

# On the Kinetics of Light-Induced Enhancement Effect in Silicon Heterojunction Solar Cells

Lifei Yang,\* Xingbing Li, Wenbin Zhang, Qingsong Yang, and Qi Wang

Silicon heterojunction (SHJ) solar cells are one of the promising technologies for next-generation high-efficiency crystalline silicon solar cells in photovoltaic industry. Recently, an interesting light-induced performance enhancement (LIE) effect has been observed in SHJ solar cells. Herein, the kinetics and stability of the LIE effect during repeated cycles of light soaking and subsequent dark annealing at 150 °C are investigated. It is found that  $V_{OC}$  of SHJ solar cells increases with light soaking time following stretched exponential, but can be reverted by subsequent dark annealing. This means that LIE effect in SHJ solar cells is not stable. The underlying mechanism of this phenomenon should be attributed to the hydrogen motion in a-Si:H layers. It is also demonstrated that increasing illumination intensity leads to faster (shorter time constant) and stronger (higher saturation level of  $\Delta V_{OC}$ ) LIE effect.

## 1. Introduction

Silicon heterojunction (SHJ) solar cells use crystalline silicon (c-Si) wafers as optical absorbers and employ bilayers of doped/intrinsic hydrogenated amorphous silicon (a-Si:H) to form passivating contacts.<sup>[1,2]</sup> SHJ solar cells have gained much attention in recent years because of their high efficiency, small temperature coefficient, and simple fabrication processes.<sup>[3,4]</sup> An efficiency of 26.6% was set as a record for single-junction silicon solar cell using SHJ structure in a fully back-contacted layout.<sup>[5]</sup>

In contrast to light-induced degradation (LID) phenomenon found in thin-film a-Si:H solar cells, which is known as Staebler–Wronski effect (SWE),<sup>[6]</sup> light-induced enhancement (LIE) effect was reported in SHJ solar cells recently. Mahtani and co-workers<sup>[7]</sup> revealed that light soaking improves the surface passivation of c-Si samples coated with bilayers of doped/intrinsic a-Si:H films. Kobayashi and co-workers<sup>[8,9]</sup> reported that light soaking with an illumination intensity of 1 Sun increases the open-circuit voltage ( $V_{OC}$ ) and fill factor (FF) of SHJ solar cells, leading to a gain in absolute conversion efficiency of up to 0.3%. This improvement was contributed to a reduced density of recombination-active interface states and thus an enhancement of surface passivation.<sup>[8]</sup> Cattin et al.<sup>[10]</sup>

investigated the effect of light soaking on SHJ solar cells with different thickness of a-Si:H(p) layers. They showed that, although light soaking improves solar cell efficiency for devices using a-Si:H(p) layer with optimal thickness, this treatment leads to performance degradation for devices with an insufficiently thick a-Si:H(p) layer on the light-incoming side. Wright et al.<sup>[11,12]</sup> demonstrated an accelerated LIE effect by using laser light soaking with high illumination intensity and high treatment temperature. Although several manufacturers and institutes,<sup>[13,14]</sup> like Gsolar Power, DR Laser, NewSouth Innovations Pty Ltd., and French Alternative Energies and Atomic Energy Commission, have already proposed industrial tools based


on LIE effect for mass production of SHJ solar cells, the kinetics and stability of this effect are still less studied.

Here, we investigate the LIE effect in SHJ solar cells by tracking their  $V_{OC}$  evolution during repeated light soaking and dark annealing cycles, from which a reversible behavior can be observed. On light soaking phases,  $V_{OC}$  increases with soaking time following stretched exponential law. On dark annealing phases,  $V_{OC}$  decays following  $\sim t_{ann}^{-\gamma}$  power law. These results indicate that LIE in SHJ solar cells corresponds to the formation of a metastable state. Furthermore, through analyzing the impact of annealing temperature on the kinetics of the  $V_{OC}$  decay during dark annealing, it is inferred that the underlying mechanism could be attributed to the hydrogen motion in a-Si:H layers. We also study the impact of illumination intensity on the LIE effect. It is found that increasing illumination intensity not only accelerates the LIE process, but also enhances the LIE effect, which is embodied by larger  $V_{OC}$  improvement. These findings would benefit a further understanding of the LIE effect in SHJ solar cells.

