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ABSTRACT

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Plasmonic Light Trapping in Ultrathin Single Crystal Silicon Membrane for Solar Cells Application

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Abstract — We report the experimental characterization of a promising light trapping scheme, in ultrathin, mechanically flexible, single crystal silicon membranes that included front surface nanotexturization and a back-surface array of plasmonic metallic nanoparticles for solar cell applications. Sub-ten micrometer free standing silicon membranes were produced by the chemical etching of silicon wafers. The produced membranes were observed to be mechanically flexible, yet sufficiently sturdy to tolerate the different processing steps during solar cell fabrication. We studied the plasmonic effects of different metallic nanoparticles for optical absorption enhancement on the nanotexturized ultrathin silicon membranes by incorporating them on the back surface of the samples. A promising short circuit current density as high as 36.43 mA/cm$^2$ was calculated from the measured optical absorption spectra in a 7.85 µm thick single crystal silicon membrane with front surface nanotexturization along with a back surface array of random mixture of gold and silver nanoparticles. The extracted current density value compares favorably well with the value of 15.68 mA/cm$^2$ associated with a flat silicon membrane of the same thickness. The described light trapping scheme may enable the possibility for demonstrating high-efficiency, mechanically flexible photovoltaic devices in the near future.

Index Terms — light trapping, plasmonics, antireflection coating, flexible photovoltaic, silicon nanowires

I. INTRODUCTION

Single crystal silicon (c-Si) solar cells, because of their relatively high power conversion efficiencies (PCE) and mature fabrication processes have dominated in the photovoltaic (PV) industry. Commercially available c-Si solar cells typically employ active silicon samples with a thickness ~180-300 µm. Such a relatively thick Si wafer is required to absorb most of the solar spectrum due to its indirect band gap. However, such a thickness also accounts for almost forty percent of the total solar cell fabrication cost. One way to reduce the cost associated with c-Si solar cells is to use less material as in ultrathin samples. Thus, in recent years, there has been a considerable interest in utilizing thinner c-Si film in novel solar cells design architectures to produce high efficiency PV devices. Unfortunately, ultrathin Si membranes suffer from relatively large transmission losses especially in the long wavelength region. Therefore, advanced light trapping is inevitable to achieve a reasonably good optical absorption in thin film c-Si solar cells. Sub-wavelength nanotexturization in the thin active layer of a solar cell can be instrumental for achieving higher photon absorption due to its broadband antireflection effects [1], [2]. Furthermore, plasmonic metal nanostructures could be employed for light trapping purposes in thin film c-Si solar cells due to strong light-matter interactions. This can lead to the preferential scattering of the incident light into the semiconductor surface over an increased angular range, thereby enhancing the optical path length [3]. Metallic NPs interact strongly with electromagnetic radiation due to the presence of localized surface Plasmon (LSPs), which are collective oscillations of free electrons on the metal surface. The spectral response of metallic NPs has been reported to be greatly dependent on many physical factors. Furthermore, the size, shape, and the dielectric functions of the metallic NPs and their surrounding media can be used to tune the plasmonic resonance at the desired wavelength range. There are various methods to fabricate metallic nanoparticles to satisfy targeted shape and size to be employed on the surface of solar cells. One such method is the self-assembly of chemically synthesized metallic NPs. Chemical synthesis is usually considered a cost-effective route over a variety of processes including photolithographic techniques. In this letter, we report the experimental observations of a novel light trapping approach compatible with ultrathin c-Si membranes with a thickness of less than ten micrometers. The scheme relies on the synergistic effect of front surface SiNW texturization in combination with plasmonic metallic NPs on the back surface. A schematic depicting the proposed light trapping scheme in ultrathin silicon membranes is shown in Figure 1a. We fabricate different metallic NPs by the chemical synthesis method, and their effects on the plasmonic light trapping were studied by measuring the absorption performance.

