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Improvement of amorphous silicon/crystalline silicon heterojunction solar cells by light-thermal processing

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It has been known that amorphous silicon/crystalline silicon heterojunction solar cells (HJT cells) can be improved by light-thermal processes. The present work aims to acquire a further understanding of the effect of illumination intensity and temperatures in a broader range and the roles of light and heat in the improvement. Naked HJT cells without grids were used for more reliable measurement of minority carrier lifetimes. Experiments of light-thermal processes of the naked HJT cells, with lighting from red LED arrays and heating/cooling from a thermal stage/air fan, have been carried out, with the illumination intensity ranging in 1–8 kW/m^2 and cell temperature ranging in 160–220 °C. The higher illumination intensity results in longer lifetimes of the cells, the optimum cell temperature appeared to be around 180 °C, with the lower temperature needing a longer processing time to reach peak lifetime increment, while the higher temperature tends to degrade the passivation of the cell. The cell temperature of 180 °C was then chosen for the light-thermal processes of commercial HJT cells of ~23.8% efficiency on a pilot line, with 12 kW/m^2 red illumination. An average efficiency gain of $0.77\%_{abs}$ and a maximum gain of $0.87\%_{abs}$ have been achieved, with a processing time of 80 s. It is encouraging that the light intensity required is much lower than the previously reported level for similar improvement, indicating much lower power consumption for industrial application of the process. Through semi-shading experimentation of the light-thermal process, it is postulated that the effect of illumination does not rely on the direct effect of the injected photons, but possibly resulted from the effect of light-generated carriers.

1. Introduction

Solar cells based on heterojunction of amorphous silicon/crystalline silicon, commonly referred to as HJT cells, have been more and more produced and applied in the recent five years, and may become a mainframe photovoltaic technology in the next years. In addition to the known advantages of high open-circuit voltage, higher energy conversion efficiency, lower thermal degradation coefficient, etc. [1–8], HJT cells have the benefit of further significant efficiency improvement by a low-cost light-thermal coupled process (hereafter referred to as LT process). The first relevant report was that the surface passivation quality of c-Si deposited with an a-Si:H layer increased after merely light soaking [9]. Kobayashi et al. demonstrated an efficiency increment of $0.3\%_{abs}$ after light soaking under a solar simulator at AM1.5 illumination of 1-sun intensity, keeping the cell at 32 ± 2 °C, and claimed that temperature has little effect on the results in the range of 25–75 °C [10]. In a further report, they claimed little effect of illumination intensity on the minority carrier lifetime in the range of 0.02–1 sun [11]. In 2019, an efficiency increment of 0.7% of HJT cells of 22.05% baseline efficiency, by a "multifunctional process", which was likely an LT process, was reported [12]. Unfortunately, no information about the multifunctional process was provided.

On the other hand, Madumelu et al. have reported a degradation behavior of HJT cells under light soaking at elevated temperature [13], similar to the known light and elevated temperature-induced degradation (LeTID) [14,15]. This is quite rare for HJT cells, even though the LeTID has been shown to affect both n-type and p-type Cz materials [16]. The mechanism for the degradation remained unknown. Cattin et al. [17] have carried out a series of examinations of the LT behaviors of the HJT cells of different architectures and reported that when the intrinsic a-Si:H layers are thick, e.g. 13.8 nm, or when the p-type layers are too thin on the front side, the LT-induced degradation tends to occur.

Recently, LT processes of HJT cells with a solid diode laser red light source have been reported [18]. An illumination intensity as high as 55

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kW/m^2 was used, while the cell temperature was maintained at ~200 °C (the peak temperature was ~255 °C). Efficiency gain as large as 0.7%$_{abs}$ has been achieved after 30 s of the process. The improvement is found to be related to an increase in open-circuit voltage and fill factor of the cells. It is convincing that high illumination intensity can make a great difference in the effect. It is also noticed that, for the cells from different suppliers, the efficiency gains after the same LT processes are quite different, varying from close to zero to 0.7%$_{abs}$. The sensitivity of the states of the metastable defects at the a-Si:H/c-Si interface to the cell materials and the processes of the different suppliers is a possible reason for such variety.

