Recent advancements in nanopillar arrays lead to more cost-effective photovoltaics.

Cost-effective photovoltaic (PV) technologies are the key for large-scale deployment of solar cells capable of producing clean energy. Although conventional planar crystalline PV cells can provide good efficiencies, they are not viable for large-scale deployment because of relatively high costs. On the other hand, inorganic and organic thin-film semiconductor-based PV cells have low material and fabrication cost, but their large-scale performance is poor.

Nanostructured materials grown with low-cost, bottom-up approaches usually have crystalline nature and, therefore, are promising candidates to achieve cost-effective PV cells. In addition, ordered nanostructures have demonstrated intriguing optical and electrical properties favoring photon broadband absorption and photocarrier collection. This suggests a potential route towards next-generation, high-efficiency PV devices. There has been extensive research into using nanostructured materials,1, 2 such as silicon and gallium arsenide nanowires. Although these materials have been widely used for high-efficiency planar solar cells, they have high surface-recombination velocities and, thus, are not ideal materials for nanostructured PV cells.

We have developed a promising solar-cell module based on vertically oriented and spatially ordered cadmium sulfide (CdS) nanowires, or nanopillars (NPLs), embedded in a cadmium telluride (CdTe) thin film. The CdS/CdTe combination has relatively low surface-recombination velocity and so is ideal for taking advantage of the high surface/junction area to promote carrier-collection efficiency. Significantly, we have also achieved template-assisted growth of highly ordered NPL arrays on aluminum foil, avoiding costly epitaxial growth.

The advantages of using NPL arrays for solar-energy collection are both optical and electrical in nature. As light passes through a 3D solar-cell structure, such as our NPL array, scattering increases the effective path length, thus increasing the absorption for a given device thickness. Further, the NPL structure presents a graded refractive index to the incident light relative to the abrupt interfaces of a planar cell, effectively suppressing reflection. Electrically, the NPL structure decouples the light-absorption and carrier-collection directions. Thus, cells with thickness well matched to the absorption coefficient and NPL pitch well matched to minority-carrier diffusion length can be engineered. To leverage these advantages, we developed a process that allows for control of the geometric parameters of the NPL array, including NPL diameter, pitch, length, and shape. In so doing, we can optimize for solar efficiency.

The fabrication process is set out in Figure 1. It begins with aluminum foil. After an electropolishing step to reduce surface roughness, the samples are anodized, resulting in the formation of an anodized alumina membrane. Anodization is an electrochemical process by which the samples are oxidized, producing a porous aluminum oxide film. Control of process conditions such as voltage, bath chemistry, and temperature produces vertically oriented and highly ordered arrays of pores ideal for templated NPL growth. Following anodization we
employ a series of etching steps to achieve the desired pore geometry. We next electrodeposit gold at the bottom of each pore to serve as catalyst for NPL growth. The latter proceeds through the vapor-liquid-solid process. The desired length of the NPLs is exposed by selectively etching the oxide template after growth. We form the pn junction, necessary for photogenerated charge separation, by depositing a light-absorbing film over the exposed NPLs. Our devices have been fabricated with n-CdS NPLs and p-CdTe film, although it should be noted that the process could also be used for other material systems. Finally, we deposit a top contact onto the film, with the aluminum substrate serving as back contact.

We demonstrated the mechanical flexibility of these solar cells by transferring the device to a flexible polydimethylsiloxane substrate and etching away the original aluminum foil (see Figure 2). A thin film of indium is deposited onto the back of the devices to replace the aluminum as the electrical back contact. Efficiencies observed versus bending radius show negligible degradation down to small radii.

A plot of the electrical characteristics measured under solar-spectrum intensities increasing from dark to 100 mW/cm$^2$ (AM1.5G) is shown in Figure 3. Devices under AM1.5G illumination exhibited an open-circuit voltage of 0.62 V, short-circuit current of 21 mA/cm$^2$, and a fill factor of 0.43, resulting in an efficiency of ~6%. These results represent a significant improvement over previously reported nanostructured solar cells. The 6% efficiency was obtained for first-generation devices without significant optimization. We expect that dramatic efficiency gains can be realized by optimizing the device contacts, materials, and geometry. Most notably, the devices were fabricated with a copper/gold top contact that was not fully transparent. Integration of a transparent conductor top contact (such as indium tin oxide) will immediately improve efficiencies.

Current photovoltaic technologies have yet to achieve the necessary combination of high efficiency and low system cost to enable economic competitiveness and widespread adoption. Significant work has been invested in the promise of nanowire-based solar cells. However, further effort is needed to achieve our goals. We have contributed to this effort by developing solar cells based on vertically aligned and spatially ordered semiconductor NPLs. These devices offer considerable advantages in

*Figure 3. Electrical characteristics of a CdS/CdTe NPL/thin-film hybrid solar cell measured for varying incident intensities of solar-spectrum radiation. J: Current per unit area. (Adapted with permission.)*
light absorption, carrier collection, and geometry control. Further, all fabrication steps are compatible with low-cost, high-throughput roll-to-roll manufacturing on inexpensive, flexible substrates. We are currently working on two major research efforts to further this technology. First, we seek to expand the portfolio of materials that can be successfully integrated into the structure. Second, we are actively optimizing the device parameters for the CdS/CdTe material system to achieve higher efficiencies.

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References