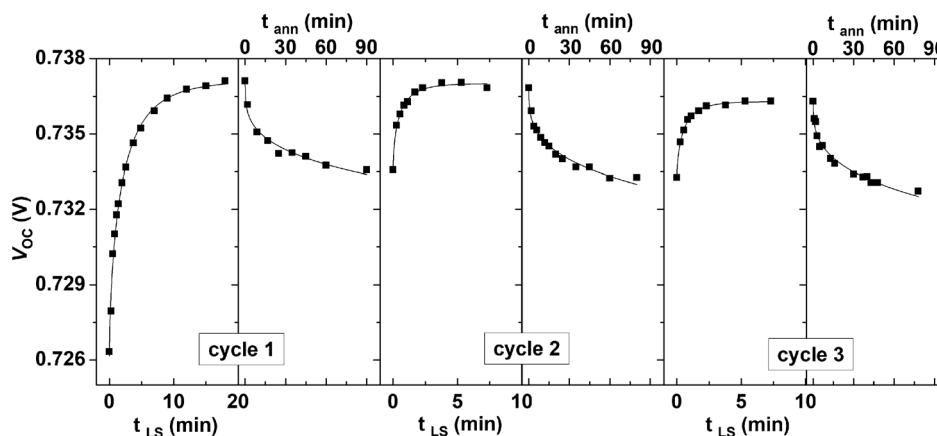
## 2. Results and Discussion

Figure 1 shows how the  $V_{OC}$  of SHJ solar cell evolves during light soaking and subsequent dark annealing cycles at 150 °C. Here, the temperature of 150 °C is chosen because the lamination temperature of SHJ modules, normally using polyolefin elastomer (POE) as encapsulation film, is close to 150 °C. A reversible  $V_{OC}$  evolution can be found in Figure 1. On light soaking phases of each cycle, light-induced  $V_{OC}$  enhancement occurs until reaching saturation. Kinetically, it can be well fitted by stretched exponential model described as Equation (1).

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DOI: 10.1002/pssr.202200356



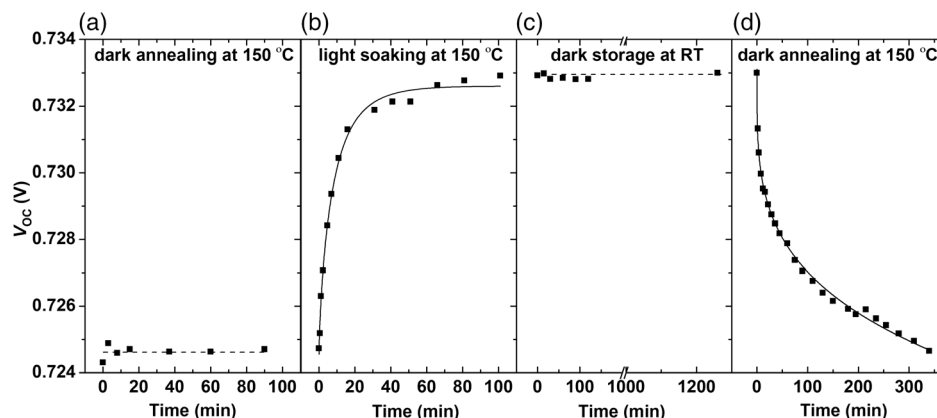
**Figure 1.**  $V_{OC}$  evolution of SHJ solar cell sample during cycles of light soaking and dark annealing at 150 °C. Light soakings are performed with an illumination intensity of 22.5 Sun. Symbols indicate measured data; solid lines show stretched exponential and power law fits for light soaking and dark annealing phases, respectively.

