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THE EFFECTS OF CONCENTRATED ULTRAVIOLET LIGHT
ON HIGH-EFFICIENCY SILICON SOLAR CELLS

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ABSTRACT

The importance of stability in the performance of solar cells is clearly recognized as fundamental. Some of the highest efficiency silicon solar cells demonstrated to date, such as the Point Contact solar cell and the Passivated Emitter solar cell, rely upon the passivation of cell surfaces in order to minimize recombination, which reduces cell power output. Recently, it has been shown that exposure to ultraviolet (UV) light of wavelengths present in the terrestrial solar spectrum can damage a passivating silicon-oxide interface and increase recombination.

In this study, we compared the performance of Point Contact and Passivated Emitter solar cells after exposure to UV light. We also examined the effect of UV exposure on oxide-passivated silicon wafers. We found that current Passivated Emitter designs are stable at both one-sun and under concentrated sunlight. The evolution of Point Contact concentrator cell performance shows a clear trend towards more stable cells.

INTRODUCTION

Two types of crystalline-Si solar cell designs have evolved recently with exceptionally high conversion efficiencies that hold the promise of cost-effective terrestrial power generation, especially for use in concentrator systems. These are the high-bulk-resistivity Point Contact (PC) cells pioneered at Stanford University [1] and a whole range of low-bulk-resistivity Passivated Emitter (PESC, PERL) designs developed at the University of New South Wales [2,3]. Both cell types rely upon extremely well-passivated surfaces to reduce recombination that would detract from cell power output.

In 1988 it was reported that the efficiency of some PC cells decreased after exposure to concentrated sunlight due to an increase in recombination at the sunward cell surface [4]. It became clear that it was the ultraviolet (UV) component of the incident sunlight which caused the damage. From UV-exposure and photoinjection experiments, Gruenbaum discovered that surface recombination velocities and interface state densities increased due to exposure of oxide-passivated silicon surfaces to UV light of energy

greater than about 3.1 eV [5]. This corresponds to light with wavelengths shorter than 400 nm, of which there is a small but significant amount present in the terrestrial solar spectrum. Figure 1 shows the energy band diagram at the Si/SiO₂ interface. The absorption of UV photons with wavelengths shorter than 400 nm could inject electrons from the Si conduction band into the oxide conduction band. Gruenbaum speculated that this photoinjection could be producing defects at the interface which decrease solar cell efficiency.

One method which improved the stability of PC solar cells was the formation of a diffused phosphorus region on the sunward surface [5]. This creates a high field region just beneath the front surface which repels photogenerated holes away from recombination centers at the interface. Then, even though the front surface recombination velocity may have increased, the surface recombination rate remained low.

For the case of low-bulk-resistivity Passivated Emitter Solar Cells (PESC), little previous work has been done to determine how their performance may be affected by long-term exposure to UV light. Like PC cells, PESC cells also rely upon a clean, thermally grown oxide layer to provide a high degree of passivation of the sunward-side cell surface. In addition, the most highly efficient PESC cells rely upon a double-diffused emitter formation process, so that the illuminated regions between the gridlines are more lightly doped to increase the cell's spectral response at short wavelengths. This creates the possibility that the junction field there may not adequately protect photogenerated holes from a UV-damaged front surface.

Some recent testing of one-sun PESC cells at UNSW showed slight degradation, but this result may be invalid because some of the tests used an excessively harsh UV spectrum. It was also discovered that cells tested while still on the wafer may have exhibited instabilities due to the exposure of peripheral wafer regions [6].

This paper first describes the results of an investigation of the UV stability of oxide-passivated Si wafers. Its original intent was to determine the oxidation conditions necessary to achieve stable interfaces, but it eventually highlighted the precautions necessary for conducting valid UV-exposure experiments. Then results of UV exposure testing on various types of PC and PESC cells are presented.

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EXPERIMENTAL PROCEDURE

The approach used in this study has been to measure the performance of solar cells before and after their exposure to a measured amount of UV light. In addition, the carrier-recombination lifetime of oxidized-Si wafers was monitored as a function of UV exposure. Figure 1 shows that deep-UV light with wavelengths equal to or shorter than 295 nm and 254 nm could produce additional defect-causing transitions at the Si/SiO₂ interface other than the electron photoinjection already mentioned. However, as Figure 2 indicates, neither the direct nor global terrestrial spectra contain significant components with wavelengths shorter than 300 nm. Therefore, it is important to exclude light of those wavelengths during simulated UV exposure to avoid inducing defects that would not be expected to occur in the field.