However, a quantitative understanding of the effect of the illumination intensity and cell temperature remains lacking. Especially from the industrial point of view, it is important to know if an illumination intensity as high as 55 kW/m^2 is essential for a good effect, or if it can be significantly lowered to save electricity in the industrial application of the LT process. Additionally, it is necessary to know if the excessive temperature in the process will hurt the power gain.

In the present work, using an experimental setup with monochromatic red LED arrays and a thermal stage to conduct an LT experiment, we examined the effect of the light intensity and the cell temperature respectively on the minority carrier lifetimes of optimal HJT cells. The naked cells without grids were used for reliable lifetime measurement. Based on the results, we carried out LT processes of optimal completed HJT cells on a pilot line, with obtainable optimum light/thermal conditions. A maximum efficiency gain of 0.87%$_{abs}$ was obtained. To understand the role of light in the process, further dedicated tests with semi-shaded samples of the naked and the finished HJT cells were conducted.

2. Experimental methods

HJT cells (~3 Ω cm of wafer resistivity, M2, bifacial) from a commercial supplier, in both completed and naked without grid printed forms, were used. The basic structure of the cells is shown in Fig. 1. The amorphous silicon films were deposited by PECVD; the ITO films were deposited by magnetron sputtering; the copper grid was electro-plated. The measured average Voc and energy conversion efficiency (η) are 737 ± 1.7 mV and 23.8 ± 0.1% respectively.

The LT experiments of the naked HJT cells have been carried out with a setup illustrated in Fig. 2. The thermal stage, the light, and the air fan work together to control the cell temperature by heating/cooling the cell. To ensure the accuracy of the temperature, the same type of cell with K-type thermocouples on the back was padded with half-silicon wafers, leaving a gap in the middle of the half-silicon wafers to facilitate the export of the thermocouple wires and repeatedly measured temperature for follow-up experiments before the formal experiments. Monochromatic red LED arrays, with maximum illumination intensity of 8 kW/m^2, were used as the light source. A quasi-steady-state photoconductance (QSSPC) measurement (Sinton Instruments, WCT-120) was

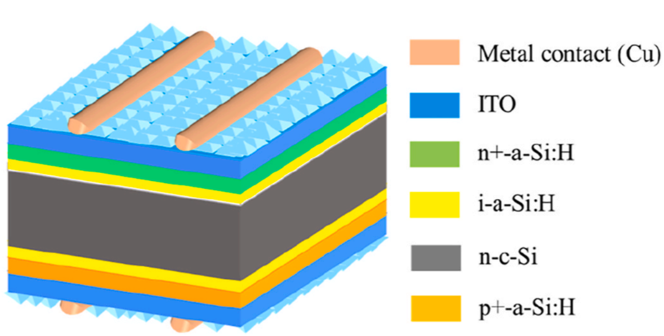

Fig. 1. A schematic diagram showing the structure of the HJT cell used in the present study.

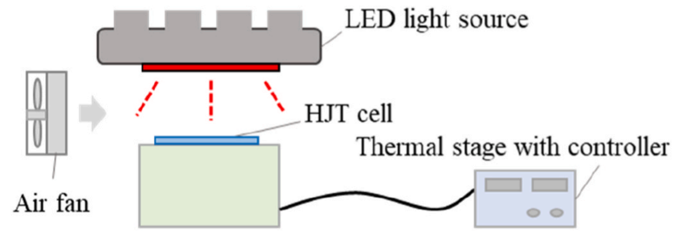

Fig. 2. An illustration of the setup for the light-thermal processing experiment.

adopted to examine the minority carrier lifetimes of the cells before and after the LT processes.

The LT processing of the completed HJT cells with chosen conditions was conducted on a homemade pilot continuous LT processing line with the same type of light source on top. The illumination intensity is 12 kW/m^2. The current-voltage (I–V) characteristics of the HJT cells were tested by a commercial IV tester (VISION, VS-6825A-GX) under Air Mass 1.5 global illumination (AM 1.5G) before and after the LT processes. The external quantum efficiency (EQE) and reflectance of the HJT cells were measured at the same location with the QE-R measurement system (PVE300-IVT) over wavelengths ranging from 300 nm to 1180 nm before and after the LT processes.

