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Surface Passivation Studies on Vertical Junction Silicon Microwire Solar Cells

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Abstract

Silicon microwire solar cells have long promised reducing the optical absorption length in Si and the enhanced photovoltaic activity in thin Si materials but have been limited to less than 10% power conversion efficiencies. Surface recombination loss of photogenerated carriers is one major component for degrading micro and nanowire solar cell performance. Controlling the microwire facets on crystal planes that are known to have low interface state densities may help in reducing surface recombination and recovering the promised performance of microwire solar cells. Here, we studied the solar cell performance in {100} and {110} square microwires and in arbitrary faceted circular microwires with similar surface area. We demonstrate that appropriate surface passivation can enhance microwire solar cell performance to over 10% efficiency. Additional tuning of optical absorption resulted in 12.5% power conversion efficiencies in 10µm long Si microwires, which is the highest reported for this type of thin Si solar cells, and promises excellent potential for powering flexible electronics.

1. Introduction

While solar energy conversion using photovoltaic (PV) technology represents one of the largest emerging businesses in any sector of the economy[1], there is a great demand for light, flexible, and efficient photovoltaic materials for powering wearable devices. Earlier approaches that focused on Si flexible solar cells for terrestrial applications have advanced thin Si stripes at the University of Illinois [2, 3], and the University of Michigan [4] using micromachined slab solar cells that attained ~ 8% power conversion efficiencies. This efficiency approaches the best reported values in thin film Si cells, amorphous Si cells, and nanocrystalline Si cells, all of which perform at ~ 10% efficiency [5].

One crucial concept that can benefit the development of thin Si PV cells for wearable electronics is to utilize an orthogonal light absorption geometry and lateral carrier separation discussed in the context of vertical junction cells [6] and more recently in the context of concentric nanowire p-n junctions [7]. Additionally, out-of-plane vertical structures such as micro and nanowires benefit from diffuse light scattering that can reduce the optical absorption length while maintaining high conversion efficiencies [8]. Cells made of such structures have progressed to deliver ~ 10 % efficiencies [9, 10], A systematic study to determine the limits and further enhance the performance of Si microwire (SiMW) solar cells is yet to be performed. In this study, we examined the influence of surface recombination on SiMW solar cells performance and demonstrated solar cells in excess of 12.5% power conversion efficiencies.

2. Experiments

Our expeirments started with a heavily doped p-type Si substrates (Boron, 2 x 10^{18} cm^{-3}), patterned with photo or e-beam lithography with 2×2 μm^2 Ni arrays as etch masks. SF_6/C_4F_8 composite reactive ion and inductive plasma etch was used to fabricate high aspect-ratio 10 µm tall SiMWs. Pattern orientation was controlled by using a reference wet etch that exposed <110> edges on {111} groves to align the SiMW surfaces parallel to either {100} or {110} planes after etching. Thermal oxidation and striping of the grown oxide layer was utilized to smoothen the surface and proximity doping technique was used for phosphorous diffusion by a rapid thermal annealing process to create a core-shell p-n junctions on a p-type core SiMW. The SiMWs were passivated with combination of a thin (10 nm) thermal oxide layer and 60 nm SiN_x layer followed by electrical isolation through mesa etching. Ti/Au pads were deposited around SiMW arrays for n-type ohmic contacts, while Al was deposited on the back side of the sample as a global p-type contact.

3. Results

Fig. 1. shows 10 µm tall SiMWs with well-defined {100} and {110} sidewall facets and of circular ones. The SEM images show smooth surface after the thermal oxidation and the striping of the grown oxide layer, which was the first step to assist in minimizing surface recombination. Fig. 2. shows the current density-voltage (J-V) characterisitcs measured under AM1.5G illmumination for the SiMWs with different facets. Before passivation, the dark J-V characteristics demonstrated large leakage currents with ideality factors of 2.2 indicating significant recombination in the cell. The non-passivated light J-V characteristics shown in Fig. 2 are therefore poor with power conversion efficiency in the range of 1.8-2.4%. After the thermally grown SiO_2 passivation shell followed by the SiN_x protection, the ideality factor of the cells became 1.01 indicating minimal recombination. As a result, the short circuit current density (J_{SC}), open circuit voltage (V_{OC}), fill factor significantly improved, resulting in overall

improvement in PCE to 10.8-11.6%. This high performance was consistent performance for several tens of devices that suprisingly showed similar performance of {100} and {110} faceted structures with PCE ~10.5-11%. Ciruclar SiMWs with the same surface area as the square SiMWs displayed PCEs ~12-12.5%, as shown in Fig. 3 due to correspondingly larger absorption volume. The absorption was further enhanced by etching small nanowires with diameters of 50-150 nm atop the SiMWs and optimizing the physical fill factor, and the doping of the starting p-type substrate.

