THE SURFACE POLARIZATION EFFECT IN HIGH-EFFICIENCY SILICON SOLAR CELLS

R. Swanson, M. Cudzinovic, D. DeCeuster, V. Desai , Jörn Jürgens , N. Kaminar, W. Mulligan, L. Rodrigues-Barbarosa, D. Rose, D. Smith, A. Terao, and K. Wilson,
SunPower Corporation, 430 Indio Way, Sunnyvale, CA 94085

Abstract: The performance of high efficiency solar cells that use silicon dioxide as a surface passivation layer has been found to temporarily degrade when they are operated in modules at high voltage. The performance degradation results from charges left behind by module leakage current. This charge can deplete the surface doped region and thereby increase surface recombination. The effect is found to be completely reversible, and can be avoided by operating modules at negative voltages with respect to ground for n-type front surfaces and positive voltages for p-type front surfaces. The theory of the surface polarization effect is presented, along with experimental verification. Systems that are properly grounded have been shown to operate without being impacted by surface polarization.

Key Words: silicon, degradation, passivation, field operation

1. Introduction

Most high efficiency silicon solar cells rely on reducing surface recombination by incorporating a surface layer of silicon dioxide, which is often capped with silicon nitride anti-reflection coating. SunPower's 20% efficient, back-contact A-300 solar cells rely on such a passivation layer on their front surface[1]. In this case, a front n-type layer is passivated by a silicon dioxide/silicon nitride stack. We have found that negative charge accumulating in the silicon nitride can overcome the inherent fixed positive charge and cause the surface potential to move toward depletion, increasing front surface recombination. The negative charge can come from module leakage current when the cells are operated at a positive voltage with respect to the module frame, or ground. No performance degradation is observed when the cells operate at negative voltage to ground, as this causes positive charge to develop on the cell surface, and hence accumulates the n-type diffusion. Modules operated at sufficiently low positive voltages are also unaffected. We find that all types of cells that are dependent on oxide interface passivation are susceptible to this effect under field operation at high voltage of the appropriate polarity; however, back junction cells are impacted more than front junction cells due to their greater reliance on front surface passivation. We term this the "surface polarization effect." Interestingly, this surface polarization effect is found to be reversible, and is completely avoidable by proper module grounding procedures. This paper discusses our experimental observations, and presents solutions to prevent performance loss under field operating conditions.

2. Initial Field Observations

We first observed the polarization effect at an outdoor test array fielded in Germany. After several months of operation, the output of the array had declined. Modules from that site were removed and re-tested. Indeed, some modules had lost output; however, the findings were initially confusing in that the power loss was dependent on the position in the series string. Figure 1 shows the percent decrease in module output versus position in several series connected strings. Remarkably, only modules at the high potential end of the strings lost power. This system used a direct coupled inverter so that modules 1 through 4 were at negative voltages, and modules 5 through 8 were at positive voltages, with module 8 experiencing an average voltage of 160 V. Similar results were observed at other test sites.

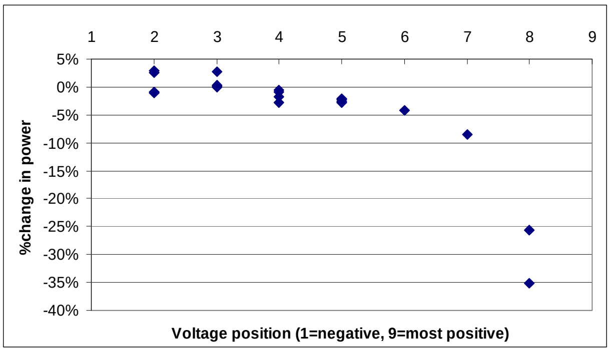

Figure 1: Change in power versus module position in several series connected strings after several months of outdoor operation.

3. Theory

After examining many possible causes of this behavior we theorized that for cells operating at positive voltages, the cell front surface was being negatively charged by module leakage current. The physical structure is shown in Figure 2, which illustrates the current paths and degradation mechanism. Figure 3 shows the surface region band structure resulting from this assumption. The very high resistivity of the silicon dioxide layer prevents conduction into the silicon, so leakage charge remains trapped in the silicon nitride, much as in a programmable memory transistor. The silicon nitride, silicon dioxide, silicon structure behaves like an MOS capacitor.