To understand the role of light in the LT process, LT processing experimentation with semi-shaded cell samples was conducted. Both the naked and the completed HJT cells respectively were used. An aluminum foil was used to shade half of the cells from illumination. The same pilot line with the same conditions as the previous experiments were used. The naked cells were characterized by the minority carrier lifetime mapping tool WT-2000 PV (Semiconductor Physics Laboratory, Co. Ltd.). As it turned up that the WT-2000 PV does not suit for mapping the completed cell with grids, we turned to the photoluminescence (PL) imaging tool (PLI-1001A, Semiconductor Physics Laboratory, Co. Ltd.) for an indirect indication of lifetime maps.

3. Results and discussions

A series of experiments on the effects of the illumination intensity and the temperature of the LT processes on the minority carrier lifetime of the optimal naked HJT cells without grids have been carried out. The results are shown in Figs. 3–4. To distinguish the effect from the thermal process out of the LT process, each sample has been annealed at 200 °C for up to 30 min and measured, before the LT processing experiment. Actually, in the production of the fully completed HJT cells, similar thermal annealing naturally exists for both copper-plated and silver-printed cells for thermal curing of the grids. So, this pre-annealing is also necessary for obtaining data referable to fully completed HJT cells. In Fig. 3a and b, and 4, the lifetimes of each sample after a different process have been normalized to their initial value. First, it is found that mere thermal annealing of the sample cells may significantly increase the minority carrier lifetime at the excess carrier density $\Delta n = 1 \times 10^{15}$ cm^{-3}, as shown in Fig. 3a, c. The intrinsic lifetime limit due to Auger and radiative recombination mechanisms as calculated according to the optimized simplified model [19], which is shown in Fig. 3c. For the change of lifetime curves, the increased quality of passivation can be ascribed to the re-distribution of hydrogen throughout the a-Si:H layers, passivating the as-deposited interface defects [20,21], and the conversion of metastable dangling bands into stable Si–Si bonds during the annealing process [22]. In our naked cells, 10 min of such annealing was found sufficient for the effect, and no more benefit can be obtained by further annealing. The curing levels by annealing among the naked cells are different, which can be attributed to the non-uniformity of the wafer materials and/or a-Si:H films deposition by PECVD.

It has been suggested that thermal annealing cures the dangling bonds in the HJT cells, leading to an increase in their lifetimes [22,23].

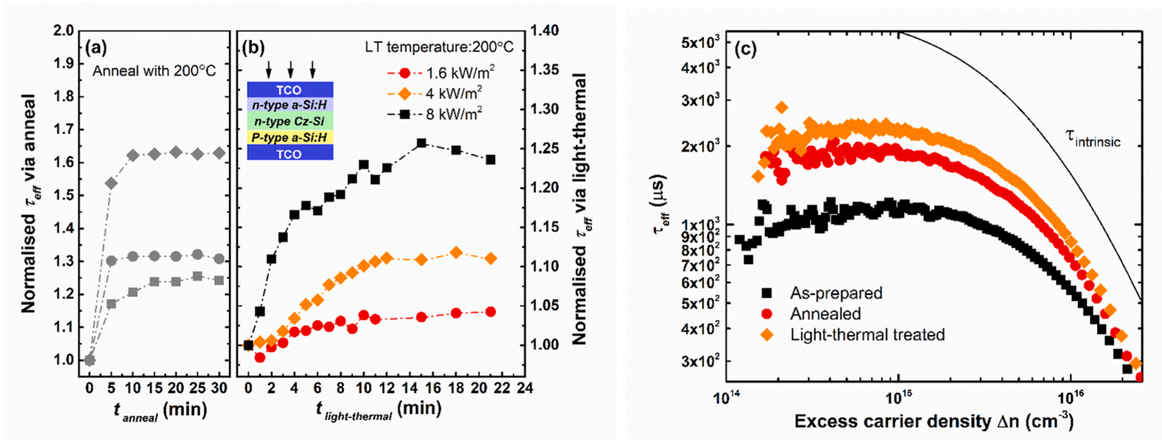

Fig. 3. Normalized minority carrier lifetimes (Each symbol shape represents a specific sample) vs. annealing duration at 200 °C (a), light-thermal process duration with different illumination intensity at 200 °C (b), and minority carrier lifetime characteristic after different processing steps (c), for the naked HJT cells without grids. Intrinsic lifetime calculated according to the model of Richter parameterization is shown for comparison. Note that each symbol shape represents a specific sample.

