Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

Multi-field coupling challenges the stability test of silicon solar cells

Cite as: Appl. Phys. Lett. **126**, 013901 (2025); doi: 10.1063/5.0245800
Submitted: 29 October 2024 · Accepted: 14 December 2024 ·
Published Online: 3 January 2025

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ABSTRACT

UV-induced degradation is an important factor affecting the stability of silicon heterojunction (SHJ) solar cells. Many works investigated the root cause of this degradation previously, but its coupling with other external stress, such as temperature, has rarely been reported. Here, we examine the decrease in SHJ solar cells induced by UV irradiation at different temperatures (−30 and 80 °C) using ultraviolet lamps at 200 W/m^2 for 300 h. The results showed that the UV-induced degradation is more severe at low temperature (−30 °C), leading to a significant power decrease (13.5% on average) compared with the power attenuation of the solar cell at 80 °C (1.59% on average). At a low temperature (−30 °C), the V_{OC} and FF evidently decrease much faster. Light soaking can repair the damage to some extent, but the power conversion efficiency cannot restore to the initial value. A 3D microscope confirmed this is because the silver metal electrodes are permanently degraded. These findings challenge the standard International Electrotechnical Commission (IEC) stability test for solar cells, in other words, we have to take into account multi-field coupling to evaluate the long-term reliability of solar cells in real environments.

Silicon heterojunction (SHJ) solar cells, due to their environmental friendliness, long service life, short fabrication procedure, high power conversion efficiency, and other advantages, have been widely utilized in the field of renewable energy.[1–4] The last few decades have seen power conversion efficiency and operating stability of solar cells being substantially improved. Now, the SHJ solar cells have achieve a high efficiency beyond 27%, holding the record efficiencies of 27.30% and 26.81% in interdigitated back contact and double-sided contact configurations, respectively.[5–7]

Despite the SHJ solar cells achieving highly efficiency, it still has the problem of long-term stability in competition with other conventional silicon solar cell technologies in the field. For crystalline silicon solar cells, the power degradation rates have approached −0.55%±0.05 per year.[8] However, state-of-the-art cells show faster degradation than their inferior counterparts. For example, according to the Department of Energy (DOE) National Laboratory Regional Test Center program, various types of high-efficiency crystalline silicon modules exhibit degradation rates ranging from −1% to −2% during the first operation year, even after the initial stabilization of light-induced degradation (LID).[9] Sinha *et al.* reported that the highly efficient modern solar cells of SHJ, n-PERT, p-PERC showed decay rates of −11%, −5 ± 2%, and −2.5 ± 1.5%, respectively, caused by UV irradiation. In contrast, conventional Al-BSF cells degraded by only −1%.[10]

For silicon solar cells, we have observed a significant power conversion efficiency (PCE) degradation after UV exposure. Previously, collaborative research investigated the root cause of the UV-induced degradation of high-efficiency silicon solar cells with different structures. Werner *et al.* reported an increase in the recombination centers at the Si/SiO_2 interface of silicon solar cells under UV exposure, because of an increase in the density of stationary charges and interfacial defects.[11,12] Gruenbaum *et al.* concluded that UV radiation causes surface defects in solar cells. Because of the UV light photoinjecting electrons from the silicon conduction band into silicon dioxide, they found that the recombination centers increased at the interface of Si/SiO_2, disrupting the surface passivation and increasing the defect density at the Si surface.[13–16] Sinha *et al.* confirmed that the decrease in power conversion efficiency was caused by the decrease in open-circuit voltage and short-circuit current, as well as the hydrogen concentration increased near the Si/passivation interface in SHJ and IBC cells after UV exposure by using secondary ion mass spectroscopy (SIMS).[10]