One clue as to the cause of degradation came from a UV exposure test. When we initially received the affected modules we were concerned that their front passivation may have been degraded by UV photons in sunlight. This seemed unlikely in that the cells are very stable under UV illumination in test conditions. Nevertheless, we subjected a degraded module to further UV exposure, and surprisingly it recovered. We now know that natural UV in sunlight repairs the polarization effect, just as UV erases an EPROM by exciting trapped electrons from the nitride into the silicon substrate, and that the overall degradation comes from a competition between module leakage causing polarization and UV photons reducing polarization.

Figure 3 shows how negative charge trapped in the silicon nitride will tend to decrease the surface potential of the n-type passivation layer. This will increase the hole concentration at the front, and hence increase the recombination rate. It does not take much charge to have a remarkable effect on recombination because the hole concentration increases exponentially with band bending.

The interface was modeled using standard MOS semiconductor modeling to compute the surface potential. If one assumes that the hole quasi-Fermi level is constant in the diffused region, then one can relate the increase in saturation current to band bending by $\Delta J_0 = J_{0,FB} e^{-q\psi_s/kT}$, where $J_{0,FB}$ is the surface component of the saturation current at flat band.

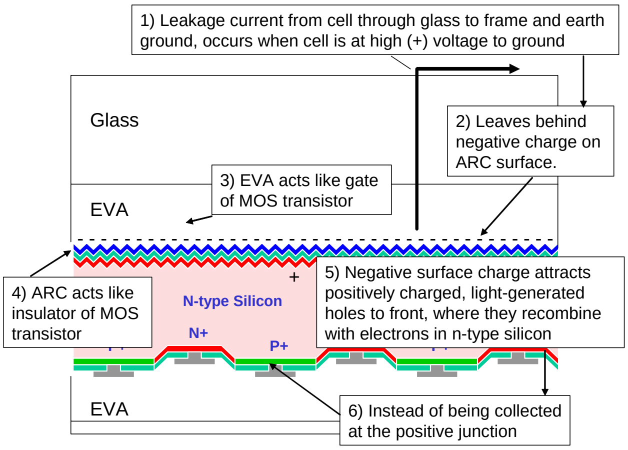

Figure 2: Cross-section of a back-contact solar cell embedded in a module showing the top, n-type passivation layer capped with a silicon dioxide, silicon nitride ARC layer[1].

Using this approach, the calculated saturation current as a function of voltage across the passivation oxide is shown in Figure 4. The important point is that voltages in the neighborhood of 10 V are all that is needed to dramatically increase J_0. A charge density of 1X10^{12} cm^{-2} can cause this amount of band bending.

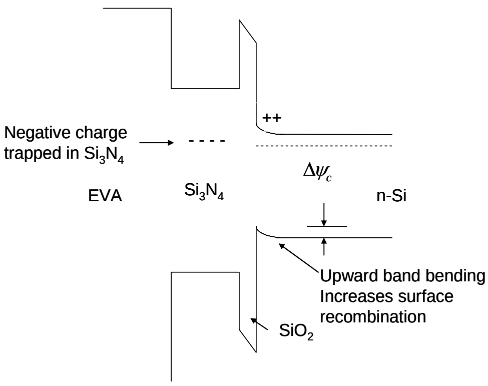

Figure 3: Band structure at the front surface of a back-contact cell.

The module leakage current through the front glass was measured by applying a voltage between the cell string and a wet layer on the front surface. At 1000 V this proved to be 0.6 nA/cm^2. A charge density of 1X10^{12} cm^{-2} will accumulate in only 4 minutes of operation at this leakage current.

The above theory was tested by taking a bare A-300 cell and applying a front surface voltage. The surface was biased by spreading salt-water on the front and applying a potential to the water. The cell J_0 was measured as a function of applied front bias using the suns-V_{oc} method[2]. The results of this test are also shown in Figure 4, confirming that surface voltage can easily affect the cell saturation current.