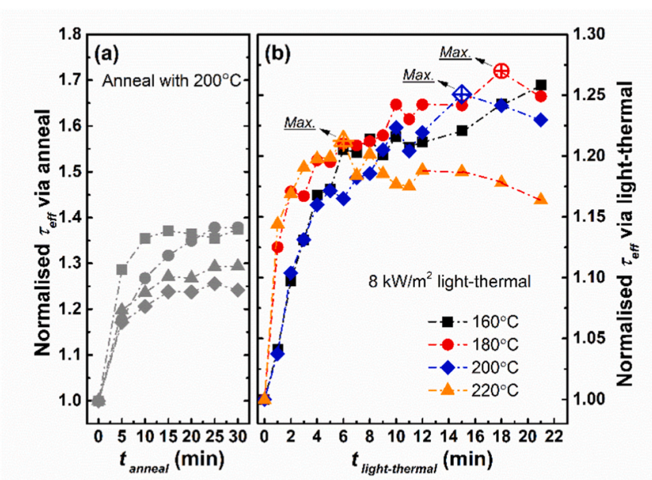

Fig. 4. Normalized minority carrier lifetimes (Each symbol shape represents a specific sample) vs. annealing duration at 200 °C (a), and light-thermal process duration with different temperatures, under 8 kW/m^2 (b), for the naked HJT cells without grids.

The samples with more dangling bonds, i.e., lower initial minority lifetime, would show greater gain in terms of the normalized lifetime. It is not surprising that such improvements all saturate and stabilized subsequently. Further light-thermal exposure significantly made a further improvement, as shown in Fig. 3b and c, suggesting that the mechanisms for the passivation improvement are different between separate annealing and light-thermal. The correlation between light intensity and increased minority carrier lifetime is significant. The minority carrier lifetime improves very slowly under 1.6 kW/m^2, while higher light intensity is more conducive to the improvement of passivation quality, with a greater achievable lifetime boost. This is similar to the light intensity dependence of efficiency boost of completed HJT cells under light soaking [18].

As shown in Fig. 4, the cell temperature affected the kinetics of the processes, particularly the time point of the minority carrier lifetime to reach its maximum, with higher temperatures leading to a shorter time to reach the maximum value. From 180 °C to 220 °C, the time point of the maximum changes from 18 min to 6 min, and the minority carrier lifetime at 160 °C has not yet reached its maximum in the processing time range. For the process at 220 °C, the maximum value is smaller than any other temperature condition and the subsequent decrease in minority carrier lifetime makes it unacceptable. For the process at 160 °C, the longer time to optimum improvement is not ideal. We choose 180 °C as the cell temperature for the further LT process experiment of the completed HJT cells, as 200 °C showed little difference in the effect from that of 180 °C, and 200 °C is closer to the risk shown by 220 °C anyway, which may be reached due to temperature fluctuation in industrial processes. As to the reason for the thermal degradation indicated by the process at 220 °C, it might be attributed to the loss of hydrogen from the amorphous silicon films on the cells, leading to degradation of the passivation by them. It has been well known that the kinetics of hydrogen diffusion/release from the films is highly temperature-sensitive above 200 °C [24–26].

Samples of the completed HJT cells with an energy conversion efficiency of 23.8 ± 0.1% were divided equally into three groups with six cells in each group. The LT treatment was carried out with the pilot line described in section 2, with the processing time being 40 s, 60 s, and 80 s for each group. The results are shown in Fig. 5, while Table 1 summarizes the average changes in the properties of each group.

