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Application of PCBM Layer as a Back Reflector of Micromorph Tandem Silicon Solar Cells

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We analyzed the effect of using PCBM layers as back reflector of tandem amorphous silicon solar cells. The new possibility of using polymer materials as a back reflector of inorganic silicon based solar cells was discussed. By applying the PCBM back reflector, short circuit current density increased from 9.83 mA/cm^2 to 11.7 mA/cm^2 with proper interface treatment. In order to obtain the tandem cell with high fill factor, HF treatment is required before depositing PCBM on n-μc-Si:H. Series resistance can significantly be increased by little amount of native oxide. Comparison between the reference cell without back reflector and thickness optimized PCBM cell indicated a decrease in open circuit voltage from 1.41 to 1.29 V. These results implied that further optimization of electrical properties, such as electrical conductivity and activation energy is required to minimize the drop in terms of open circuit voltage and fill factor.

Keywords: Micromorph Silicon Solar Cell, PCBM, Back Reflector, Light Trapping.

1. INTRODUCTION

Thin film silicon solar cells are widely researched, because they need significantly less material than that in the crystalline silicon (c-Si) solar cell technology.[1,2] The thin and light nature of the thin film and their potential for large area manufacturing make the possibility of industrial application more realistic. Although there are many advantages of thin film silicon based solar cells, energy conversion efficiency of single junction hydrogenated amorphous silicon (a-Si:H) solar cell is not sufficient for industrialization. Oerlikon Solar showed the module efficiency up to 11% is achievable by introducing a-Si:H/hydrogenated microcrystalline Si(μc-Si:H) double junction.[3] The light trapping capacity of the tandem cell covers not only ultraviolet but the infrared region.

μc-Si:H is multi-phase material that include both amorphous and polycrystalline Si phase. By adjusting the deposition parameters, crystallinity of the material can be modified. When the gas flow ratio of SiH_3 to H_2 increases the crystallization is activated. The crystallinity, ratio of the crystalline phase to amorphous phase, can be measured by Raman scattering analyzer.[4] Generally, energy band gap of the material is considered as 1.1 eV. One major advantage of this material is higher absorption coefficient than that of c-Si because of the existence of amorphous components. Low absorption rate in longer wavelength region make the μc-Si:H absorption layer almost 10 times thicker than a-Si:H absorption layer. We used VHF plasma CVD at 60 MHZ for the fabrication of i-μc-Si:H because the deposition rate is higher than that of RF system.[5,6] If the reflection from the backside electrode is enough, the thickness of absorbing layers can be reduced because effectively reflected light passes the absorbing layer again, indicative of the increase in optical path.

For the effective light trapping parasitic absorption losses, which are occurring at electrodes should be avoided by applying proper back reflector.[7,8] There are many candidate materials for the back reflector of the solar cell, aluminum doped zinc oxide (AZO), n-μc-SiOx:H and so on.[9,10] The low refractive index of the back reflector

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is preferable for total reflection. Refractive index of AZO film is around 2.0. Also, the conductivity should be high to reduce series resistance of the solar cells. We considered Phenyl-C61-butyric acid methyl ester (PCBM) material as a back reflector because the transmittance of our PCBM layer is higher than 80% in the wavelength region over 600 nm.[11] Transmittance of short wavelength region is not important because almost every light in short wavelength region is absorbed by upper side a-Si:H absorbing layers in our tandem solar cells.

In this article, we experimentally investigated the functionality of the PCBM back reflector by analyzing the cell parameters thin film tandem solar cells. We obtained the atomic force microscopy (AFM) images, surface roughness and scanning electron microscopy of the layer. Furthermore, we explained the current–voltage (I–V) characteristics of the PCBM applied micromorph tandem solar cells, as well as their quantum efficiency.