$$V_{OC}(t_{LS}) = V_{OC}^{sa} - (V_{OC}^{sa} - V_{OC}^0) \exp \left[ - \left( \frac{t_{LS}}{\tau} \right)^\beta \right] \quad (1)$$

where  $V_{OC}^0$  is the  $V_{OC}$  of SHJ solar cell at the beginning of each cycle before light soaking,  $V_{OC}^{sa}$  is its saturation value,  $t_{LS}$  is the light soaking time,  $\beta$  is the dispersion parameter, and  $\tau$  is the time constant. In the literature, stretched exponential often describes the relaxation phenomena of a-Si:H film. It was explained as arising from dispersive diffusion of hydrogen that characterized by a time dependence of the diffusion coefficient following a  $\sim t^{-r}$  power law. The dispersion parameter  $\beta$  is given by  $\beta = 1 - r$ .<sup>[15]</sup> This implies that the LIE effect in SHJ solar cell may have a microscopic mechanism related to hydrogen motion. For repeated cycling, it can be observed a slight decay of  $V_{OC}^{sa}$ . This may be related to the loss of hydrogen in the a-Si:H bilayers. Hydrogen may diffuse out of the a-Si:H bilayers during the repeated light soaking/dark annealing cycles,<sup>[16]</sup> which could cause the decay of the interface passivation of the heterojunction structure and thus the decay of  $V_{OC}^{sa}$ . Note that the light soaking time suffice for  $V_{OC}^{sa}$  saturation is shorter in the second and third

cycles than that in the first cycle. This is because  $V_{OC}$  enhancement in the first LIE cycle is partially reverted by its subsequent dark annealing process in this experiment. In the following, we will show that  $V_{OC}$  enhancement can be annihilated if SHJ solar cell is dark annealed for longer time (see Figure 2b,d).

Now we turn to the dark annealing phases following light soaking; a long-term  $V_{OC}$  decay occurs over annealing time. Kinetically, this degradation process can be fitted by a  $\sim t_{ann}^\gamma$  power law model, where  $t_{ann}$  is the annealing time. Notably, the values for coefficient of determination ( $r^2$ ) for all fits are higher than 0.97. It is well known that the kinetics of SWE can be described by  $\sim t_{LS}^{1/3}$  power law,<sup>[17]</sup> where  $t_{LS}$  is the light soaking duration. The similar kinetics implies that there may be a link between LIE in SHJ solar cells and SWE in bulk a-Si:H. The above results indicate that LIE in SHJ solar cells corresponds to the formation of a metastable state, which can be reverted via dark annealing. As shown in Figure 2a, dark annealing of SHJ solar cell without light soaking do not cause  $V_{OC}$  decay. On the other hand,  $V_{OC}$  of SHJ solar cell after LIE appears stable during long-term dark storage at room temperature (see Figure 2c).



**Figure 2.**  $V_{OC}$  evolution of SHJ solar cell sample during: a) dark annealing at 150 °C before light soaking, b) light soaking under 5 Sun at 150 °C, c) dark storage at room temperature after (b), d) dark annealing at 150 °C after (c). Symbols indicate measured data; solid lines show stretched exponential and power law fits in (b) and (d), respectively. Arbitrary horizontal dash lines are guide to the eyes in (a) and (c).

These results confirm that the observed  $V_{OC}$  enhancement and degradation in Figure 1 are attributed solely to light soaking and subsequent dark annealing.

The above findings agree well with the results obtained by Cattin et al.<sup>[18]</sup> They found that the enhanced cell performance by light soaking can be partly reset by the dark annealing treatment occurring in the lamination process for solar module production. We further investigate the stability of LIE under light and evaluated temperature condition, which simulate the real working condition of solar cell outdoors. A SHJ solar cell sample after LIE is exposed to an irradiation of  $1000 \text{ W m}^{-2}$  under  $75^\circ\text{C}$  for 200 h. It is observed that its  $V_{OC}$  witnesses a slight increase from 0.736 to 0.737 V, demonstrating good stability of LIE in this condition.