As can be seen from Fig. 5 and Table 1, an average gain of cell efficiency of 0.77%$_{abs}$ has been achieved, with the maximum reaching 0.87%$_{abs}$, of which the full IV behavior is demonstrated in Fig. 6. Further examination showed that the improvement is attributed to an increase in open-circuit voltage (Voc) and the fill factor (FF), The increase of Voc is related to the enhancement of passivation, which agrees well with the results of Figs. 3 and 4, the minority carrier lifetime increases ~25% and the implied Voc increases 5 mV on the pre-annealed naked cell under 8 kW/m^2 exposure. The change of FF is mainly related to the reduction of series resistance (Rs), which was attributed to the decrease in density of interfacial defect states, the hydrogen may dominate in the process [9–12,17,18]. Multiple reports have shown no significant change in the short-circuit current density (Jsc) by light soaking [11,12,18], while our results also show little change on average in the groups of 40 s and 80 s. We noticed that some individual samples showed a relatively significant rise in Jsc. Fig. 7 shows EQE and reflectance (Refl.) spectra curves of one of the completed HJT cells with Jsc improved during the LT process in Fig. 5b. The EQE enhances in the region of 300–900 nm, while no change of reflectance is observed in the whole region, suggesting that the gain is not attributable to changes in reflectance. The differential performance of Jsc may be ascribed to the changes of parasitic absorption in a-Si:H films, which is related to the hydrogen content and bond structure [8], however, the mechanism needs to be further investigated. The effect of light-thermal has increased profoundly with a processing time and tended to be saturated after 60 s.

