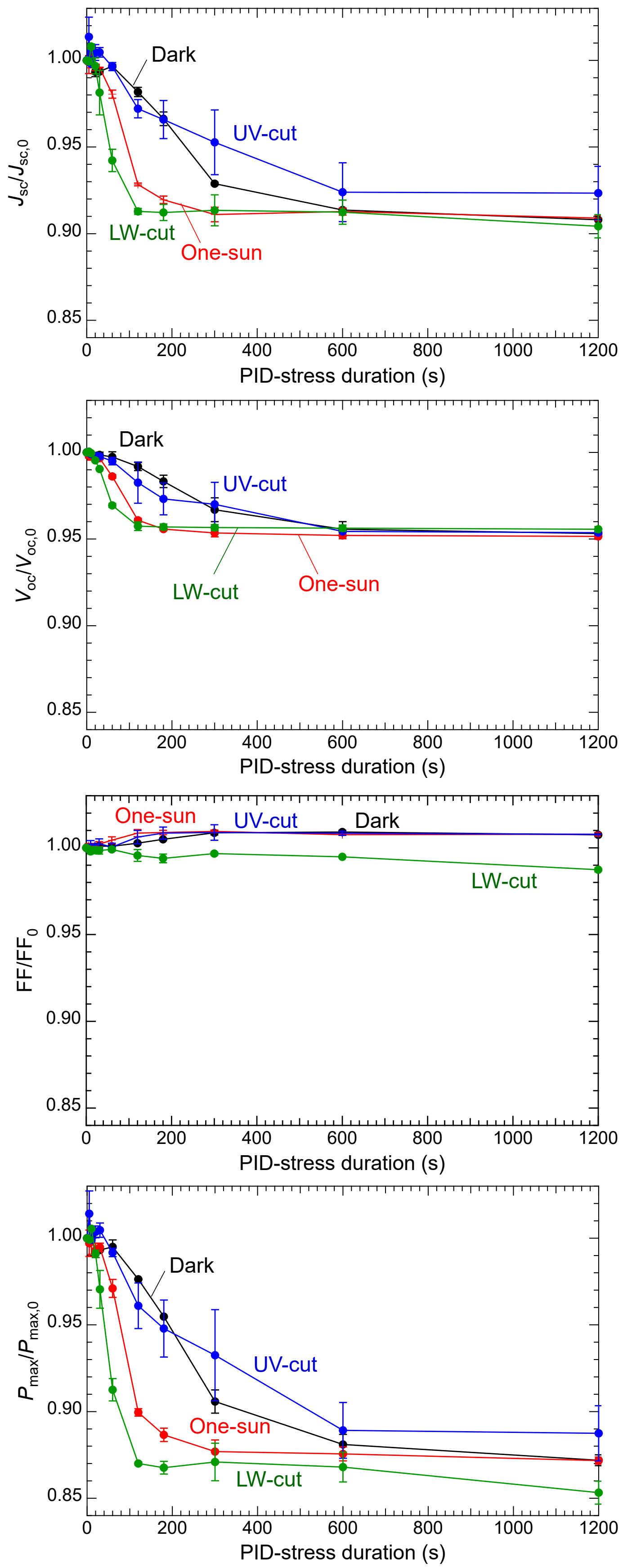

Dark
UV-cut
LW-cut
One-sun
$J_{sc}/J_{sc,0}$
PID-stress duration (s)
Dark
UV-cut
LW-cut
One-sun
$V_{oc}/V_{oc,0}$
PID-stress duration (s)
One-sun
UV-cut
Dark
LW-cut
FF/FF_0
PID-stress duration (s)
Dark
UV-cut
One-sun
LW-cut
$P_{max}/P_{max,0}$
PID-stress duration (s)