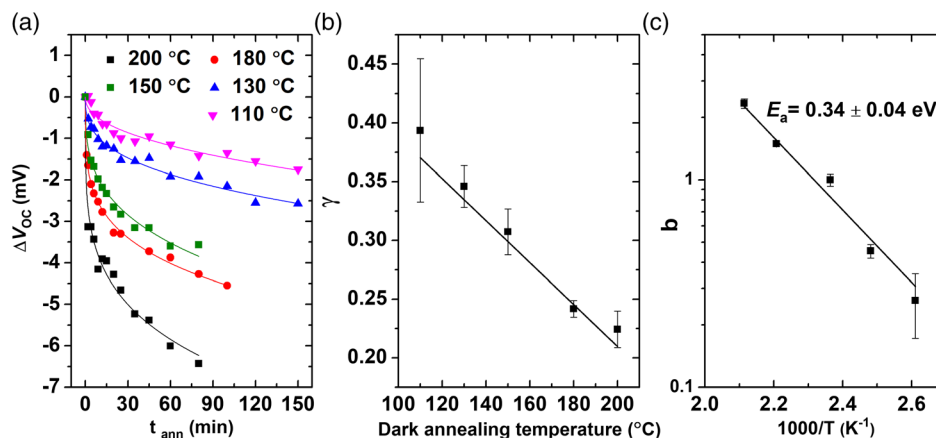
In the work reported by ElMhamdi et al.<sup>[19]</sup> it was found that light soaking of a-Si:H(i)/c-Si/a-Si:H(i) sample induces passivation degradation following  $\sim t_{LS}^\gamma$  power law, while this LID effect can be reverted by a subsequent dark annealing process following stretched exponential law. This phenomenon is different from our observation for SHJ solar cell shown in Figure 1. However, the similarity in kinetics is very interesting, which indicates a possible link between those phenomena. Considering the fact that the difference between a-Si:H(i)/c-Si/a-Si:H(i) sample and SHJ solar cell is the existence of a doped a-Si:H overlayer on top of a-Si:H(i) layer in the latter structure, the doped a-Si:H layer may play an important role in the LIE effect. For instance, the Fermi-level position of a-Si:H(i) layer can be affected by doped a-Si:H overlayer, which influences the diffusion of hydrogen in a-Si:H layer.<sup>[20]</sup> Note that LIE is actually generated by the carrier injection rather than light soaking itself.<sup>[8,9]</sup> In microscopic point of view, we propose that the carrier injection into the doped a-Si:H or a-Si:H(i) layers triggers the hydrogen motion to form a metastable state that can change the field or chemical passivation property of the SHJ structure. To get deeper insight into the possible mechanism related to hydrogen motion, impact of dark annealing temperature on the kinetics of  $V_{OC}$  decay is investigated. The SHJ solar cells received the LIE

treatment at 7.5 Sun/ $150^\circ\text{C}$  for 60 min before dark annealing. A higher illumination is used here to shorten the treatment time needed for  $V_{OC}^{sa}$  saturation (see the discussion below about the impact of illumination intensity on the kinetics of LIE).