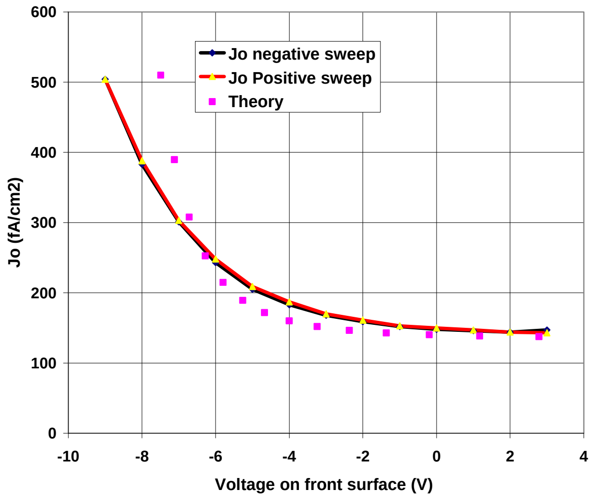

Figure 4: Measured and theoretical cell saturation current as a function of voltage applied across the front passivation oxide.

A similar effect was recently found in high efficiency n-base PERT cells with boron top junctions. They degrade during operation, and, remarkably, degrade even during storage for long periods[3]. The cause of the degradation was identified as surface potential change due to positive charge accumulating in the passivation nitride and/or oxide (as opposed to the negative charge that causes degradation in the n-type front surface of the A-300). Due to the relatively low boron surface concentration, the positive charge moved the surface potential towards depletion, increasing the both surface minority carrier concentration and recombination. The source of the positive charge was not identified, but the effect was found to be completely reversible by varying the surface charge using a corona discharge gun. It is clear that these cells would degrade when operated in modules at negative voltage with respect to ground.

Interestingly, after discovering the polarization effect, we have tested conventional commercial modules that use surface passivation and have noticed the same effect. In one example the module output decreased 10% upon application of a positive 1000 V to the cells. The output reduction in this case is less than for back contact cells because front junction cells are less sensitive to front surface recombination velocity; however, surface polarization may be impacting the field performance of conventional modules. This degradation mechanism is not revealed by the standard module qualification procedure.

4. Laboratory Measurements

Numerous tests have been performed that verified the above polarization theory. Several are discussed below. The first test was to take modules from the field that had reduced output, and subject them to negative voltage. Figure 5 shows an affected module from an outdoor test array where the cells operated positive-to-ground. In its degraded state, it had an output of 140 W. After applying a negative 1000 volts to the cells for one hour, the module recovered to an output of 203 W. During the voltage application the front surface of the module was grounded via a water film.

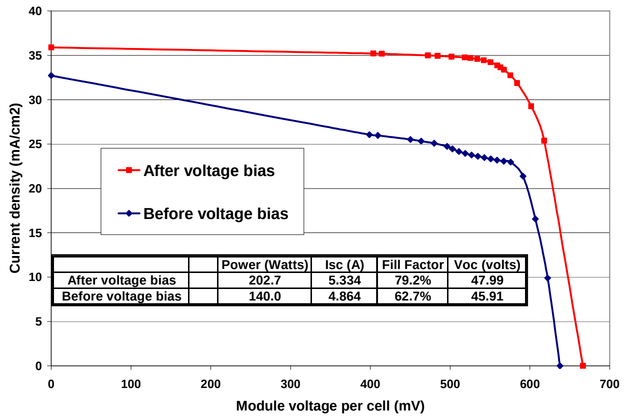

Figure 5: Module performance after receipt from the field and after voltage bias.

Another test is shown in Figure 6. Here three-cell coupons, built in a manner similar to that of full-size modules, were degraded by the application of positive cell voltages. It is seen that the coupon efficiency decreases over time from 19.5% to a stabilized 9%. Modeling shows that 9% is the expected efficiency for the A-300 when the front surface recombination becomes very large and the front saturation current is simply the diffusion limited injection across the front doped layer. The time to degrade, however, is dependent on the applied voltage, increasing with voltage in the same manner as the leakage current.

