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Efficient Crystalline Si Solar Cell with Amorphous/Crystalline Silicon Heterojunction as Back Contact

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***Abstract* — We study an amorphous/crystalline silicon heterojunction (Si HJ) as a back contact in industrial standard p-type five-inch pseudo-square wafer to replace Al back surface field (BSF) contact. The best efficiency in this study is over 17% with open-circuit (V_{oc}) of 0.623 V, which is very similar to the control cell with Al BSF. We found that V_{oc} has not been improved with the heterojunction structure in the back. The typical minority carrier lifetime of these wafers is on the order of 10 µs. We also found that the doping levels of p-layer affect the FF due to conductivity and band gap shifting, and an optimized layer is identified. We conclude that an amorphous/crystalline silicon heterojunction can be a very promising structure to replace Al BSF back contact.**

***Index Terms* — silicon, amorphous, photovoltaic cells, heterojunction.**

I. Introduction

The crystalline silicon (c-Si) heterojunction (HJ) solar cell with both hydrogenated amorphous silicon (a-Si:H) emitter and back contact is one of the most successful device structures for manufacturing high-efficiency crystal silicon solar cells at low temperatures (<250 ºC), such as the Sanyo HIT® cell. Si heterojunction solar cells achieve high open-circuit voltage (V_{oc}) of 747 mV [1] and high efficiency of 23% [2] on 100 cm^2 n-type c-Si. We apply the similar structure to the industrial standard *p*-type five-inch pseudo-square wafer and replace the screen printed Al back surface field (BSF) contact with amorphous/crystalline heterojunction contact. With the advantage of the heterojunction approach, we were expecting higher open-circuit voltage (V_{oc}) and possible higher cell performance. We will report our process, cell results, and understanding.

II. Experimental

The c-Si solar cell with back heterojunction contact has a structure of metal grid/SiN_x/$POCl_3$ diffused emitter/c-Si(p)/*a-Si:H (i)/a-Si:H (p)*/ITO/metal. The c-Si wafer size is about 148 cm^2. The front emitter, SiN_x, and metal grid of the cell were finished in an industrial cell process provided by JA Solar. The firing process was applied to the unfinished cell to ensure a good finger contact to the emitter. The heterojunction back contact consists of both amorphous i-layer and 10 nm p-layer, followed by a sputtered 100 nm indium tin oxide (ITO) layer, and lastly 1.0 µm Ag. We vary the thickness of *i*-layer and dopant level of *p*-layer. All a-Si:H films were deposited using the plasma enhanced chemical vapor deposition (PECVD) technique in a cluster tool made by MVSystems, Inc. The amorphous *i*-layer used pure SiH_4, and the *p*-layer was made from mixture of pure SiH_4 and 2.6% B_2H_6 in H_2. The finished cells are tested using an Oriel solar AM 1.5 simulator for cell performance evaluation.

III. Results and Discussion

The best efficiency in this study is over 17% with open-circuit voltage (V_{oc}) of 0.623 V, short-circuit current density (J_{sc}) of 36.11 mA/cm^2, and fill factor (FF) of 0.762. This efficiency is very similar to the control cell with a traditional Al BSF. Although we did not improve the cell performance, we did find a way to apply a heterojunction structure to the standard p-type c-Si solar cell.

We found that the V_{oc} was close to the value of the control diffused junction solar cell. The heterojunction should enhance the V_{oc} with better surface passivation. However, we have not achieved this improvement. In the standard cell process, the wafer underwent $POCl_3$ diffusion, and it may be difficult to completely remove the residual phosphorus from the back. For standard Al BSF contacts, the Al-Si BSF after firing is relatively insensitive to residual phosphorus. A heterojunction back contact necessitates appropriate surface cleaning. In order to preserve the wafer front, we performed single side HF vapor etching on the back side to try to remove the oxide before loading the wafer for deposition. We measured the minority carrier lifetime at various stages to track the surface passivation.

Figure 1 shows the mapping of the lifetime in the as-received state (A), where the lifetime is about 3 µs. After HF etching, the lifetime is 9 µs. After *i*- and *p*-layer deposition, the lifetime is 10 µs as shown in the Figure 2. The minimal change in lifetime before and after *i*-layer deposition indicates that the *i*-layer has little effect on the surface passivation of these cells. It is possible that the HF vapor etch was incomplete, thereby minimizing a-Si:H passivation. Alternatively, unfavorable deposition conditions, such as inappropriate silane/hydrogen plasma chemistry, ion bombardment, or epitaxial growth may have also contributed to the lack of effective passivation.

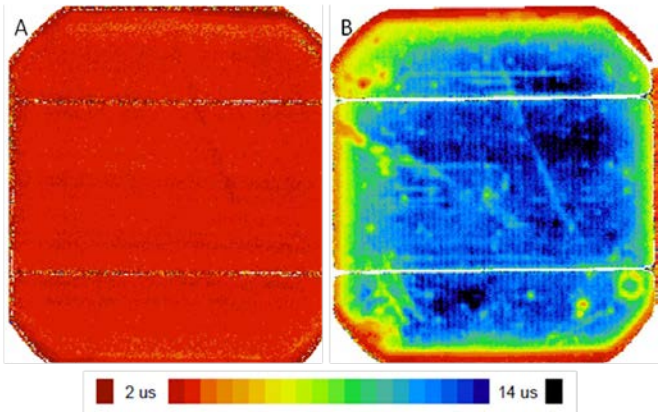

Figure 1. Minority carrier lifetime of as received (A) and *i*-,*p*-deposited (B) wafers.