In this work, we experimented the decrease in SHJ solar cells induced by UV irradiation at different temperatures (−30 and 80 °C). We found that the performance of silicon solar cells degraded slowly under UV irradiation at 80 °C. However, at −30 °C, the UV-induced degradation of V_{OC} and FF evidently increased. Additionally, we also showed that light soaking (LS) of long-wavelength photons can activate boron and phosphorus doping in hydrogenated amorphous silicon, which helps to improve the efficiency of solar cells.[17–19] IEC defined that photovoltaic products are subjected to stability tests, which include damp heat test, damp freezing test, thermal shock test, UV pretreatment test, etc.[20] For example, Liu *et al.* reported that the solar cells retain 99.62% of their power after thermal cycling between −70 and 85 °C for 120 h.[4] They also reported that the cell modules successfully passed IEC 60068-2-78 (damp heat degradation at 85 °C and 85% relative humidity, DH85) and IEC 61215-2:2016 (thermal cycle degradation between −40 and 85 °C with applied current at 100% I_{mpp}).[17] However, all the standard tests are conducted under a single external stress, so they cannot comprehensively evaluate a coupling effect caused by multi-physics fields. In this regard, the IEC tests face challenges to estimate in-site stability of solar cells in practical conditions. Here, as a typical example, we study the effect of UV irradiation on SHJ solar cells at different climate temperatures.

Figure 1(a) shows the structure of a SHJ solar cell in this work. The wafers (236.7 cm^2) are n-type monocrystalline silicon. These wafers were cleaned by the standard Radio Corporation of America (RCA) process and etched in KOH and hydrogen fluoride (HF) water solution. Next, an intrinsic a-Si:H (i-a-Si:H) passivation layer was deposited on the both sides of textured c-Si wafer in plasma-enhanced chemical vapor deposition (PECVD). Subsequently, n-type hydrogenated nanocrystalline silicon (n-nc-Si:H) and p-type hydrogenated nanocrystalline silicon (p-nc-Si:H) films were deposited on the front and rear surfaces, respectively. Then, indium tin oxide (ITO) films were deposited on both sides by reactive plasma deposition (RPD). Finally, silver metal electrodes were screen-printed on both sides with a low-temperature silver paste. A typical current–voltage (I–V) curve of a SHJ solar cell in the work was tested under AM1.5G illumination at 25 °C, as shown in Fig. 1(b).

Figure 2 shows the short-circuit (J_{SC}), V_{OC}, FF, and power conversion efficiency (PCE) of SHJ solar cells exposed UV irradiation at different temperatures (−30 and 80 °C). The duration of UV irradiation is 300 h. At 80 °C, the UV-induced performance degradation is slight, where J_{SC}, V_{OC}, and FF degrade by 0.55%, 0.21%, and 1.38%, respectively. As a consequence, the PCE degrades by only 1.59%. However, when the cell is exposed to UV light for 300 h at a low temperature of −30 °C, the short-circuit current (J_{SC}) showed a significant attenuation of 5%. Simultaneously, V_{OC}, FF, and PCE degrade by 5.0%, 7.2%, and 13.5%, respectively.

Evidently, all parameters degrade much faster by same UV irradiation at lower temperature. As control experiments, we also put the cell at 80 and −30 °C, respectively, for the same time duration. In these conditions, the performance of cells degrades very slightly. This concludes that neither UV irradiation nor extreme temperature can degrade the cell performance very fast in a short time, but a coupling of UV photons and low temperature can accelerate the degradation significantly. For silicon, as an indirect semiconductor, its conduction band and valence band poles correspond to different wave vectors.

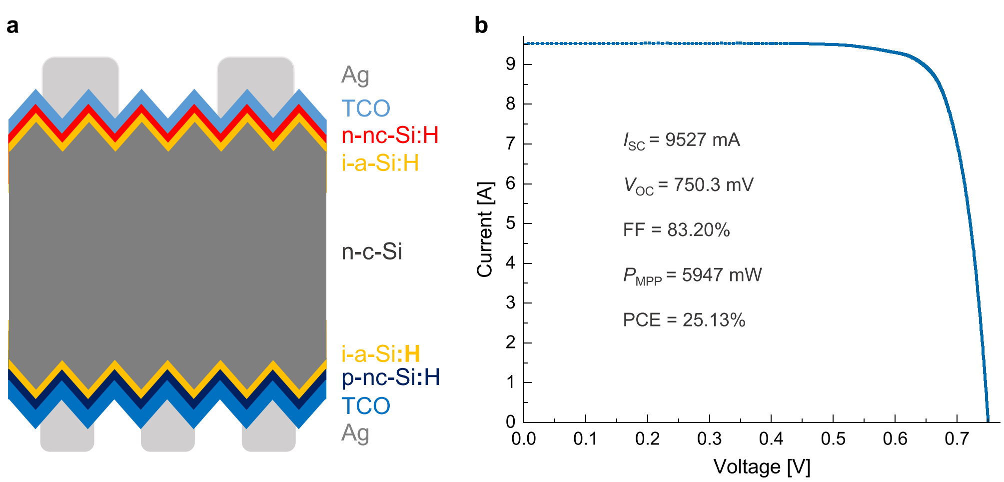

FIG. 1. (a) Schematic and (b) I–V curve of a SHJ solar cell.

