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RAPID COMMUNICATION

Tandem structured spectrally selective coating layer of copper oxide nanowires combined with cobalt oxide nanoparticles

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Abstract
Increasing the light absorption across the wide solar spectrum has important implications for applications in solar-thermal and photovoltaic energy conversion. Here, we report novel tandem structures combing two different materials with complementary optical properties and microstructures: copper oxide (CuO) nanowires (NWs) and cobalt oxide (Co_3O_4) nanoparticles (NPs). Copper oxide NWs of 100–200 nm in diameter and 5 μm long are grown thermally on copper foil in air and cobalt oxide NPs of 100–200 nm in diameter are synthesized hydrothermally. Tandem structures of spectrally selective coating (SSC) layer are built with three different methods: spray-coating, dip-coating of cobalt oxide NPs into copper oxide NWs forest, and transferring of copper oxide NWs layer onto cobalt oxide NPs layer. The tandem-structured SSC layers fabricated from the spray-coating, dip-coating and transferring methods exhibit figure of merit (FOM) values of 0.875, 0.892 and 0.886, respectively, which are significantly higher than that of the starting copper oxide NWs (FOM=0.858) and cobalt oxide NPs

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(FOM=0.853). Our results demonstrate the efficacy of using novel tandem structures for enhanced light absorption of solar spectrum, which will find broad applications in solar energy conversion.

Introduction

The Earth receives an enormous amount of incoming solar radiation generated by fusion reaction in the sun, which is expected to remain stable for the next 4 billion years [1,2]. Therefore, solar energy is the most plentiful resource for energy supply. Photovoltaic (PV) solar cells, concentrating solar power (CSP) systems, solar thermoelectric generators as well as photoelectrochemical water splitting systems harvest solar energy for electricity or fuel [3-8].

CSP system uses heliostat mirror arrays to concentrate sunlight to the spectrally selective coating (SSC) layer on the solar receiver structure (such as a corrosion-resistant Inconel alloy tube) to heat up a heat transfer fluid inside (e.g., a molten salt), which is then transported to create high-pressure steam and utilized to drive a steam-turbine-type heat engine to generate electricity. The CSP system is already commercialized with a multi-gigawatt level power generations, with a fast industrial growth in progress, especially with a recent recognition of CSP's advantage of potentially inexpensive energy storage (e.g., by using molten salt reservoir), which can be quite useful and beneficial for control of energy distribution in energy grid systems [4].

Among many approaches to increase the efficiency of solar-based energy conversion devices, nanowire (NW) structures have been used for enhanced light absorption and charge separation, such as demonstrated in Si micro-nanowires for PV solar cells [9–12] and copper oxide NWs for photoelectrochemical water splitting systems [13,14]. For CSP type solar thermal applications, Si NWs are not suitable because the band gap of Si (1.12 eV at 300 K [15]) is not sufficiently low to absorb near-infrared (IR) sunlight spectrum and pure Si can be easily oxidized when exposed to air at high temperature. For instance, ~45 nm of silicon oxide will grow on Si when it is annealed at 700 °C for 100 h under dry oxygen atmosphere [16] and Si nanoparticle has been reported to increase its weight by ~15 wt% through the oxidation at 750 °C for 2 h in dry oxygen [17]. In this regard, copper oxide (CuO) is a better candidate material because it is already oxidized into a stable oxide form and should be resistant to oxidation in air. For highly efficient CSP system, it is desirable that the SSC layers absorb as much sunlight as possible with high absorption and low sunlight reflectivity in the visible and near-IR spectrum range and have high reflection in the spectrum range longer than near-IR to obtain low thermal emission. The wavelength regime of interest for CSP solar energy absorption includes the visible spectrum range (<~700 nm) and near IR spectrum range (~700 nm to 1.6 um). Based on our measurements, copper oxide NWs exhibit relatively high sunlight reflection characteristics in near-IR spectrum, even though the reflection in visible spectrum is quite low. Copper oxide (CuO) has been reported to have band gap of 1.2–1.4 eV which corresponds to the absorption from the wavelength of 890–1030 nm [18,19]. This optical property of CuO results in high reflectance of near-IR spectrum longer than 890–1030 nm. Therefore, it is necessary to combine another near-IR absorbing material layer with copper oxide NWs structure, which could then enable efficient sunlight absorption over a broader spectrum range.

As a desirable material to absorb near-IR spectrum, semiconducting metal oxides with small band gap can be utilized. For example, one phase of cobalt oxide, Co_3O_4, has absorption bands at several spectrum ranges including 0.82–0.85 eV (~1500 nm), 0.93–1.03 eV (1340–1200 nm), 1.5–2.07 eV (850–700 nm) and 1.88–3.1 eV (660–400 nm) [20–24] which means Co_3O_4 can become a candidate to increase the absorption of near-IR spectrum when combined with copper oxide NWs structure. We have introduced a hybrid structure containing both Co_3O_4 and Cu oxide NWs so as to broaden

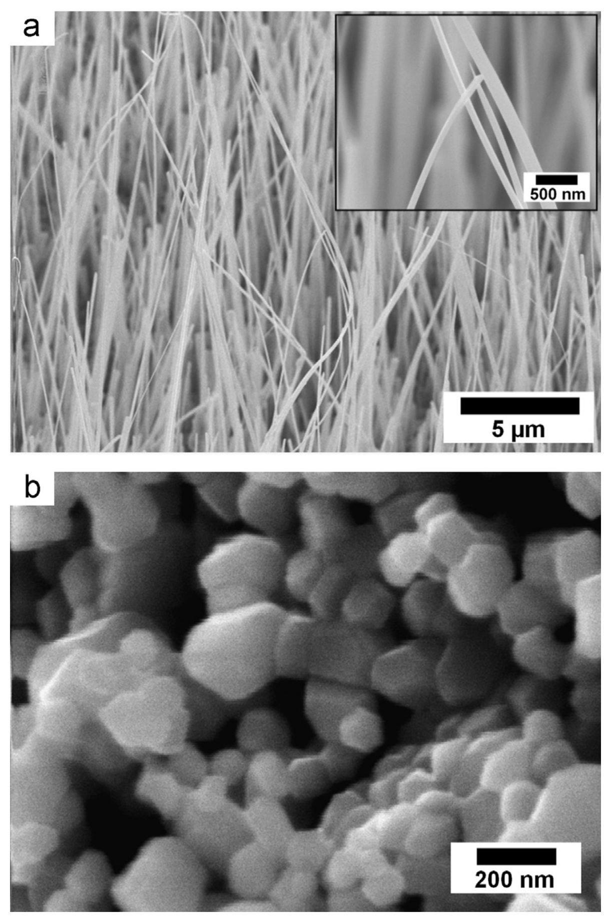

Figure 1 SEM images observed for (a) copper oxide NWs longer than 5 μm with a diameter of 100–200 nm and (b) cobalt oxide NPs having mainly 100–200 nm in particle size.