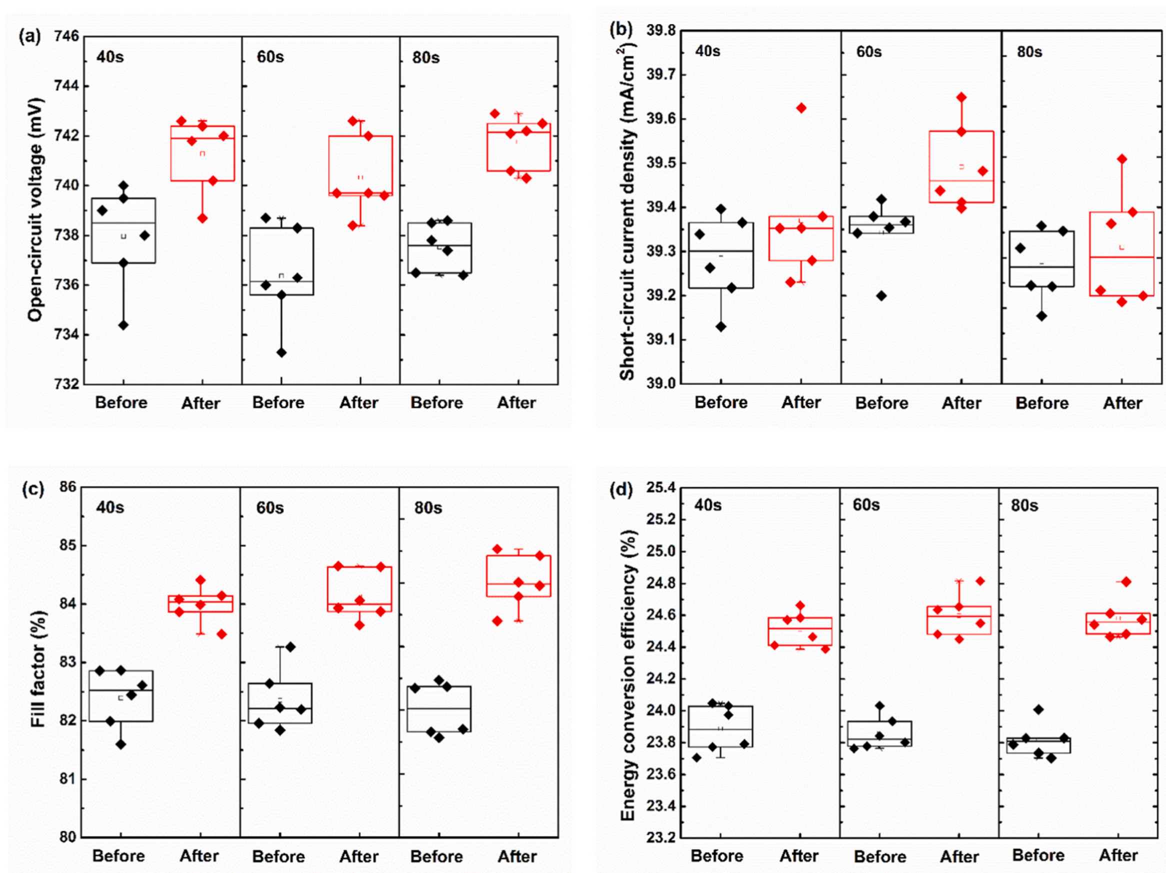

Fig. 5. The photovoltaic properties of the completed HJT cells, before and after the light-thermal processing, under 12 kW/m^2 illumination of red light, at 180 ± 5 °C, for 40 s, 60 s, and 80 s respectively. (a) open-circuit voltage (Voc), (b) short-circuit current density (Jsc), (c) fill factor (FF), (d) energy conversion efficiency.

Table 1
Average changes and standard deviations of the photovoltaic properties of the HJT cells after the light-thermal processes under 12 kW/m^2 red light illumination at 180 ± 5 °C anneal.

Processing Time	Δ Jsc (mA/cm2)	Δ Voc (mV)	Δ FF(%)	Δ Efficiency (%)
40 s	0.08 ± 0.09	3.32 ± 0.58	1.6 ± 0.26	0.62 ± 0.06
60 s	0.15 ± 0.08	3.97 ± 0.56	1.78 ± 0.2	0.74 ± 0.05
80 s	0.07 ± 0.11	4.23 ± 0.31	2.0 ± 0.23	0.77 ± 0.07

The experimentation of the LT process with half of the cell shaded from the illumination was conducted to get some clue about the mechanism for the effect of the illumination. Fig. 8 shows the results. First, the naked cell without grids (Fig. 8a) was illuminated by the full area, and Fig. 8b shows the improvement of minority carrier lifetime on the full area after LT treatment. The other naked cell indicated an explicit contrast in the lifetime map after the LT process, with the half exposed to the light demonstrating a significantly higher lifetime, Fig. 8d. However, for the completed cell with grids, though Fig. 8f shows only a little brighter than Fig. 8e and reflects the improvement of minority carrier lifetime for the completed cell, the contrast of left and right halves disappeared, which contrasts to the naked cell. This phenomenon indicates that the gathering of the light-generated carriers, during the process, may play a role in the improvement of the cell by the LT process. It created a minority carrier lifetime contrast on the LT-processed naked cell without grids (Fig. 8d) because the light-generated carriers failed to transfer to the shaded region before their recombination. While on the completed cell with grids, such transfer can proceed fast enough, through the metallic grids, so that no similar contrast can be observed. Instead, an overall improvement of the cell, as indicated by the measured cell efficiency labeled in Fig. 8e and f, is achieved, even though only half of it has been under illumination. As expected, the efficiency gain in such a case, 0.35%$_{abs}$, is roughly about half of that obtainable without the semi-shading.

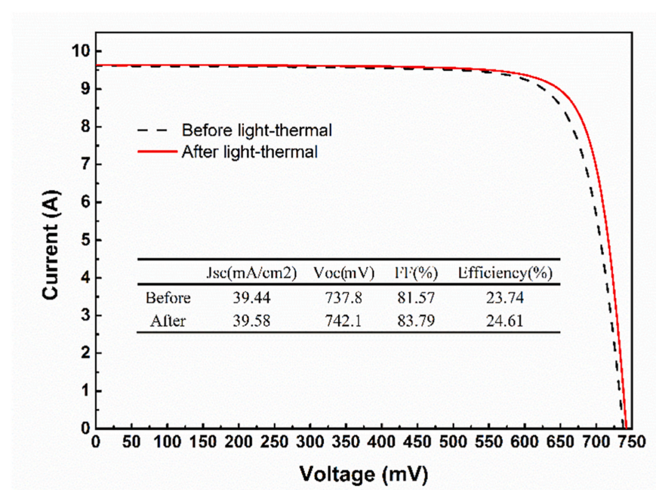

Fig. 6. The IV curves of the HJT cell sample with the maximum efficiency gain after 80 s of the light-thermal process with 12 kW/m^2 red light illumination at 180 ± 5 °C.