Figure 3a shows  $\Delta V_{OC}$  evolution as a function of  $t_{ann}$  under different annealing temperatures. Here,  $\Delta V_{OC} = V_{OC}(t_{ann}) - V_{OC}^0$ , where  $t_{ann}$  is the dark annealing time and  $V_{OC}^0$  is the  $V_{OC}$  of the solar cells just after light soaking, which is in the range of 0.734–0.737 V. All measurement data can be fitted by a power law model in form of  $-bt_{ann}^\gamma$ , where  $b$  and  $\gamma$  are the prefactor and power coefficient, respectively. It can be observed that  $V_{OC}$  decay becomes faster as the annealing temperature increases. The value of  $\gamma$ , however, is found to be following a linear decrease with the annealing temperature as shown in Figure 3b. Thus, the  $V_{OC}$  degradation is in fact governed by the increase of  $b$  as the annealing temperature increases. In 1987, Street and co-workers<sup>[21]</sup> demonstrated that hydrogen diffusion coefficient ( $D_H$ ) for doped a-Si:H was not uniquely determined by the temperature but did depend on the annealing time ( $t_{ann}$ ) following  $\sim t_{ann}^{-\gamma}$  power law. The value of  $\gamma$  was found to be decreased with increasing the annealing temperature and equaled to 0.2–0.25 at  $200^\circ\text{C}$  for a-Si:H(p). Our finding in Figure 3b is consistent with the results, and the value of  $\gamma$  is also extracted to be 0.2–0.25 at  $200^\circ\text{C}$ . These similarity implies that the kinetics of  $V_{OC}$  decay of SHJ solar cells during dark annealing after LIE might be related to hydrogen motion in the doped a-Si:H layers. As shown in Figure 3c, the value of  $b$  obeys an Arrhenius relationship described as Equation (2).

$$\ln(b) = \ln(b_0) - E_a/kT \quad (2)$$

where  $k$  is the Boltzmann constant and  $E_a$  is the activation energy. The value of  $E_a$  is extracted to be  $0.34 \pm 0.04 \text{ eV}$ . This value is agreed with the activation energy of 0.399 eV, which is obtained by Li and co-workers<sup>[22]</sup> through analyzing the FF decay of SHJ solar cells during dark annealing after LIE. They believe that the  $E_a$  is related to the energy barrier of hydrogen motion in the a-Si:H(p) layer. Light soaking induces the



**Figure 3.** a)  $\Delta V_{OC}$  evolution of SHJ solar cell samples during dark annealing under varying annealing temperatures from 110 to  $200^\circ\text{C}$ . The SHJ solar cell samples are all receiving a LIE treatment at 15 Sun/ $150^\circ\text{C}$  for 60 min before dark annealing. Symbols indicate measured data; solid lines show power law fits. b) The extracted values of power coefficient  $\gamma$  as a function of dark annealing temperature. Symbols indicate measured data; solid line shows linear fit. c) The extracted values of prefactor  $b$  in logarithmic scale fitting to Equation (2). Symbols indicate measured data; solid line shows linear fit. The error bars in (b) and (c) are standard deviations of  $\gamma$  and  $b$  determined by curve fittings in (a).

diffusion/hopping of the weakly bound hydrogen atoms in a-Si:H(p), which allows the activation of B-Si<sub>4</sub> doping and thereby improves the performance of the SHJ solar cell.<sup>[22]</sup> This is a possible mechanism for LIE. However, how the injected carriers induce hydrogen diffusion and whether the LIE and dark annealing decay share the same mechanism or not are still not clear.