Figure 2 also shows the filtered-UV lamp spectrum we used for the cell exposures, which was tailored to approximate a simple scalar multiple of about 20 times the global solar spectrum between 300 and 400 nm. The spectrum was obtained from a xenon-arc lamp source using Pyrex glass filters. The integrated spectral irradiance from our lamp between 300 nm and 400 nm was measured before and after cell exposures and found to remain constant at between 20 and 28 times that of the ASTM standard. The measured values were used to calculate UV exposure in sun-hours. Wavelengths longer than 400 nm were not considered to contribute to degradation but to simply generate heat in the open-circuited cells. The heat was extracted from the cells by a water-cooled vacuum chuck so that the cells were kept near room temperature during exposure.

A different Xe arc lamp was used for the oxidized-Si wafer exposures. Schott glass filters were generally used to exclude the hard UV light below 300 nm, and a water filter was used to remove the long wavelength infrared to minimize the amount of sample heating. The wafers were held on an air-cooled vacuum chuck which maintained the sample temperature below 35°C. The output of the lamp used for the bare oxide studies varied between 0.1 and 8.3 suns (below 400 nm), depending on the particular filter used.

Figure 3 shows the importance of filtering and monitoring the spectral output of the Xe lamp used for testing. The graph illustrates the decrease in carrier recombination lifetime (as monitored by a microwave-detected photoconductance decay technique [7]) as a function of UV exposure. The upper curve taken from one quadrant of a wafer shows apparent stability until the 305-nm cutoff filter was removed. The Xe bulb used in exposing Sample Q2 was inadvertently destroyed. Subsequent exposures of another quadrant from the same wafer (Sample Q1), were done with a new Xe bulb. This sample displays degradation even with a 375-nm cutoff filter in place. The difference in behavior between the two samples may illustrate either variability with location across a wafer or differences in spectral output of a new and old bulb (or both). The major point here is that it is imperative to monitor the lamp output and to filter out light of sufficient energy to initiate

other damage mechanisms (hole injection, for example) which will not be present in the terrestrial solar spectrum.

To account for the variability of nominally identical cells, several cells of each type were exposed and tested. Because of the imperfect repeatability of successive cell measurements and degradation that may occur due to other factors, several control cells which were not exposed to the UV light were tested at the same time as the exposed cells.

The solar cells used for UV-exposure tests are shown in Fig. 4-7. The first type of PC cells tested, shown in Fig. 4, were p-i-n structures fabricated at Stanford University [8]. These high-bulk-resistivity cells have boron-diffused point contacts on the front side and phosphorus-diffused point contacts on the back. In addition, a floating n-type phosphorus diffused region was present on some of the cells to promote UV stability. Three variations were tested here: cells with no front phosphorus diffusion and cells that were diffused to either 165 or 85 Ω/□.

Some back-contact PC cells fabricated by SunPower Corp., a new company formed by some researchers from the original Stanford group, were also tested. Their cell structure is shown in Fig. 5. These cells represent further refinement of the PC cell process and incorporate changes to facilitate cost-effective manufacturing. The two types tested for this study had front phosphorus diffusions of 80 or 180 Ω/□.

The low-bulk-resistivity PESC cells studied were n⁺/p/p⁺ structures with phosphorus-front and aluminum-back diffusions as shown in Fig. 6. These concentrator cells were all from the same lot supplied by Applied Solar Energy Corp. (ASEC) and were diffused to about 100 Ω/□ between gridlines.

Passivated Emitter and Rear Locally-diffused (PERL) cells from the University of New South Wales were also tested before and after UV-exposure. These cells, shown in Fig. 7, were designed for one-sun performance and could not be tested under concentrated illumination. The sheet resistance of the emitter diffusions ranged from 100-150 Ω/□. These cells were tested while still on the wafer, so that an unexposed control cell adjacent to the exposed cell was subjected to all the same conditions except the actual exposure. Following advice from UNSW, an opaque mask was used which shaded all portions of the wafer except the cell under test to avoid ambiguities due to effects from exposed peripheral wafer regions.

RESULTS: OXIDIZED WAFERS

We attempted to produce UV-stable Si/SiO₂ interfaces by oxidizing Si wafers under various conditions in our laboratory. If surface recombination could be kept low without resorting to front surface diffusions, higher PC cell efficiencies could be attained [5]. We have investigated many processing steps involved in growing the thermal, passivating oxides including cleaning procedures, damage removal etches (which alter the microstructure of the surface), oxidation equipment maintenance, and the oxidation parameters themselves (temperature, ambient, and

time). Typical results from these types of experiments are depicted in Fig. 8, which deals with oxide thickness. Generally we observe early degradation of the lifetime from initial values over one millisecond to values of a few hundred microseconds. Occasionally the degradation seems to stop, with lifetimes leveling off at 400 - 600 microseconds. Assuming no change in the bulk lifetime or back surface passivation, this corresponds to an increase in estimated front surface recombination velocity from 5 to 85 cm/s.

