Zinc oxide nanoparticles as luminescent down-shifting layer for solar cells

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The efficiency of commercial solar cells can be significantly improved by using an energy down-shifting material on their front surfaces.

The manufacturing of photovoltaic (PV) devices has developed considerably in recent decades, spurred by continuous growth in the demand for renewable energy sources. About 90% of currently fabricated solar arrays are made of crystalline silicon (Si). Considerable research effort has been applied to increasing the efficiency of Si PV devices. However, the spectral response of a Si PV device does not match the solar emission spectrum owing to the limited absorption of the Si constituting the PV solar cell active layer (see Figure 1). A single-junction Si solar cell is transparent to photons with energies below the bandgap energy, and additional sunlight is lost because of thermalization induced by higher-energy (UV) photons. This is the origin of the largest proportion of losses in commercially available Si solar cells. One way to increase solar cell efficiency is to transform the solar emission spectrum so that it overlaps better with the Si absorption spectrum.

Up-conversion and down-conversion techniques are among those used to convert the incident solar light into a spectrum that matches the absorption of the active layer in solar cells. Up-conversion permits the conversion of IR light to visible light by simultaneous absorption of two photons. This is a nonlinear process, so the probability of such a transition is quite low. In down-conversion, one photon with higher energy (UV or blue) can be converted into two identical photons of equal energy, two times lower than the initial one. This concept is interesting but limited, as it requires the existence of an intermediate energy level exactly in the middle of the bandgap of the down-converting material.

Our research focuses on the down-shifting technique. Like down-conversion, down-shifting also permits the conversion of high-energy photons into one or more lower-energy ones, contributing to the generation of additional electron-hole pairs and thus to a potential increase in the overall solar cell efficiency. It also involves fewer constraints than down-conversion because it does not require the presence of an intermediate energy level in the bandgap. Figure 2 illustrates the principle of the down-shifting process.

Efficient down-shifting requires materials that are absorbent in the UV. Therefore, we chose zinc oxide (ZnO) for its wide bandgap (3.37eV at room temperature), larger absorption coefficient compared to other wide bandgap materials such as gallium nitride, low cost, abundance, good chemical stability, and non-toxicity. Because Si solar cells have the best spectral response in the green-red spectral range, our idea is to enhance the luminescence of the ZnO nanoparticles (NPs) in this spectral domain, to the detriment of their UV excitonic emission, and apply them as a down-shifting layer optically coupled to the front surface of a Si solar cell. This enhancement of the green-red

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luminescent emission can be achieved by deliberate introduction of oxygen defects in the NPs’ crystal structure, making them non-stoichiometric.\textsuperscript{6}

ZnO NPs are fabricated using low-energy cluster beam deposition (LECBD). The LECBD experimental setup is schematically illustrated in Figure 3. Using this method, plasma containing Zn and O species generated by laser ablation of a stoichiometric ZnO target undergoes a supersonic adiabatic expansion while moving from the nucleation chamber to the high-vacuum deposition chamber through a micrometric nozzle. The obtained NPs can be deposited on any given substrate without being destroyed because their kinetic energy per atom is about one order of magnitude lower than the binding energy per atom within the clusters. Most importantly, the stoichiometry of the ZnO NPs can be manipulated by controlling the oxygen pressure in the nucleation chamber so as to enhance their green-red emission intensity.\textsuperscript{6} Photoluminescence and excited photoluminescence measurements of the ZnO NP layers permit us to evaluate their down-shifting potential.

Next, the ZnO NPs are deposited on the front side of the Si photosensitive devices. Figure 4 shows the structure of the resulting Si solar cell. The NPs’ external quantum efficiency (EQE) is then measured to check whether the expected increase is observed. Figure 5 shows the UV-blue spectral zone, demonstrating that although the EQE of the Si photosensitive device increased, the overall EQE of the device decreased. Thus, the layer thickness and morphology of the ZnO NP layer must be optimized to maximize the global EQE.

To prevent deterioration of the ZnO NPs after their exposure to air and humidity over long periods of time and to ensure their good mechanical stability and adherence to the solar cell surface, a host matrix must be present. However, it was reported that some host matrices quench the luminescence emission of

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the NPs. An exhaustive study of the influence of various matrices on the efficiency of down-shifting in ZnO NPs is ongoing.

The limits of the efficiency of PV devices can be surpassed if we apply new concepts of solar emission spectrum management for better overlap with solar cell active layer absorption. The efficiency of PV cells can be improved though the down-shifting effect using ZnO NPs mechanically and optically coupled to the front side of a Si solar cell. We believe this is one of the most promising concepts for the improvement of the overall EQE of existing and commercially available Si PV devices. We are considering other methods of down-shifting layer deposition on large-area solar cells so that a potential transfer to industry in the future is possible.

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References