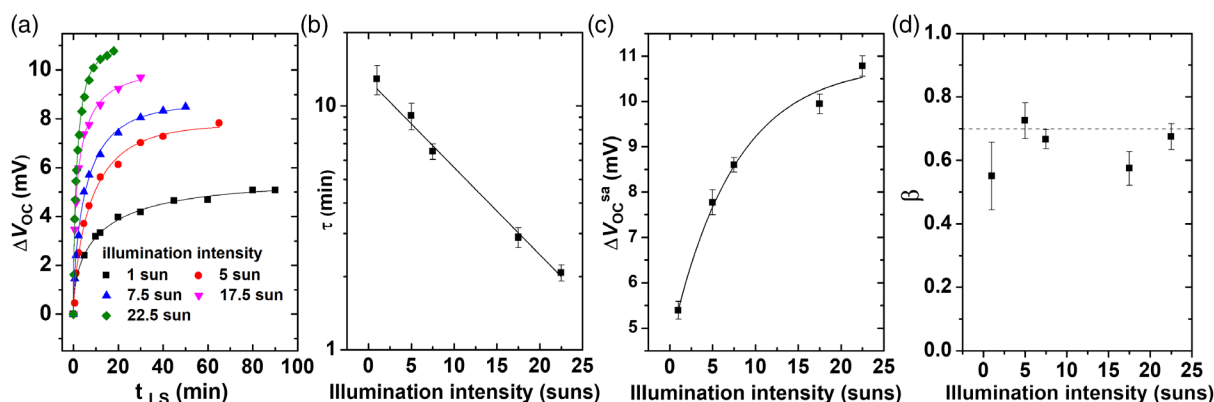
We also investigate the impact of illumination intensity on the kinetics of LIE. Figure 4a shows  $\Delta V_{OC}$  evolution of SHJ solar cell samples as a function of light soaking time under illumination intensity of 1, 5, 7.5, 17.5, and 22.5 Sun, respectively. Here,  $\Delta V_{OC} = V_{OC}(t_{LS}) - V_{OC}^0$ , where  $t_{LS}$  is the light soaking time and  $V_{OC}^0$  is the original  $V_{OC}$  of the solar cell before light soaking. It can be found that larger illumination intensity induces faster kinetics of LIE and higher  $\Delta V_{OC}$ . As discussed above, the LIE effect should be related to the formation of a metastable state, which leads to improved surface passivation and increased  $V_{OC}$ . It may be inferred that higher illumination intensity induces higher concentration of metastable state, thus resulting in higher  $\Delta V_{OC}$ . All experiment results are adequate to be fit by stretched exponential described as Equation (1). Notably, the values for coefficient of determination ( $r^2$ ) for all fits are higher than 0.99. Figure 4b,c show the extracted values of  $T$  and  $\Delta V_{OC}^{sa}$  as a function of illumination intensity, where  $\Delta V_{OC}^{sa}$  is the saturation value of  $\Delta V_{OC}$ . It can be seen that  $T$  decreases from 12.9 to 2.1 min, and  $\Delta V_{OC}^{sa}$  increases from 5.4 to 10.8 mV as the illumination intensity varies from 1 to 22.5 Sun. Moreover, it is interesting to found that  $T$  in logarithmic scale follows a linear dependence on illumination intensity. Meanwhile,  $\Delta V_{OC}^{sa}$  increases with illumination intensity following an exponential growth model described as Equation (3).

$$\Delta V_{OC}^{sa} = C + A \exp(I) \quad (3)$$

where  $I$  is the illumination intensity,  $A$  is the pre-exponential factor, and  $C$  is a constant. Here, we think that higher intensity illumination drives the formation of the metastable state with a larger maximum concentration, which gives to a higher maximal

passivation level of the heterojunction structure and thus a higher  $\Delta V_{OC}^{sa}$ . Kakalios and co-workers<sup>[15]</sup> showed that the stretched exponential relaxation of a-Si:H was arisen from dispersive diffusion of hydrogen, and the dispersion parameter  $\beta$  was shown to be dependent on temperature by  $\beta = 0.00165 T$  (in Kelvin), whereas its relationship to illumination intensity was not investigated. Here, we show that  $\beta$  is independent to the illumination intensity (Figure 4d). Considering that the temperature of light soaking is 150 °C, the extracted values of  $\beta$  are comparable to that in the literature.<sup>[15]</sup> This gives another clue that the LIE effect should be related to hydrogen motion in the a-Si:H layers.