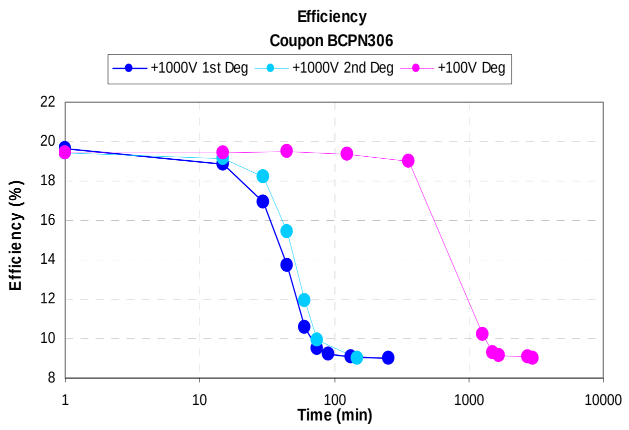

Figure 6: Voltage dependence of output reduction due to front surface polarization.

We have conducted repeated degradation-recovery cycles on numerous samples and have found the output reduction is completely reversible. One example is shown in Figure 7.

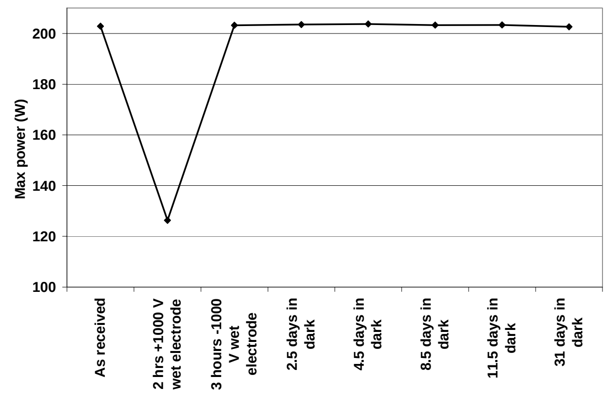

Figure 7: Example of a module which was polarized at 1000 V, then recovered at -1000 V, after output remained constant.

Another concern was that prolonged leakage through the front passivation oxide would degrade the passivation quality over time. To look for this effect we forced a large current through the front passivation using a salt water gate. The result is shown in Figure 8. Driving current through the front passivation forces Fowler Nordheim tunneling current through the silicon dioxide. No impact was seen up to the maximum charge tested, which was 34 coulombs. This corresponds to 110 years of operation at the observed module leakage for wet modules at 1000 V.

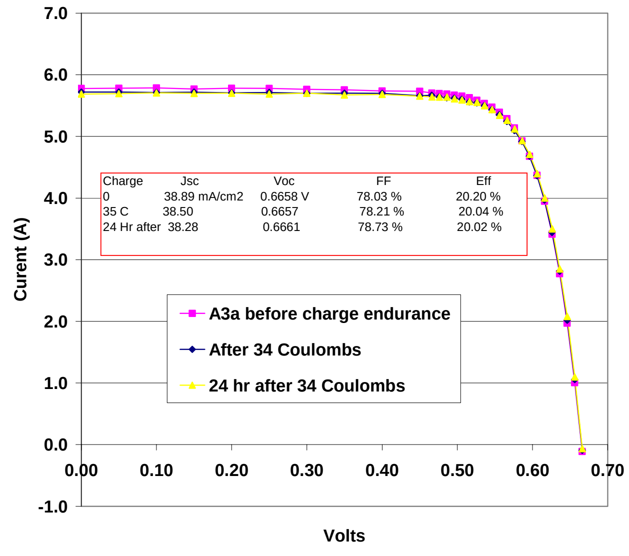

Figure 8: Cell IV curves before and after passing 34 coulombs through the front passivation. No change in performance is seen.

5. Avoiding Polarization

The polarization effect can be easily avoided by designing systems so that modules only see negative voltage. All of SunPower's system integration partners have developed grounding procedures that prevent module operation at positive voltage. If a system is mistakenly installed with the incorrect grounding, modules will temporarily lose power, but no permanent damage occurs. Because the polarization effect is completely reversible, once the grounding problem is corrected, modules will quickly recover to their initial performance without any further intervention, due to the combined effects of reversed leakage current and UV discharge. .