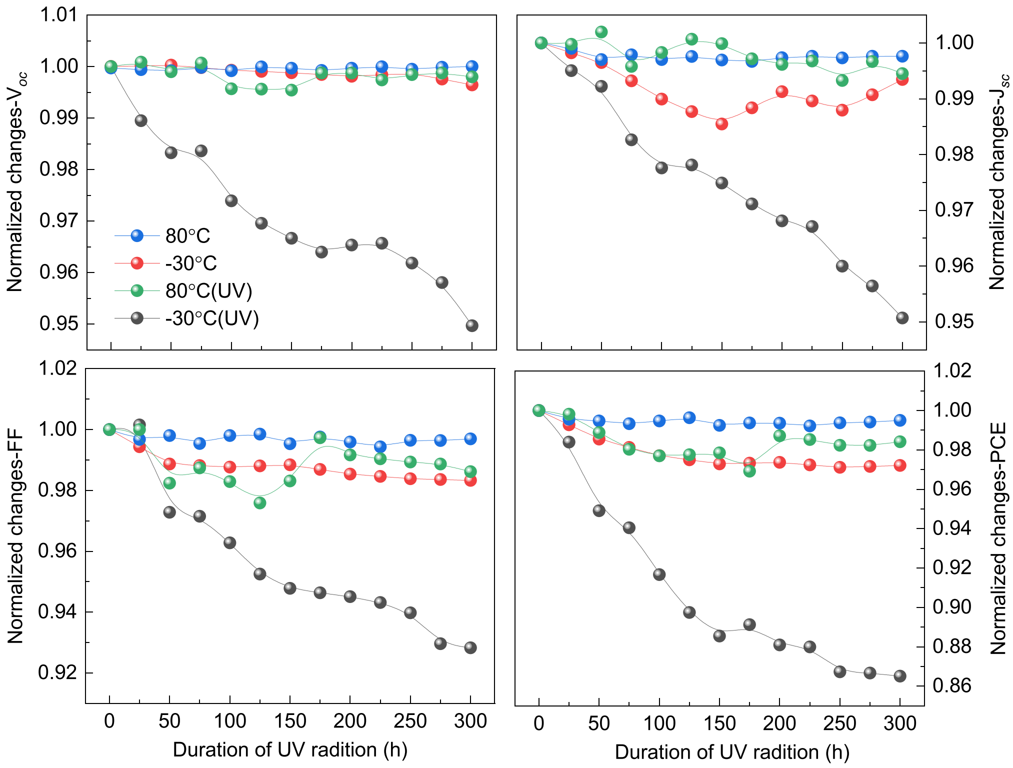

FIG. 2. Normalized performance changes of SHJ solar cells during UV exposure testing: (a) open-circuit voltage (V_{OC}), (b) short-circuit current density (J_{SC}), (c) FF, and (d) cell efficiency (PCE).

Thus, the phonons emitted or absorbed by lattice vibrations should be considered to explain the energy transitions. According to the Bose–Einstein function, the relationship between phonon occupation number n (ω, T) and temperature is

$$n(\omega, T) = \frac{1}{e^{\hbar\omega/kBT} - 1},$$

where ω, T, k_B, and $\hbar$ are phonon frequency, temperature, Boltzmann constant, and reduced Planck constant, respectively. We conclude that, at low temperatures, the number of phonons is relatively small and the lattice vibration is weaker. In this regard, broken Si–H bonds are difficult to recover at low temperatures because of weak lattice vibration. As a consequence, the UV-induced degradation of SHJ solar cells is faster at a low temperature compared to that at a high temperature.