In fact, more than one solar cells are checked here at a given illumination intensity except 1 Sun, to investigate the reproducibility of the observation. As shown in Figure S1, Supporting Information, similar LIE kinetics can be observed between different samples. All experiment data can be fitted by stretched exponential with the coefficient of determination ( $r^2$ ) larger than 0.99. For the LIE experiments taken under 22.5 Sun, the extracted  $\Delta V_{OC}^{sa}$ ,  $T$ , and  $\beta$  have an average value of 10.8, 2.3, and 0.6, with a standard deviation of 0.3, 0.2, and 0.1, respectively. Note that LIE also leads to the increase of FF besides  $V_{OC}$ . In the light soaking experiments taken under 22.5 Sun, FF increases from 81.1% to 82.3%, with a standard deviation of 0.7% and 0.9%, respectively. Together with the enhancement of  $V_{OC}$  with an average value of 10.2 mV, LIE leads to an average efficiency increase from 22.39% to 23.02%, with a standard deviation of 0.13% and 0.19%, respectively. For a typical solar cell sample, FF enhancement from 81.74% to 82.99% is observed. At the same time, its pFF is found to be increased from 85.18% to 85.76%. Note that FF increases more than pFF, indicating a decrease of series resistance ( $R_s$ ) of the solar cell.  $R_s$  is extracted using  $R_s = (pFF - FF) \times V_{OC} \times J_{SC} / J_{mpp}^2$ <sup>[23]</sup> and found to be decreased from 0.74 to 0.59  $\Omega \cdot \text{cm}^2$ . Here,  $J_{mpp}$  is the current density of the solar cell at the maximum power point. Consequently, the FF improvement can be ascribed to the combination effects of improved passivation (increased pFF) and



**Figure 4.** a)  $\Delta V_{OC}$  evolution of SHJ solar cell samples as a function of the light soaking time under illumination intensity of 1, 5, 7.5, 17.5, and 22.5 Sun, respectively. Symbols indicate measured data; solid lines show stretched exponential fits. b) The extracted values of time constants  $T$  in logarithmic scale as a function of illumination intensity. Symbols indicate measured data; solid line shows linear fit. c) The extracted values of  $\Delta V_{OC}^{sa}$  as a function of illumination intensity. Symbols indicate measured data; solid line shows exponential growth fit. d) The extracted values of  $\beta$  as a function of illumination intensity.  $\beta$  value for a-Si:H at 150 °C is 0.70<sup>[15]</sup> as indicated by the dash line. The error bars in (b), (c), and (d) are standard deviations of  $T$ ,  $\Delta V_{OC}^{sa}$ , and  $\beta$  determined by curve fittings in (a).



improved charge transport (decreased  $R_s$ ). This result is consistent with the finding obtained by Veirman et al.<sup>[24]</sup>

### 3. Conclusion

In summary, we demonstrate that light soaking of SHJ solar cell induces the enhancement of  $V_{OC}$ , but it can be reverted by a subsequent dark annealing process. This indicates that LIE in SHJ solar cells corresponds to the formation of a metastable state. The underlying mechanism of LIE and its reversible process during dark annealing should be related to hydrogen motion in the a-Si:H layers. We also found that LIE effect depends on illumination intensity. Higher illumination intensity leads to faster (shorter T) and more remarkable (larger  $\Delta V_{OC}^{sa}$ ) LIE process. This means that light soaking tools equipped with high intensity light sources can be compatible with the production line to boost the efficiency of the SHJ solar cells. However, it should be aware that the LIE effect will be partially reverted in the interconnection and lamination processes in the production of solar module due to the involvement of dark annealing. More research work need to be done to suppress this drawback.