SunPower has many installed systems around the world that have been operating since early this year, and these systems have shown no loss of performance over this period. The German test system where the polarization effect was originally discovered has been restored to its original performance by reversing the polarization effect. This system consists of two side-by-side arrays. One array comprises 10, 160 W conventional multi-crystalline modules and the other 8, 210 W SunPower modules, allowing for accurate comparison. Since the grounding modification was installed in February, 2005, the SunPower array has performed flawlessly. Recent data from these two arrays is plotted in Figure 9. The SunPower array delivers about 4% more energy delivery on a kWhr/kWrated basis, due to the excellent low light performance and low temperature coefficient of efficiency of SunPower modules[4].

SunPower is currently modifying the A-300 to include a front surface conductive layer. This layer shunts leakage current and completely eliminates the polarization effect. Production is slated for 2006.

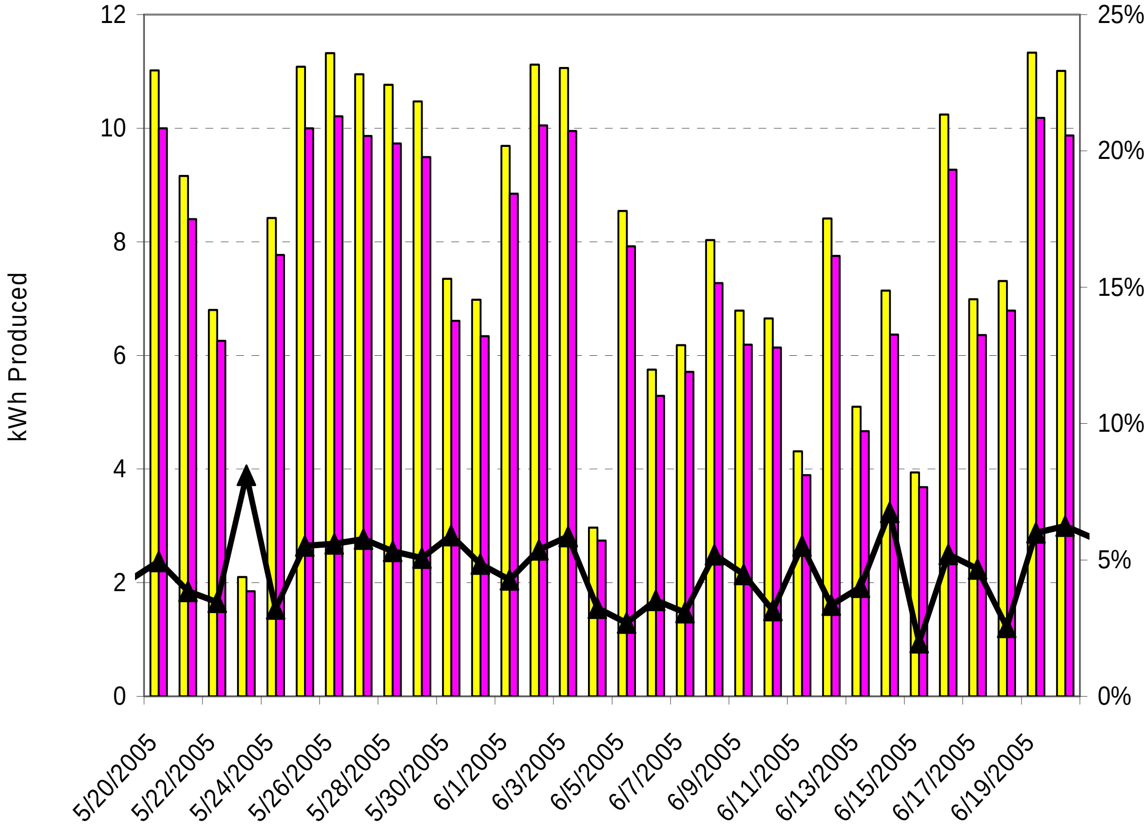

Figure 9: Energy delivery comparison of two side-by-side arrays located in southern Germany, one comprised of conventional multi-crystalline modules and the other of SunPower modules. The left bar at each date is the energy delivery of the SunPower array and the right bar the energy delivery of the multi-crystalline array. The black triangles give the ratio of kWhr/kWrated for the two arrays, with the increase of the SunPower array over the multi-crystalline array tied to the scale on the right.

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