We have not been able to establish any correlation of stability with specific processing steps or parameters. We have some evidence that there may be considerable variation in the degradation rates of oxides on nominally identical wafers (i.e., wafers from the same box, batch-processed together). We found no correlation of stability with oxide thickness as has been suggested by other studies [5].

Figure 9 demonstrates the beneficial effects of including a front phosphorus diffusion to reflect carriers away from the damaged interface. The figure compares results from some of our most stable oxides without diffusions with a sample incorporating an 830 $\Omega/\square$ phosphorus diffusion. The difference is quite striking even though the diffusion used on this particular wafer is much lighter than those normally used in current PC and PESC designs.

RESULTS: SOLAR CELLS

The effect of the UV exposure on Stanford's p-i-n cells agrees with observations that have been published previously [8]. The 100-sun efficiency of the undiffused or lightly-diffused cells suffered severe degradation as shown in Figure 10, while the most heavily diffused 85 $\Omega/\square$ cells were more stable. Much of the degradation of the phosphorus-diffused cells is due to the loss of short-circuit current, which is due to a decrease in the responsivity of the cells. High-bulk-resistivity cells are known to have sublinear responsivities at high solar concentrations [9]. By plotting the ratio of the amount by which the 100-sun current decreased to the amount that the 1-sun current decreased (Fig. 11), one can determine the increase in sublinearity.

On the other hand, the one-sun efficiency degradation of these cells is primarily due to losses in open-circuit voltage and fill factor, as shown in Figs. 12 and 13. Again, the cells with the heaviest front-surface diffusion suffered the least amount of degradation. A comparison of internal quantum efficiency measured at low illumination levels of a severely degraded exposed cell with that of a control cell shows no change, which is consistent with the unchanged one-sun short-circuit currents.

The high-resistivity PC cells from SunPower proved to be far more stable, as shown in Fig. 14. The cells with the 80 $\Omega/\square$ diffusion show a much smaller amount of degradation than the earlier 85 $\Omega/\square$ Stanford cells after much longer exposures. The single exposed 180 $\Omega/\square$ SunPower cell seems to exhibit complete stability, but more cells of this type need to be tested to establish the desired level of confidence in this result. It is in

agreement, however, with stability testing that was conducted by EPRI on these 180 $\Omega/\square$ cells [10]. They were exposed outdoors behind a 500X geometric ratio Fresnel lens for 50 hours and suffered no performance degradation. This confirms that our indoor test is no more severe than a realistic outdoor exposure. In addition, a concentrator module of similar cells tested by EPRI was also reported to be stable [11].

The performance of the low-resistivity ASEC cells at 50 suns is shown in Fig. 15. The efficiency of the exposed cells lies within the range of values measured for the unexposed controls, the average of which declined slightly. This shows the importance of including several controls. For this exposure duration which was sufficient to cause significant degradation of the 85 $\Omega/\square$ Stanford cells, the ASEC cells were stable.

The efficiencies of the low-resistivity UNSW PERL cells at one-sun are shown in Fig. 16. The expanded vertical scale accentuates the noise in the measurements, but it is clear that the exposed cells were not degraded by the UV exposure.

DISCUSSION

The degradation in performance of the Stanford PC cells is consistent with the model of UV-created recombination centers at the sunward Si/SiO₂ interface. The large decrease in fill-factor observed at one-sun conditions on the cells with heavy front phosphorus diffusions can be understood as the result of an increase in the forward shunt conductance. Dark I-V measurements, like those in Fig. 17, show a large shunt conductance in the reverse direction that far exceeds the forward conductance. This can be explained as a low-voltage reverse breakdown of the heavily-doped p/n junction on the front surface. Before exposure, this junction has a normal diode characteristic in the forward direction. After the UV-exposure there is a dramatic increase in the forward conductance until it reaches the value in the reverse direction. This could be caused by UV-generated interface states at the junction which promote sufficient tunneling to short-out the junction. This increase in forward conductance, generally about 5-10 mS/cm², is enough to account for the large drop in fill-factor observed on these cells.

The cells with the heavier front phosphorus diffusion had a much smaller drop in fill factor consistent with a much smaller increase in forward conductance. Because of the heavier doping, these cells already showed considerable forward shunting, so the increase due to UV-exposure was not as large.