2. EXPERIMENTAL DETAILS

AZO films were deposited on the glasses for the front side transparent electrode using RF magnetron sputtering system. The AZO deposited glasses were used as substrates. Our micromorph tandem solar cells were prepared in a cluster type PECVD system, using power sources with a radiofrequency of 13.56 MHz for p and n chambers, and a very high frequency of 60 MHz for i chamber. The deposition temperature was 180 °C for all overlying films. After the PECVD process, interface treatment is required to minimize series resistance caused by native oxide on n-μc-SiOx:H. Three different interface treatments were tested. First one is organic solvent cleaning to avoid organic contamination using acetone and ethanol with ultrasonic cleaner. After dipping in the organic solvents and DI water, N_2 blowing was done to remove residual liquids. Second approach is HF treatment. After dipping into the 1:250 HF:DI water to remove the contamination and native oxide layer until contact angle changed from hydrophilic to hydrophobic.[14,15] Third method was applying first and second method sequentially. PCBM layers were deposited on the interface treated samples using spin coater with different revolutions per minute (RPM) to make a difference in thickness of layers. Then, silver and aluminum electrodes were deposited in a separate vacuum chamber by a thermal evaporation method. The complete device structure of the micromorph tandem solar cells are glass/ZnO:Al (800 nm)/p-μc-Si:H (10 nm)/p-μc-SiOx:H (20 nm)/i-a-Si:H(350 nm)/n-μc-Si:H (40 nm)/p-μc-Si:H (40 nm)/i-μc-Si:H (3 μm)/n-μc-Si:H (50 nm)/PCBM back reflector/Ag (500 nm)/Al (1 μm). Spectroscopic ellipsometry (VASE®, Woollam, 240 nm < λ < 1700 nm) was used to measure the film's thickness at the incidence angle of 65°, in the spectral range of 240 to 1700 nm. The current voltage (I–V) characteristics of the cells were measured under light intensity of 100 mW/cm^2 (AM1.5) at room temperature of 25 °C. The quantum efficiency (QE) of the micromorph tandem solar cells was measured by using a xenon lamp, monochromator, and optical filters, which filtered out the high orders of a certain wavelength, as the light probe beam impinged normally on the samples.

3. RESULTS AND DISCUSSION

Figure 1 represented a root mean square and average roughness of surface depending on the sequence of PCBM deposition with AFM images. We analyzed the surface roughness before we deposited the PCBM layer on the n-μc-Si:H layer. Extremely high HF ratio could result in surface texturing. Our optimized HF to DI water ratio is 1:250. As shown in the graph, root mean square roughness and average roughness increased from 2.73 to 3.03 nm and from 2.05 to 2.28 nm, respectively. The changes of surface roughness were negligible. By depositing PCBM layers by spin coating method, root mean square roughness and average roughness decreased to 0.65 and 0.47 nm, respectively. Although the quantity was very tiny, within 3 nm, surface flattening effect was observed by AFM results. Thus, the thickness nonuniformity of PCBM was due to the different deposition methods for the inorganic silicon parts and organic PCBM part.

Figure 2 showed LIV results of tandem solar cells with different interface treatment conditions between n-μc-Si:H and PCBM layers and series resistance and shunt resistance of the cells. Comparison between the short circuit current density (Jsc) of reference cell without PCBM layer and PCBM applied cells indicated that the value was increased for all samples. The short circuit current density of reference cell was 9.83 mA/cm^2, whereas the values of the cells treated by organic solvents, HF and both organic solvents and HF were 11.41, 11.25 and 11.58 mA/cm^2, respectively.

When organic solvents are treated, the series resistance was increased from 52.11 to 1907.51 ohm; whereas, the value was decreased to 174.297 ohm with HF alone. Application of both organic solvents and HF resulted in the

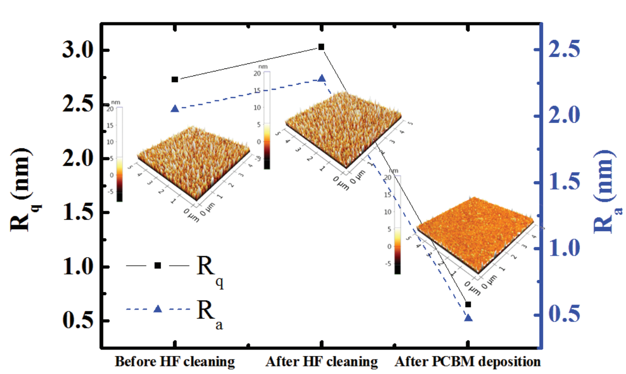

Figure 1. Root mean square and average roughness of surface according to the sequence of PCBM deposition with AFM images.