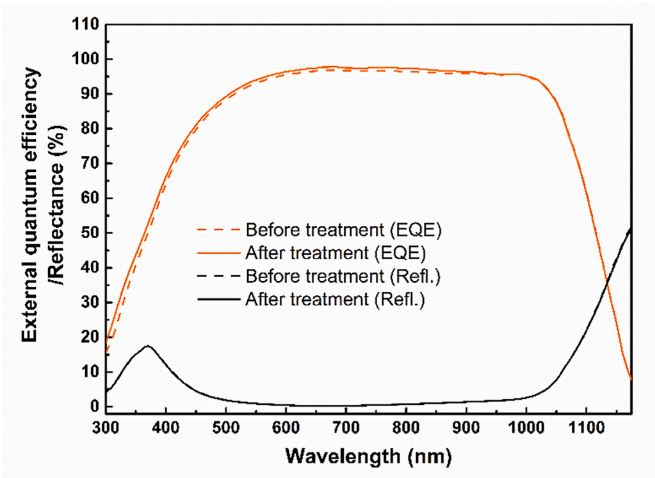

Fig. 7. External quantum efficiency (EQE) and reflectance (Refl.) spectral curves of one of the completed HJT cells with Jsc improved in Fig. 5b before (dash-dot) and after (solid) light-thermal treatment.

The results shown in Fig. 8 have been well confirmed by repeated experiments. The fact that a semi-shaded cell with grids may still have about half of the benefit from the LT process strongly suggests that the effect of illumination is not from the light itself. It is rather from the light-generated carriers, which may be transported to the shaded part of the cell through the metallic grids. While without the grids, the ITO film alone is not able to do the transport fast enough, before the recombination of the carriers [27–29], and the effect from them, or apparently from the illumination, is restricted in the shaded part of the cell. Furthermore, as an elevated temperature is also required, it is believed that the correct temperature can provide additional power to the enhancement process. The improvement of the HJT cell by the LT process is therefore assumed to be attributed to the interaction of the light-generated carriers with thermally mobilized hydrogen, re-configuring to a structure more favorable to the passivation. Further study is required to understand the interaction itself.

Compared with the previous report [18], the present result is encouraging in that it shows that a much lower intensity of illumination, 12 kW/m^2 versus 55 kW/m^2, is needed to obtain a similarly good improvement of HJT cells, though with a longer process time, the 80 s versus 30 s. This means much lower power consumption in lighting, and much lower load in temperature control of the cells, in the industrial application of the LT process technology for the HJT cell production.

4. Concluding remarks

The light-thermal process of naked HJT cells without grids, with 1.6 kW/m^2, 4 kW/m^2, and 8 kW/m^2 monochromatic red illumination and at 160–220 °C cell temperature, can increase the minority carrier lifetime of the cells. The higher illumination intensity results in a longer lifetime of the cells and enhances the cell efficiency improvement. The optimum cell temperature appeared to be around 180 °C, with the lower temperature needing longer processing time to reach peak lifetime increment, while the higher temperature results in premature degradation or close to the risk of such degradation. Light-thermal processes of commercial completed HJT cells of ~23.8% efficiency on a pilot line, with 12 kW/m^2 monochromatic red illumination and 180 ± 5 °C cell temperature, have been carried out. An average efficiency gain of 0.77%$_{abs}$