Shunting effects become less important at higher cell currents, and indeed voltage and fill-factor at 100-sun operation were not affected much by the UV exposure for the phosphorus-diffused cells. Instead, the primary degradation mechanism becomes loss of short-circuit current. This is primarily due to a decrease in the responsivity of the cells that can be thought of as an increase in their sublinearity. Sublinear current response is due to any recombination mechanism whose recombination rate increases faster than linearly with photogenerated carrier concentration.

Recombination in the diffused regions increases as the square of the bulk carrier concentration, because the bulk is in high injection at 100 suns. Therefore, an increase in diffused-region recombination due to UV-induced defects at its surface results in increased sublinearity. This effect is much smaller for the more heavily-diffused cells, possibly because their doping provides better shielding from the surface states. This agrees with previous work that showed that sublinearity increases with an increase in total front-surface saturation current density [12].

The Stanford cells with no front phosphorus diffusion generally exhibit a large drop in open-circuit voltage at one sun as the primary effect of UV exposure. This is due to an increase in $n=2$ dark current as shown in Fig. 18. There is still a significant decrease in fill-factor at 100 suns for the cells without front phosphorus diffusions because the increase in $n=2$ current decreased the slope of their dark I-V curves even at the 100-sun maximum-power point.

The SunPower cells exhibit improved UV stability at conversion efficiencies of 20-23%. These cells use recently developed techniques to create a shallower front-surface phosphorus doping profile with a higher surface concentration. The result is a higher electric field that is presumably more effective at repelling holes away from the surface. Thinner phosphorus diffused-regions have also been shown to result in lower saturation current densities, thereby increasing the achievable efficiency [13].

Both the ASEC and UNSW low-resistivity cells were insensitive to the UV exposure and maintained their efficiencies of between 19 and 21%. This is consistent with simple modeling of n/p junction cells which shows they are not sensitive to front surface recombination velocity until it exceeds about 10^4 cm/s [14]. Also, low-resistivity cells do not suffer from sublinearity for the illumination intensities of interest [15].

CONCLUSIONS

This study showed for the first time that low-resistivity cells are not affected by UV-exposure that is sufficient to cause degradation in some types of high-resistivity PC cells. Evidence was also presented to show that more recent vintage high-resistivity cells are much less sensitive to UV-degradation than earlier versions have been. Longer-term exposures with larger sample sizes need to be done to assure the validity of this result.

Our work with wafer oxidation techniques has so far not resulted in a procedure for forming simple passivating oxide interfaces which are UV-tolerant.

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Figure 1. Si/SiO₂ Energy Band Diagram.

Figure 2. Terrestrial solar spectra normalized to 1000 W/m² and filtered lamp spectrum.

Figure 3. Degradation of carrier recombination lifetime for different wafer quadrants. Different bulbs and various UV filters were used as noted.

Figure 4. Stanford p-i-n cell with front phosphorus diffusion.

Figure 5. SunPower Back-Point-Contact Cell.

Figure 6. ASEC cell with microgrooved PESc structure.

Figure 7. UNSW PERL Cell.

Figure 8. Typical degradation behavior for Sandia-grown oxides due to UV exposure.

Figure 9. Recombination lifetime vs. UV exposure demonstrating the beneficial effects of a front surface phosphorus diffusion.

Figure 10. Normalized 100X efficiency vs. UV exposure for Stanford p-i-n cells with various phosphorus front surface diffusions.

Figure 11. Ratio of proportional decrease in short-circuit current at 100X and 1X vs. UV exposure for Stanford cells showing increased sublinearity.

Figure 12. Normalized 1X open-circuit voltage vs. UV exposure for Stanford p-i-n cells.

Figure 13. Normalized 1X fill factor vs. UV exposure for Stanford p-i-n cells.

Figure 14. Normalized 100X efficiency vs. UV exposure for SunPower back-contact cells. These cells were much more stable than the 85 $\Omega/\square$ Stanford cells.

Figure 15. Normalized 50X efficiency vs. UV exposure for ASEC PESC cells.

Figure 16. Normalized 1X efficiency vs UV exposure of UNSW PERL cells.

Figure 17. Dark I-V characteristics of a Stanford cell with a 165 $\Omega/\square$ front surface phosphorus diffusion. The shunt conductance in the forward direction increased dramatically after 480 sun-hours of UV exposure.

Figure 18. Forward dark I-V curves for a Stanford cell with no front surface diffusion showing increased n-2 current after UV exposure.

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