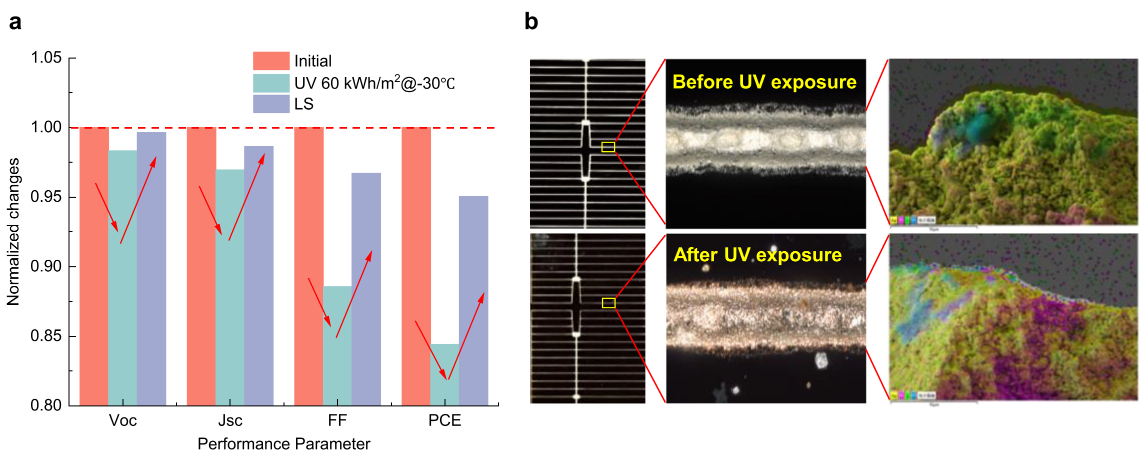

FIG. 3. (a) Normalized performance changes of SHJ solar cells by UV exposure at −30 °C, followed by LS treatment. (b) Comparison of device electrodes by 3D microscope and SEM before and after the UV exposure.

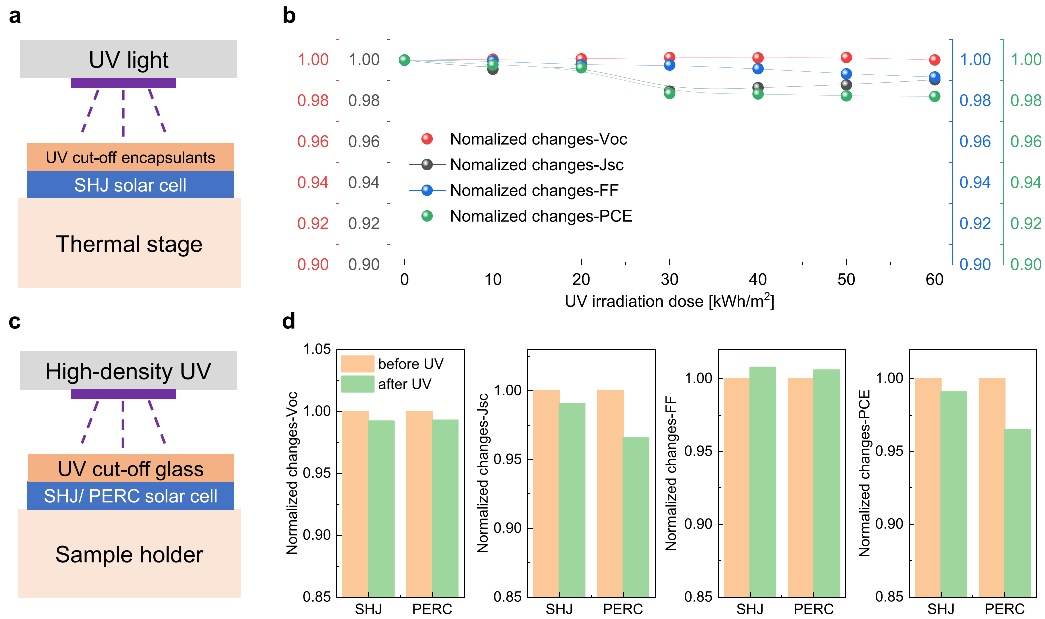

FIG. 4. (a) The UV test platform of SHJ solar cells in the work. (b) Normalized performance changes of SHJ solar cells during UV exposure testing with UV cutoff encapsulants. (c) The test platform of SHJ and PERC solar cells under high-density UV exposure modeling space radiation. (d) Comparison of normalized performance changes between SHJ solar cells and PERC solar cells under high-density UV exposure modeling space radiation (the radiation dose is 236 kWh/m^2).