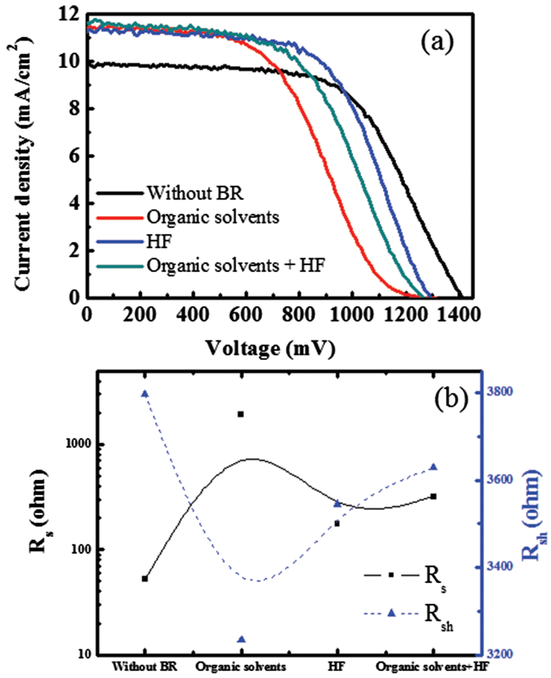

Figure 2. (a) LIV results of tandem solar cells with different interface treatment conditions between n-μc-Si:H and PCBM layers and (b) sheet resistance and shunt resistance of the cells.

series resistance of 318.16 ohm. The scale of series resistance was logarithmic in the graph, whereas the scale of shunt resistance was linear. This suggested no significant variation of shunt resistance. The slopes around y-intercept in the LIV curves appeared almost similar. This result indicated that HF treatment is required before the PCBM deposition. Native oxide between n-μc-Si:H layer and PCBM causes high series resistance.[12] The fill factor of the cell with HF treatment alone showed highest value, 60.84%.

Figure 3 indicated LIV results of tandem solar cells with different spin coating conditions of PCBM layers. Based on the above results, we fixed the interface treatment condition, HF treatment alone. In order to optimize the PCBM back reflector, we changed RPM values of spin coating to optimize the thickness. The fill factors of the samples were almost similar at around 60%. Short circuit current density showed noticeable change. The value was 11.24, 11.19 and 11.70 mA/cm^2 when the PCBM was deposited at 1500, 2500 and 3500 RPM.

Figure 4 showed SEM images of PCBM layers with different spin-coating conditions of PCBM layers. From this magnification of SEM image, we were unable to observe surface morphology because the surface is almost flat, which was also noticed by AFM results. The thicknesses of PCBM layers were 50.6, 48.7 and 32.8 nm when the samples were deposited at 1500, 2500 and 3500 RPM.

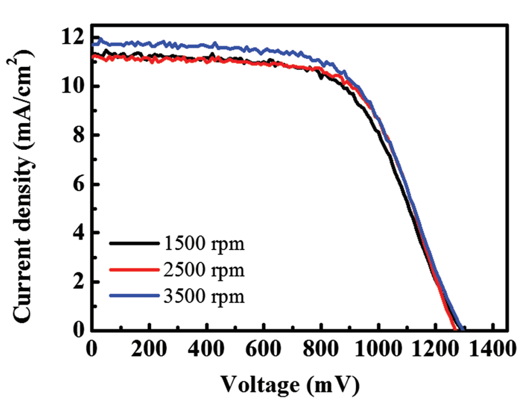

Figure 3. LIV results of tandem solar cells with different spin coating conditions of PCBM layers.