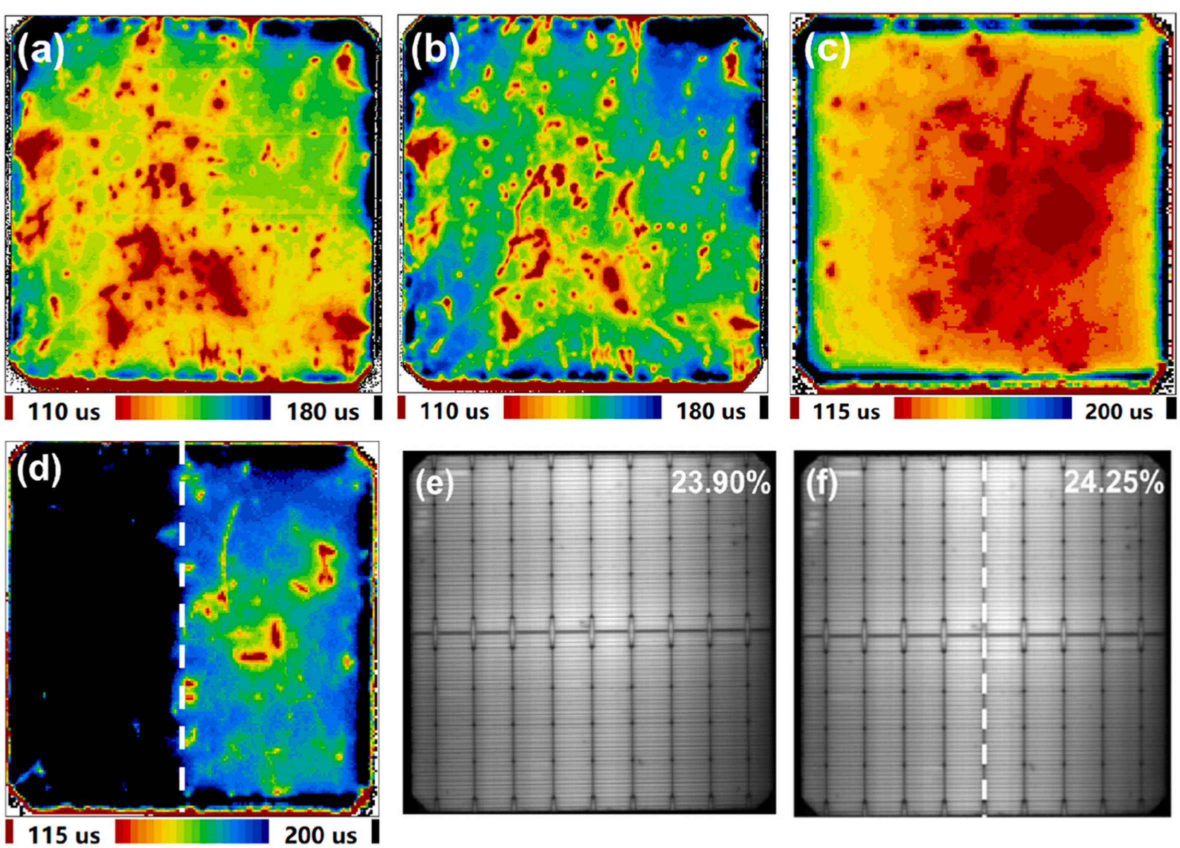

Fig. 8. The minority carrier lifetime maps of a naked HJT cell without grids, before (a) and after (b) the light-thermal process without shading from the illumination, before (c) and after (d) the light-thermal process with its right-half-shaded from the illumination, and the PL images of a completed HJT cell, before (e) and after (f) the light-thermal process with its right-half-shaded from the illumination. The numbers in Fig. e and f give the cell efficiency measured. The white dotted lines in Fig. (d) and (f) indicate the border of the shading.

and a maximum gain of 0.87%$_{abs}$ have been achieved with a processing time of 80 s. Through semi-shading experimentation of the light-thermal process, it is postulated that the effect of illumination does not rely on the direct effect of the injected photons, but possibly resulted from the effect of light-generated carriers.

CRediT authorship contribution statement

Qingguo Zeng: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Guangxing Guo:** Investigation, Data curation. **Zibo Meng:** Investigation. **Lei Gao:** Investigation. **Hongchen Meng:** Writing – review & editing, Investigation. **Lang Zhou:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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