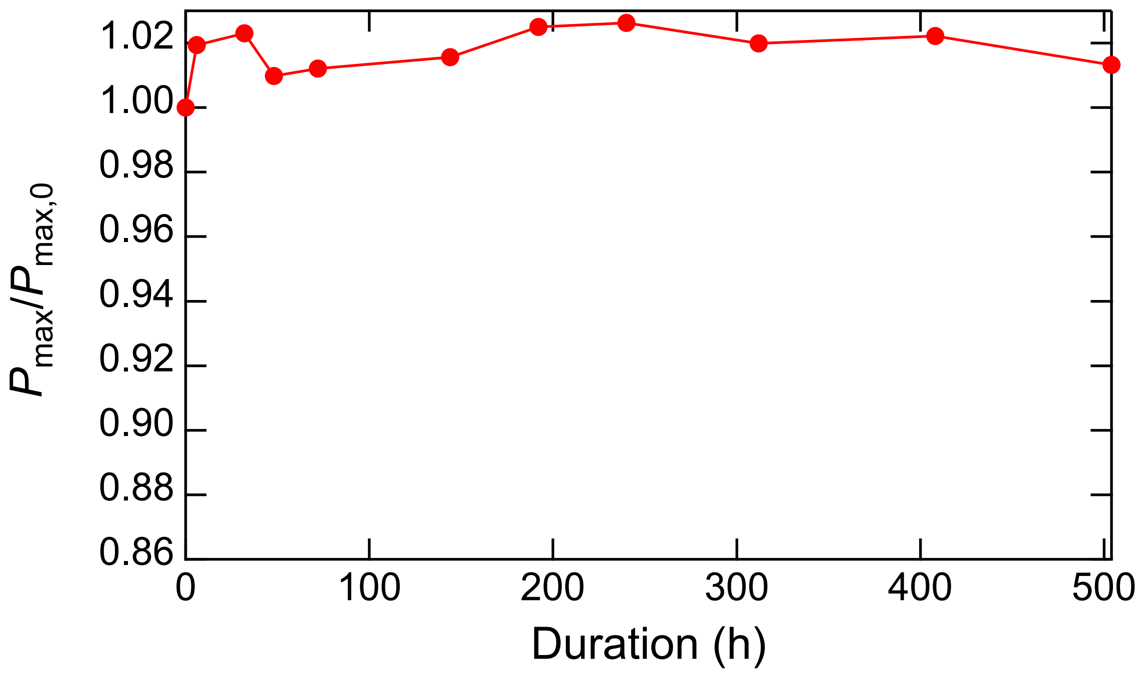

Fig. 4 R. Zhao et al.,

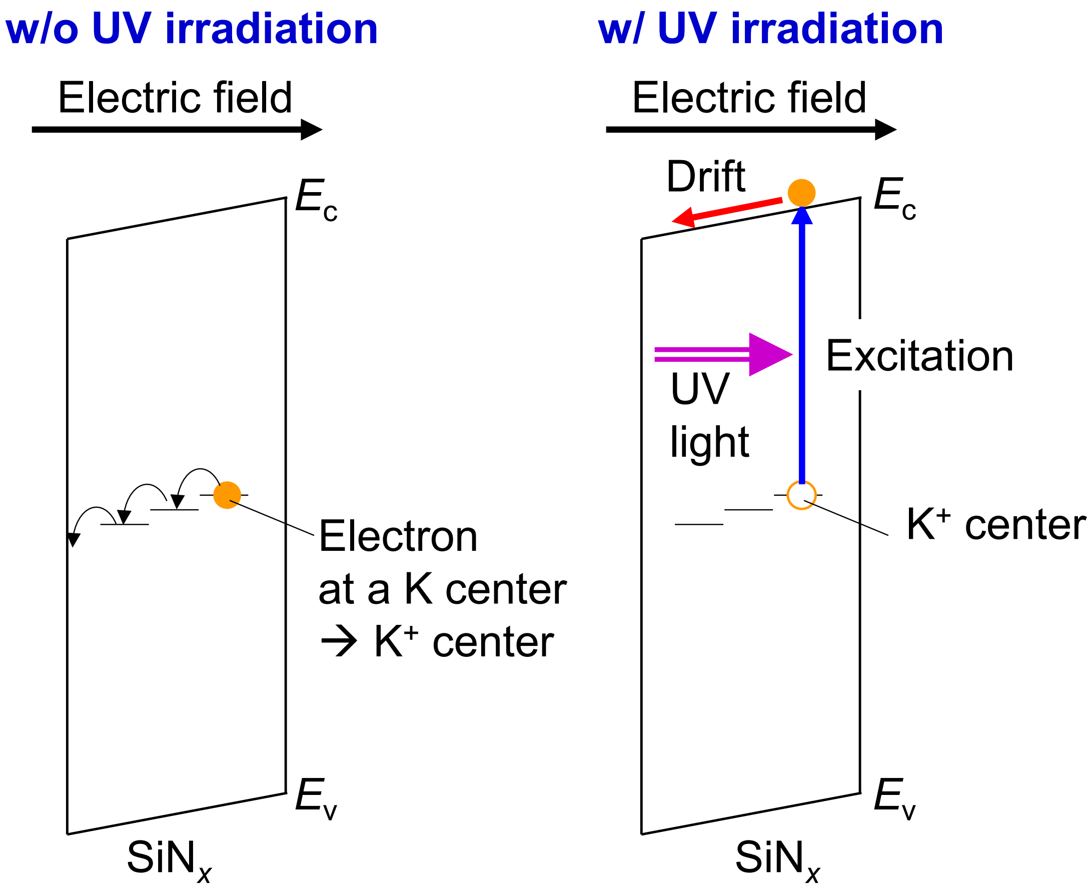

Fig. 5 R. Zhao et al.,