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Programmable Three-Dimensional Nanophotonic Structures for Thin-film Photovoltaic Applications

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Efficient light absorption is crucial for enhancing the performance of thin-film photovoltaic (PV) devices, which requires both broadband antireflection coatings and efficient light trapping techniques. Properly engineered three-dimensional (3-D) nanophotonic structures have demonstrated highly promising capability of harvesting sunlight over a broad range of wavelengths and incident angles. In particular, arrays of a variety of 3-D nanophotonic structures, such as nanowires, nanopillars (NPLs), nanowells (NWLs), nanocones, nanopyramids, nanospheres, and so forth, have been extensively studied for light trapping and solar energy conversion with photonic materials including Si, Ge, CdS, and Cu(In, Ga)Se (CIGS), *etc.* By rational integration of these 3-D nanostructures, photons can be trapped efficiently within the thin-film absorber layer, consequently improving light absorption and thus conversion efficiencies. Additionally, enhanced absorption efficiency leads to utilization of thinner absorber layer, which improves carrier collection, as well as reduces production costs and environmental concern for solar cells made of rare materials, *e. g.* CIGS, and environmentally unfriendly material. *e. g.* CdTe. These results shed light on light trapping mechanism in complex 3-D nanophotonic structures for thin-film photovoltaics.

Our previous work demonstrated that a properly designed 3-D NWL array fabricated by a low-cost and scalable approach can serve as an efficient photon harvester confirmed by both experiments and simulations systematically.[1, 2] In this work, it was found that highly regular NPL arrays can be fabricated with precisely controlled wet chemical etching after obtaining 3-D NWL arrays. In addition, a unique integrated-NPL-NWL (i-NPW) structure has been successfully realized by carefully designing and controlling the wet etching and anodization processes.[3] Systematic optical property investigations on the obtained 3-D structures have been performed experimentally assisted with optical simulations. It was found that NWL arrays with cylindrical cavities provide efficient geometric confinement for normal incident incoming photons naturally, while NPL arrays with small diameter tips lead to a broadband suppression of reflectance with superior angular absorption performance. Therefore, a rationally vertical integration of the two types of 3-D nanostructures, *i. e.* i-NPW, leads to much improved photon harvesting property over large wavelength and incident angle range. Impressively, the 2 μ m thick i-NPW arrays with only 40 nm a-Si coating obtained a day-integrated absorption of 89.27%, as opposed to only 33.45% for the planar control sample. Moreover, nanocone structure has been achieved due to the capability of programmable structural design and fabrication. It is noteworthy that the nanocone structure is a highly promising structure for efficient light harvesting, due to the gradually changed effective refractive index, thus it has been widely demonstrated as an excellent candidate for improving performance of solar cells. Furthermore, thin-film solar cells have been fabricated based on the nanocone structures, which show distinct enhanced energy conversion efficiency compared to that based on planar structures.

REFERENCES AND NOTES

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