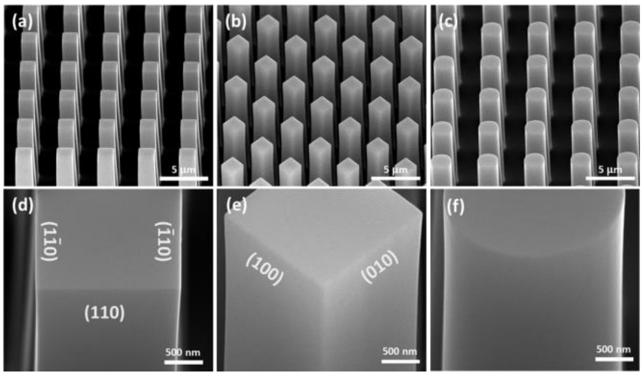

Fig. 1. SEM images (45° view) of SiMWs. (a), (b) and (c) show SiMWs with {110}, {100} and circular faceted side walls, respectively. (c), (d) and (e) are the zoom-in images of a single SiMW of {110}, {100} and circular faceted side walls, respectively, showing smooth surface after thermal oxidation and BOE striping.

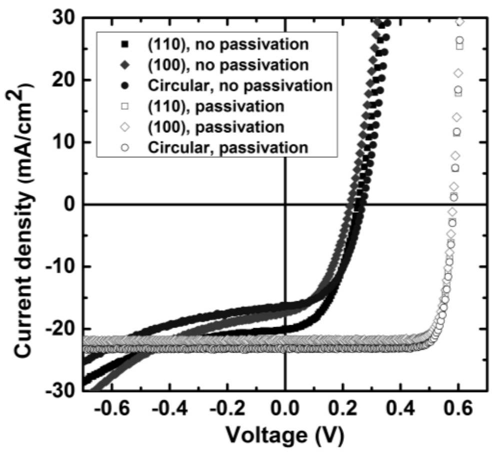

Fig. 2. Light J-V characteristics of SiMW solar cell devices with different facets without passivation layer and SiMW solar cell devices with passivation layer (SiO_2/SiN_x 10/60 nm), measured at AM 1.5 G illumination.

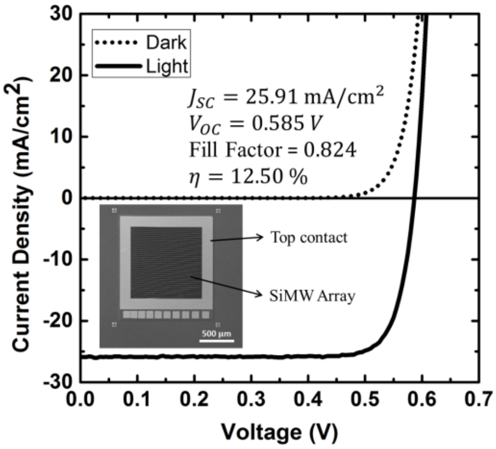

Fig. 3. J-V characteristic of SiMW solar cell device measured at AM 1.5 G illumination indicating V_{OC} = 0.585 V, J_{SC} = 25.91 mA/cm^2, FF = 0.824, and efficiency = 12.50 %. Inset shows a top-view SEM image of a solar cell device with 1 mm^2 SiMW array surrounded by Ti/Au top contact.

4. Conclusions

We carried out systemtic surface passivation studies on various types of 10μm high vertical junction SiMW solar cells that resulted in PCE of > 12 % for the best performing devices. Our results suggest that surface recombination in microwire solar cells can be controlled by having clean and smooth surface of SiMWs and with optimal natural SiO_2 surface passivation. These cells have been implemented on thin flexible layers. We will report on the latest performance metrics in these endeavors and the performance analysis for fully flexible thin microwire solar cells.

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