Nanostructured Materials for High-Efficiency Thin Film Solar Cells

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Objective
This research aims at developing a proof-of-concept, solution-processable multijunction solar cell using nanostructured materials as building blocks for both the active layers and the transparent electrode contacts. The application of low-cost processing techniques to the fabrication of high-efficiency multijunction cells could result in a novel thin-film technology with comparable or lower cost but energy-conversion efficiency substantially higher than existing single-junction devices.

Background
Multijunction photovoltaics can achieve extremely high solar-energy-conversion efficiency compared to single-junction solar cells by reducing the thermodynamic losses associated with the absorption of photons with energy larger than the bandgap of the active layers thereby making a more efficient use of the whole solar spectrum. Triple-junction cells have theoretical efficiencies close to 50% and to date, III-V-based triple-junction laboratory cells have reached record efficiencies exceeding 40%. Although high efficiency is beneficial in decreasing the cost of solar energy conversion, the impact of this technology on the energy market might be hampered to some degree by the elevated fabrication costs due to the low-rate and high-vacuum deposition processes used to grow high-purity bulk semiconductor crystals.

The present research addresses this limitation by proposing a multijunction device concept where all layers can be sequentially deposited using solution-based processing techniques. The resulting structure would thus be free of complex lattice-matching requirements and compatible with low-cost and large-volume roll-to-roll fabrication technologies. Colloidal nanocrystals and nanowires are the material of choice for this application. Optical and electric properties of

Figure 1: Diagram of the proposed multijunction thin-film (<1μm thick) photovoltaic. Individual cells are separated by thin transparent contact junctions for lateral photocurrent extraction.
nanocrystalline semiconductors can be tuned by choosing the right composition and size to match the requirements of all subcells in the multijunction. Metal or metal-oxide nanowires can be used to build highly conductive transparent electrodes to be inserted between each subcell. This design allows the lateral extraction of the photocurrent at each junction (see Figure 1), thereby making each sub-cell independent and decoupled from the underlying structure. The current matching requirement of series-connected multijunctions is thus eliminated and the subcells can be deposited and optimized independently.

**Approach**

A variety of colloidal semiconductor nanocrystals will be investigated to build the active layers of the proposed multijunction device. This work is based on recent advances in nanoparticle-based single-junction cells showing that charge separation in nanocrystal solar cells is not driven by the presence of a built-in electric field as in the case of conventional thin films but rather requires — similarly to organic photovoltaics — a donor-acceptor heterojunction where charge separation results from charge diffusion directed by different energy levels across the junction. Therefore, each cell consists of a nanocrystal bilayer — forming the heterojunction — with bandgap and energy levels that must be carefully engineered for each separate cell by controlling quantum-confinement effects and material composition. Individual cells are separated by highly conductive transparent electrodes that serve as electric junctions and allow for lateral charge extraction. This parallel connection design implies that the total photocurrent results from the addition of the current produced by the individual cells so that they can be optimized independently since no current matching is required.

![Figure 2](image.png)

**Figure 2:** (a) Sheet resistance and transmittivity of ideal metal gratings, ITO, and silver nanowire meshes; Scanning Electron Microscope micrograph of a ZnO nanowire mesh.

Metal and highly doped metal-oxide nanowires will be studied to develop transparent electrodes amenable to solution-processing and compatible to large-area fabrication. Preliminary results illustrated in Figure 2a show that solution-synthesized silver nanowire meshes can compete with traditional ITO (Indium-Tin-Oxide) electrodes. Optical and electrical network models will be used to explore the limits of optical transmission and sheet resistance of random nanowire meshes and to optimize the wire coverage and aspect ratio. Highly-doped ZnO (zinc oxide) films as shown in Figure 2b also have the potential to outperform the state-of-the-art ITO, but deposition techniques compatible with roll-to-roll manufacturing have still to be developed. Non-aqueous synthesis and doping processes will be investigated and optimized to control the morphology and aspect ratio of the nanowires. Finally, various techniques will be explored to further enhance the conductivity of both the metal and metal oxide-based films by aligning the nanowires during processing. All layers of the multijunction are deposited sequentially and independently. Spin-coating deposition will be used in the initial phase of the project to optimize the design of the device and the material combinations. Subsequently, screen printing deposition and other processes amenable to large-area manufacturing will also be investigated. In order to optimize the design of the multijunction and all processing parameters (layer number, thickness, and morphology, band-edges and work-function position), a comprehensive simulation tool will be developed to study a variety of fabrication and operation conditions.