II. EXPERIMENTAL DETAILS

The vertically aligned SiNW arrays were fabricated on ultrathin silicon membranes, employing room temperature, metal assisted electroless chemical etching (MACE) methods. Sub-ten micrometers free-standing flexible silicon membranes were produced by the chemical etching of double side polished Si (100) wafers in a KOH solution with a concentration of 50 wt% at 90°C. Figure 1b is the optical image of a free-standing silicon membrane of thickness 7.85 µm with back surface light illumination. The wavelength of light corresponding to the
results and discussion

Fig. 2 includes SEM micrographs of (a) spherical Au NPs, (b) spherical Ag NPs, and (c) Au NRs, respectively. The average particles size for Au and Ag NPs were 85 and 90 nm, respectively, while the average size of the Au NRs was 50 nm in length and 16 nm in diameter. The produced NPs were embedded on the back surface of the fabricated ultrathin c-Si film having front surface SiNW array texturization. Figure 3a shows a cross-section view of the random SiNW array fabricated on an ultrathin c-Si membrane 7.85 µm thick. The self-assembled Ag NPs embedded in 40 nm ALD deposited aluminum oxide (Al2O3) on the back surface of the SiNW array texturized ultrathin silicon membrane is shown in Figure 3b. The inset in the lower left corner shows a higher magnification image of the embedded Ag NPs, while the inset on the upper right corner shows the random distribution of Au NPs on the back surface of the ultrathin silicon sample. The surface coverage of all the metal NPs were ~7-8%, as observed in the SEM micrographs. We measured the light trapping performance of the described devices having front surface SiNW array texturization and plasmonic metallic NPs on the back surface. The absorption spectra were calculated from the measured reflection and transmission spectra using the relation, A = 100 - (R + T). The transmission and reflection spectra were measured by using a UV-VIS Varian Cary-5000 spectrometer equipped with integrating sphere. The front surface silicon nanowire array texturization exhibits an excellent broadband antireflection effect. The reflectivity of the SiNW array texturized sample (green curve in Figure 4a) is well below planar reference sample that had no texturization (red curve in Figure 4a). We maintained the length of the SiNWs fixed at 2.31 µm during this experimental exercise.
Photon transmission was greatly reduced by the utilization of a front surface SiNW array texturization due to light trapping effects (green curve in Figure 4b). The transmittance was further suppressed by the incorporation of metallic NPs. This can be attributed to be due to the plasmonic back scattering of photons into the higher index Si thin membrane. The presence of Au NRs was found to be more effective (brown curve in Figure 4b) compared to the spherically shaped Au or Ag NPs. This is due to the broad plasmonic resonance of Au NRs in the long wavelength region. However, a random mixture of Au and Ag NPs on the back surface of SiNWs was even more effective than Au NRs to suppress the transmittance of the sample.

Fig. 4. (a) The reflectivity of planar (flat surface) and SiNW array texturized c-Si thin membrane 7.85 µm thick. (b) Comparison of transmission spectra for different geometries of the described devices.

Fig. 5. (a) Comparison of the absorption spectra of Si thin membranes with flat surface, front SiNW array texturized surface, and front SiNW array texturized surface with back surface plasmonic metallic NPs, respectively. (b) The computed short circuit current density for different topographies of the described device are shown in Figure 5b. The computed value of $J_{SC}$ increases from 15.68 mA/cm$^2$ to 35.21 mA/cm$^2$ due to the presence of the front surface SiNW array texturization. The incorporation of metallic NPs on the back surface further improves the value of $J_{SC}$. Specifically, the values of $J_{SC}$ of 35.41 mA/cm$^2$, 35.80 mA/cm$^2$, and 36.22 mA/cm$^2$ respectively, were obtained for random distributions of Au NPs, Ag NPs and Au NRs. A maximum value of $J_{SC}$ of 36.43 mA/cm$^2$ was computed for the device with a front surface SiNW array texturization in combination with a random mixture of Au and Ag NPs on the back surface, which is ~133% higher compared to flat samples (with no texturization thin Si membrane) of the same thickness.

IV. CONCLUSIONS

In conclusion, we report a promising light trapping scheme on free-standing, mechanically flexible, ultrathin c-Si membranes for solar cell applications. Large area ultrathin c-Si membranes were produced by the KOH etching of Si wafers. The light trapping scheme described herein comprises a front surface SiNW array texturization in combination with a metallic NP array on the back surface. The effect of plasmonic back scattering due to different metallic NPs located on the back surface of an ultrathin Si membrane were studied. A maximum value of $J_{SC}$ of 36.43 mA/cm$^2$ was calculated for a sample that included a front surface SiNW array texturization and a random mixture of Au and Ag NPs as plasmonic back scattering sources in the back surface. This value is 133% higher compared to that calculated for a flat c-Si membrane of the same thickness. The light trapping method described herein could enable the demonstration of high efficiency, ultrathin, mechanically flexible photovoltaic devices in the near future.

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REFERENCES