### 4. Experimental Section

The SHJ solar cell samples were fabricated using 6 in ( $156 \times 156 \text{ mm}^2$ ) n-type c-Si (100) wafers with resistivity of  $2\text{--}4 \Omega \text{ cm}$ . The saw damage was removed in 20 vol% alkaline solution at  $80^\circ\text{C}$  for 2 min. Then a random pyramidal surface texture was formed via immersion in 2 vol% alkaline solution at  $80^\circ\text{C}$  for 8 min. The textured wafers were then cleaned with a standard wet-chemical cleaning sequence RCA 1 and RCA 2, followed by a dip in 2 vol% hydrofluoric acid water. The intrinsic hydrogenated amorphous silicon (a-Si:H(i)) and doped hydrogenated amorphous silicon (a-Si:H(p) and a-Si:H(n)) stack layers were deposited on both side of the wafer via a Hot Wire CVD system (ULVAC). The current passing through the catalyzing wires was 30 A. The deposition temperature was  $200^\circ\text{C}$ . The gas flow ratios in sccm for growing a-Si:H(i), a-Si:H(n), and a-Si:H(p) were  $[\text{H}_2]:[\text{SiH}_4]=90:170$ ,  $[\text{H}_2]:[\text{SiH}_4]:[\text{PH}_3]=300:200:300$ , and  $[\text{H}_2]:[\text{SiH}_4]:[\text{B}_2\text{H}_6]=120:200:300$ , respectively. Hydrogen-plasma treatments were applied before and after a-Si:H(i) deposition. The thickness of a-Si:H(i), a-Si:H(n), and a-Si:H(p) layers was about 5, 10, and 12 nm, respectively. ITO layers were deposited on both sides of the wafer by using a magnetron sputtering system (VON ARDENNE) installed ITO targets ( $\text{In}_2\text{O}_3/\text{SnO}_2$  90/10 wt%). The thickness of the ITO layers was 80 nm. The deposition temperature was about  $200^\circ\text{C}$ . Finally, silver electrodes on both sides were formed by screen-printing low-temperature silver paste and then curing at  $200^\circ\text{C}$  for 30 min. The original  $V_{OC}$  values of the solar cell samples were between 0.724 and 0.729 V and their efficiency was between 22.0% and 22.4%.

Light soaking of SHJ solar cell in open-circuit conditions with an illumination intensity of 1 Sun was carried out using a commercial solar simulator (Industrial Vision Technology, VS-6820), and its actual temperature was controlled by a hotplate at  $150^\circ\text{C}$  with a deviation less than  $5^\circ\text{C}$ . Light soaking of SHJ solar cells with illumination intensities of 5, 7.5, 17.5, and 22.5 Sun were performed using a home-made equipment, which is installed with an infrared LED array with wavelength of 850 nm. The illumination intensity of the infrared LED array was tuned by adjusting its input current. The temperatures of the solar cells were controlled via a wind cooling system, whose flow rate can be adjusted continuously. The actual temperatures of the treated cell were controlled at  $150^\circ\text{C}$  with deviation about  $10^\circ\text{C}$ .

The illumination intensities applied on the samples were calibrated by measuring the short-circuit current ( $I$ ) of an in-house-made reference cell under light soaking and calculated via  $I/I_{1\text{Sun}}$ , where  $I_{1\text{Sun}}$  is the short-circuit current of the reference cell measured under  $1000 \text{ W m}^{-2}$

AM1.5 G with the cell temperature controlled at  $150^\circ\text{C}$ . Dark annealing of SHJ solar cell samples was carried out by using a heating plate. To track  $V_{OC}$  evolution of solar cell samples, their current density–voltage ( $J$ – $V$ ) characteristics were measured under  $1000 \text{ W m}^{-2}$  AM1.5 G illumination at  $25 \pm 0.3^\circ\text{C}$  with a solar cell  $I$ – $V$  tester (Industrial Vision Technology, VS-6820) configured with a steady-state solar simulator. A reference cell which is not light soaked and dark annealed was used to calibrate the light intensity of the measurement system every day before its first run. The  $V_{OC}$  of the reference cell is stable for multiple measurements.

### Acknowledgements

This work was supported by the Program for Leading Talents in Innovation and Entrepreneurship Pioneering of Suzhou City (Contract No. ZXL2021074).

### Conflict of Interest

The authors declare no conflict of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### Keywords

heterojunction, kinetics, light-induced enhancement, solar cells

Received: September 19, 2022

Revised: December 8, 2022

Published online: December 28, 2022

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