We found that thickness of *i*-layer affects the FF. A thicker *i*-layer leads to a lower FF. Figure 2 shows the effect of *i*-layer thickness on the FF, where an *i*-layer thickness greater than 2 nm results in decreasing FF. We did not observe any effect on the V_{oc} as shown in the same figure. Interestingly, the V_{oc} is independent of *i*-layer thickness, even without an *i*-layer. Based on Figure 2, we keep our *i*-layer at 2 nm for the optimized thickness. Our best FF was 0.780 at 2 nm *i*-layer thickness, which is very high for Si HJ contact over a large area cell.

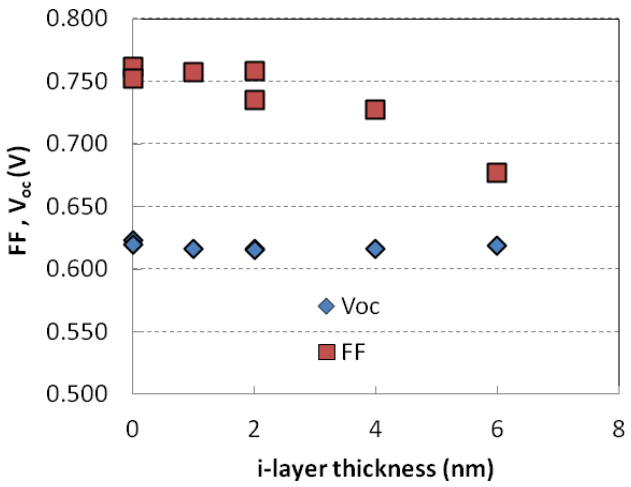

Figure 2. Fill factor and V_{oc} as a function of *i*-layer thickness.

We also report the effect of boron doping on the cell performance. Figure 3 shows the effect of boron concentration in gas phase via the ratio of B/Si on the band gap and the dark conductivity. With increasing ratio, the conductivity increases to mid 10^{-4} S/cm and then decreases to low 10^{-5} S/cm, and the band gap decreases after the ratio is greater than 1.0. With further increase of the B/Si ratio, the band gap saturates at the lowest value of 1.55 eV.

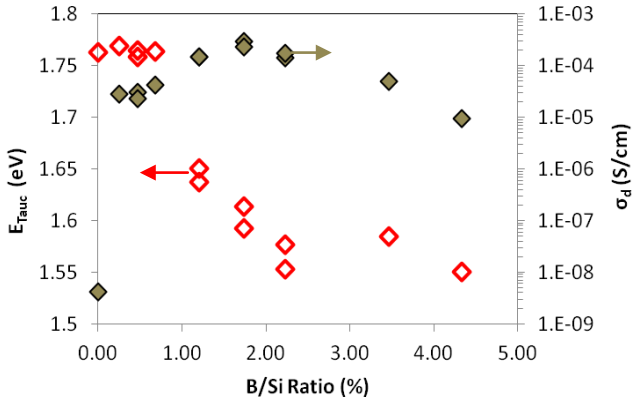

Figure 3. E_{Tauc} and dark conductivity as a function of B/Si ratio.

Figure 4 shows the effect of boron doping on the solar cells. We found that there is a detrimental effect to the J_{sc} with higher B/Si ratio. We understand that the decrease in J_{sc} with increase B/Si ratio is primarily due to the decrease of band gap of *p*-layer. Therefore, a wider gap *p*-layer is preferred to reduce absorption in the *p*-layer. With the increase of B/Si ratio, V_{oc} and FF remain unchanged. The optimized *p*-layer for this study is using the B/Si ratio around 1.0 to keep J_{sc} high.

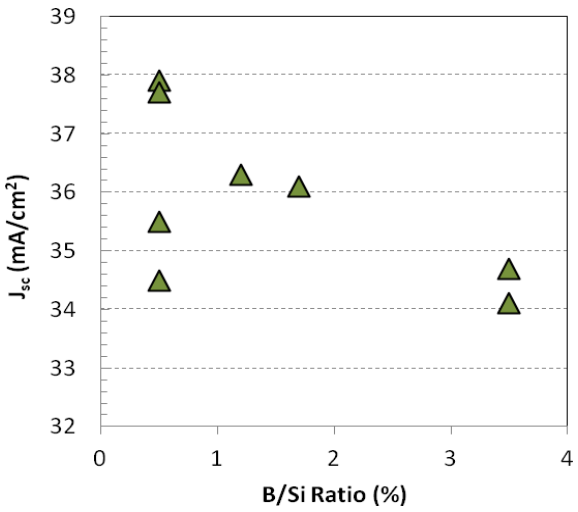

Figure 4. J_{sc} as a function of B/Si ratio.

IV. Conclusion

In summary, we have successfully demonstrated high efficiency c-Si solar cells with an amorphous/crystalline silicon heterojunction as the back contact. Further optimization is required to improve V_{oc}, including initial surface preparation and improved a-Si:H passivation via PECVD.

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