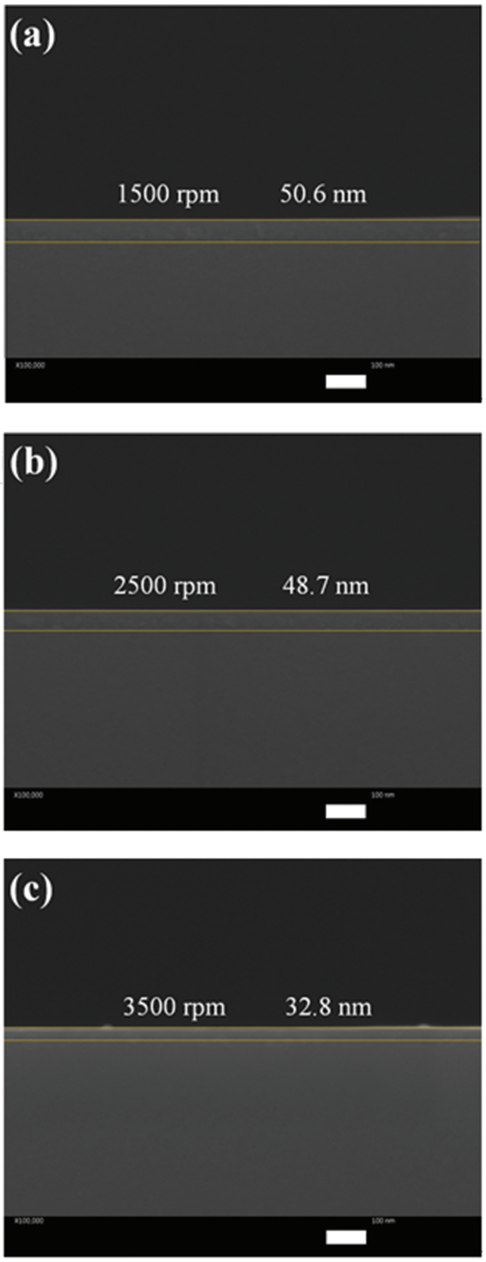

Figure 4. SEM images of PCBM layers with different spin-coating condition (a) 1500, (b) 2500 and (c) 3500 rpm.

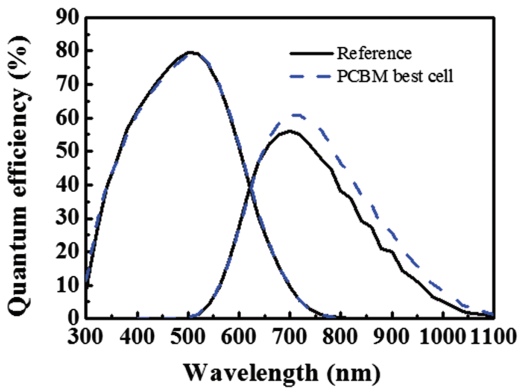

Figure 5. Quantum efficiency of reference and PCBM tandem cells.

The thickness change from 1500 RPM to 2500 RPM samples were only 3.8%, whereas the change of 32.6% was observed between 2500 RPM and 3500 RPM samples.

Quantum efficiency of reference cell and the best PCBM tandem cell was shown in Figure 5. The left curve shows the quantum efficiency of top amorphous silicon cells. The quantum efficiency reaches zero around the wavelength of 750 nm because the bandgap of amorphous silicon is around 1.7 eV. The modification at the rear side of tandem cell rarely affects quantum efficiency of short wavelength region.[13]

The right curve means the quantum efficiency of bottom microcrystalline silicon cells. As discussed earlier, the effective light trapping technology is required to improve the quantum efficiency of bottom cell because of the low absorption capacity in longer wavelength region. By applying the PCBM back reflector, the quantum efficiency of bottom cell increased in the wavelength region from 650 to 1100 nm. The short circuit current density of tandem cell is limited to the lower value among the top and bottom cells. In our case, the quantum efficiency of the top cell was already 11.7 mA/cm^2. The increase of short circuit current density to 1.87 mA/cm^2 were caused by the increased light trapping properties in longer wavelength region.

4. CONCLUSION

We found proper interface treatment condition to apply PCBM back reflector on micromorph tandem solar cells. HF dipping method enhanced the fill factor without introducing the organic solvents like acetone and ethanol. The light trapping property, which can be observed by short circuit current density and quantum efficiency, was improved by applying the PCBM back reflector with optimized thickness. The short circuit current density increased 1.87 mA/cm^2. If we further optimized the electrical properties of PCBM layer, there is a strong possibility of enhancement in terms of fill factor and series resistance of tandem cells.

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