Figure 3(a) shows the changes in I–V parameters of n-type SHJ solar cells after UV exposure and LS treatment. The LS is applied for SHJ solar cells after 60 kWh/m^2 of UV exposure at $-30\,^{\circ}$C. We find the UV-induced degradation of the SHJ solar cells could be greatly restored through a brief LS treatment. The decrease in V_{OC} and FF is caused by UV-induced degradation of chemical passivation on the c-Si surface.[21–25] By virtue of LS, the passivation is substantially improved.[11,26,27] However it cannot be repaired to the initial state. This is because the silver metal electrodes are destroyed by the UV exposure, which decreases their ability of collecting current. We compared the surface silver metal electrodes before and after UV exposure by 3D microscope and SEM. As shown in Fig. 3(b), the surface electrodes on a SHJ solar cell are much rougher compared with the initial state under the 3D microscope, probably caused by moisture induced degradation under UV irradiation. In addition, there is a phenomenon of agglomeration of the organics in the electrodes after UV exposure. This explains why the solar cell cannot recover to the original performance by LS treatment.

We also monitor performance changes of SHJ solar cells with UV cutoff encapsulants. Figure 4(a) shows the UV test platform. The UV cutoff encapsulants used in this experiment is 380 nm UV cutoff EVA, which could reduce the photon transmittance of UV light shorter than 380 nm. EVA UV cutoff adhesive film's raw materials usually contain EVA resin, antioxidant, cross-linking agent, silane coupling agent, and UV absorber. The film thickness is about 560 μm and the weight is 420 g/m^2. Figure 4(b) shows the performance changes of SHJ solar cells with UV cutoff encapsulants in the experiment. We clearly find that the UV-induced attenuation is greatly alleviated by using the UV cutoff encapsulants. In addition, we also test the performance changes of SHJ and PERC solar cells under a high-density UV exposure modeling space irradiation as shown in Fig. 4(c), the devices are capped with a glass that can cut off UV light. The radiation dose is 236 kWh/m^2 in this test. Figure 4(d) finds SHJ solar cells degraded by 0.9%, much slower than their PERC counterpart (3.5%), so the SHJ devices may operate more stable in space applications. These results indicate that it is important to separate UV light and low temperature, otherwise their coupling will degrade the performance of silicon solar cells very fast in a short duration.

We investigated the effect of UV irradiation on unencapsulated SHJ solar cells at different temperatures. The decrease in PCE is mainly caused by the degradation of V_{OC} and FF. Evidently, the degradation is more severe at low temperatures. The LS process can greatly restore the loss, but cannot reach the initial state as a result of the destroyed silver metal electrodes. The degradation of SHJ solar cells is greatly alleviated by using the UV cutoff encapsulants or high temperatures. This result emphasizes that a single external stress cannot sufficiently evaluate the in-site stability of solar cells, multi-field coupling must be considered in future IEC test standards.

The authors acknowledge the financial supports from the National Natural Science Foundations of China (Nos. T2322028, 62004208, and 62074153), the Science and Technology Commission of Shanghai Municipality (No. 22ZR1473200), the Talent plan of Shanghai Branch, Chinese Academy of Sciences (No. CASSHB-QNPD-2023-001), the Shanghai Rising-Star Program (No. 23QA1411100), and the Sichuan Science and Technology Program (No. 2023ZYD0163).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Na Wang and Qi Deng contributed equally to this work.

Na Wang: Data curation (equal); Formal analysis (equal); Writing – original draft (equal). **Qi Deng:** Data curation (equal). **Xuehui Gu:** Writing – review & editing (equal). **Xiaohua Xu:** Writing – review & editing (equal). **Su Zhou:** Writing – review & editing (equal). **Chen Yang:** Writing – review & editing (equal). **Jiakai Liu:** Writing – review & editing (equal). **Fanying Meng:** Resources (equal). **Liping Zhang:** Writing – review & editing (equal). **Zhengxin Liu:** Writing – review & editing (equal). **Jian Yu:** Resources (equal); Supervision (equal); Writing – review & editing (equal). **Wenzhu Liu:** Funding acquisition (equal); Methodology (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

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