Building radial junction thin-film solar cells on silicon nanowires

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Mature silicon thin-film deposition techniques combined with advanced radial junction designs could yield a new generation of photovoltaics that compete on cost with national power grid infrastructures.

Radial junction thin-film solar cells grown over silicon nanowires (SiNWs) offer an opportunity to decouple the path of light absorption and carrier separation. Silicon thin-film deposition is an industrially proven and environmentally friendly technology that has the potential to deliver terawatt-scale solar energy without presenting a material availability issue. Combining advanced radial junction designs with mature Si thin-film deposition techniques could lead to a new generation of photovoltaics capable of bridging the gap toward grid parity.

One critical challenge is to grow the SiNWs using a standard industrial technique: ideally, using plasma-enhanced chemical vapor deposition (PECVD) systems, on low-cost heterogeneous substrates, and at low process temperatures. High throughputs of SiNWs can be produced on top of inexpensive glass or metal surfaces via a metal-nanoparticle-catalyzed vapor-liquid-solid method. However contamination from the metal catalyst during growth can reduce carrier lifetime in the material. Commonly used gold (Au) catalysts are known to cause mid-gap recombination centers. As a consequence, Au-catalyzed SiNWs require ex situ high-temperature oxidation and chemical cleaning steps before being incorporated into photovoltaic devices. Prototype solar cells built on untreated Au-catalyzed SiNWs have so far suffered from low $V_{oc}$ (<0.3V) and poor fill factors. To address this issue, we have been working on a group of low-melting-point alternative catalysts, including indium, tin, and gallium to catalyze SiNW growth in a PECVD system on low-cost substrates.1–5 Besides the immediate benefit of achieving growth at temperatures as low as $240\degree C$, these catalysts introduce shallow levels in the c-Si (crystalline silicon) bandgap and show evidence of removal from the SiNWs by in situ hydrogen plasma treatment.4–7

To incorporate SiNWs into Si thin films deposited by PECVD, we have established an in situ catalyst formation control to tailor the density and size distribution of the SiNWs. Catalyst drops several tens of nanometers wide can be formed by hydrogen plasma treatment of a ZnO/Al (zinc oxide/aluminum)-glass substrate coated with a thin ITO (indium tin oxide) or SnO$_2$ (tin oxide) layer: see Figure 1(a). The distribution, density, and size dispersion of the catalyst particles can be controlled by appropriate plasma conditions: see Figure 1(c). This control allows us to engineer the SiNW arrangements and achieve the best trade-off between light trapping and uniform coverage.

We have also made SiNWs by a vapor-liquid-solid method mediated by low-melting-point/low-surface-tension catalysts. Having investigated their growth mechanism, we resolved the paradox concerning the growth stability of SiNWs mediated by the low-surface-energy catalyst.6,7 As shown in Figure 1(b), the growth of p-type SiNWs can be triggered by introducing a mixture of H$_2$ (hydrogen gas), SiH$_4$ (silicon hydride gas), and trimethylboron at 240–500$\degree$C. After the SiNW growth, the catalyst drops can be removed in a H$_2$ plasma environment, as

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**Figure 1.** (a and b): Plasma-assisted in situ catalyst formation and vapor-liquid-solid (VLS) silicon nanowire (SiNW) growth mechanism in a standard plasma-enhanced chemical vapor deposition reactor. (c) Scanning electron microscope (SEM) images of indium catalyst drops formed on top of zinc oxide (ZnO)/aluminum-coated glass at various temperatures during a hydrogen plasma process, and of SiNWs.$^8$ PECVD: Plasma-enhanced chemical vapor deposition.
observed in the scanning electron microscope (SEM) images presented in Figure 1(c).

We then carried out a systematic and broad parametric study on the construction of radial junction a-Si:H (amorphous silicon hydride) thin-film cells over the SiNWs, and explored the impact of doping, length, density of the SiNWs, and the absorber thickness on the performance of our devices.\(^8\)–\(^12\) Figure 2(a) and (b) shows a schematic illustration and SEM image of a complete a-Si:H radial junction p-i-n SiNW solar cell. The final fabrication step is an ITO contact layer (~120nm thick) on the top of the junctions that makes it possible to shed light through the cell surface. Figure 2(c) shows a photograph of the SiNW radial junction solar cell on a \(5 \times 5\) cm\(^2\) substrate (with a 40nm-thick i-layer). Based on the effective density control in catalyst formation, we are able to fabricate solar cells with SiNW density ranging from \(2.3 \times 10^7\) /cm\(^2\) to \(6.3 \times 10^8\) /cm\(^2\)—see Figure 3(a–c)—and evaluate the direct impact of nanowire density on the density-voltage characteristics and external quantum efficiency spectrum of the devices. Recent advances on Sn-catalyzed SiNW solar cells have led to efficiencies of up to 5.6%.\(^8\)–\(^10\) These results set an encouraging benchmark for further optimization of radial junction thin-film photovoltaics.

Our future work will aim at adopting atomic layer deposition for a high-quality conformal transparent conductive oxide coating layer. We will also explore depositing and optimizing hydrogenated microcrystalline silicon as an intrinsic absorber for a radial junction solar cell, investigate the benefits of thin-film tandem radial junction structures, and the eventual deployment of a new generation of high-performance and cost-effective SiNW thin-film solar cell.

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Linwei Yu is a permanent CNRS researcher. His work focuses on the development of next-generation thin-film photovoltaics:

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References