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Silicon nanowires for solar photovoltaic applications

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The low optical reflection from nanowire arrays could be exploited to improve the photon absorption efficiency of solar cells.

The majority of solar photovoltaic modules sold are silicon-based, but in recent years increased demand for silicon solar cells has inflated the price of raw silicon materials. The shortage of high-quality silicon has lead to research to find novel ways to design photovoltaic cells using inexpensive, low-quality silicon alternatives. Photovoltaic cells based on silicon nanowire arrays have emerged as a promising candidate for solar energy harvesting.[1,2] Silicon nanowire solar cells consist of arrays of radial p-n junction nanowires (see Figure 1) where the darker outer shell is composed of n-type silicon, to which the electron acceptor phosphorous has been added, and the lighter inner core from p-type silicon, to which the electron donor boron has been added. Each individual nanowire in the array has a p-n junction and acts as a tiny photovoltaic cell.

Silicon solar cells based on nanowires have much shorter p-n junctions that thin film solar cells. In the nanowire structure, photo-excited electrons and holes (carriers) travel very short distances before being collected by the electrodes. This results in a higher carrier-collection efficiency in the core-shell nanowire structure, and this advantage leads to a higher tolerance for material defects and allows the use of a lower-quality silicon. The core-shell nanowire structure addresses the carrier-collection issue, one of the key factors that determine the overall efficiency of a solar cell. However, the efficiency of photon capture in the nanowire structures, another very important factor, has not yet been determined.

Nanowire arrays are expected to possess significantly different optical properties from their bulk-length counterparts because they are smaller than the wavelength of visible light. In our recent work,[3] we performed numerical simulations to study optical absorption in silicon nanowire structures with a diameter between 50 and 80nm. Wave effects are taken into account by numerically solving the full-wave Maxwell's equations. Our study reveals the silicon nanowire structures have desirable anti-reflection characteristics across a broad spectrum.

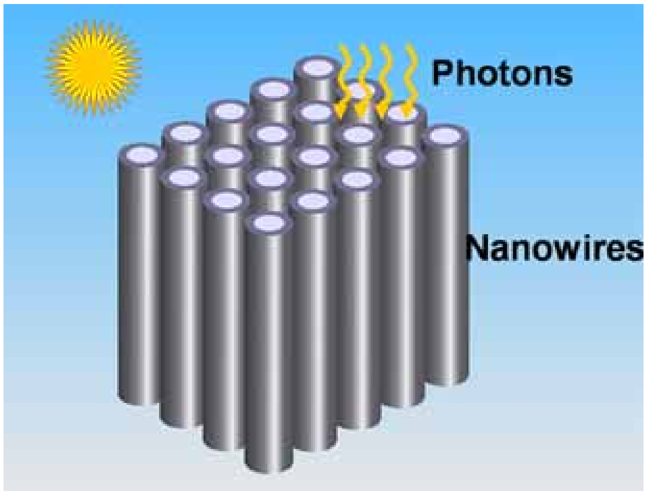

Figure 1. Diagram of the silicon nanowire solar cell. Each individual nanowire is a tiny p-n junction. The darker outer shell is n-type silicon. The lighter inner core is p-type silicon.

First, we investigated the effect of wire length on optical absorption. Figure 2(a) shows the optical absorbance of an array of silicon nanowires with a diameter of 50nm. Three wire lengths, 1.16, 2.33, and 4.66μm, are selected to show the thickness-dependent absorptance. The light is incident (falls upon) the top of the nanowire structure in the normal direction along the wire axis. The absorptance of a 2.33μm silicon film is plotted in the same figure as a reference. The graph shows that the optical absorption is limited in the low-frequency regime, particularly for shorter wires. Longer wires tend to compensate for insufficient light absorption in the low-energy regime, and as the frequency increases, the absorptance in the nanowires rises and reaches a plateau. Absorptance in the nanowires in the high-frequency regime is higher than that in the thin film compared to the low-frequency regime where absorption in the film is more efficient.

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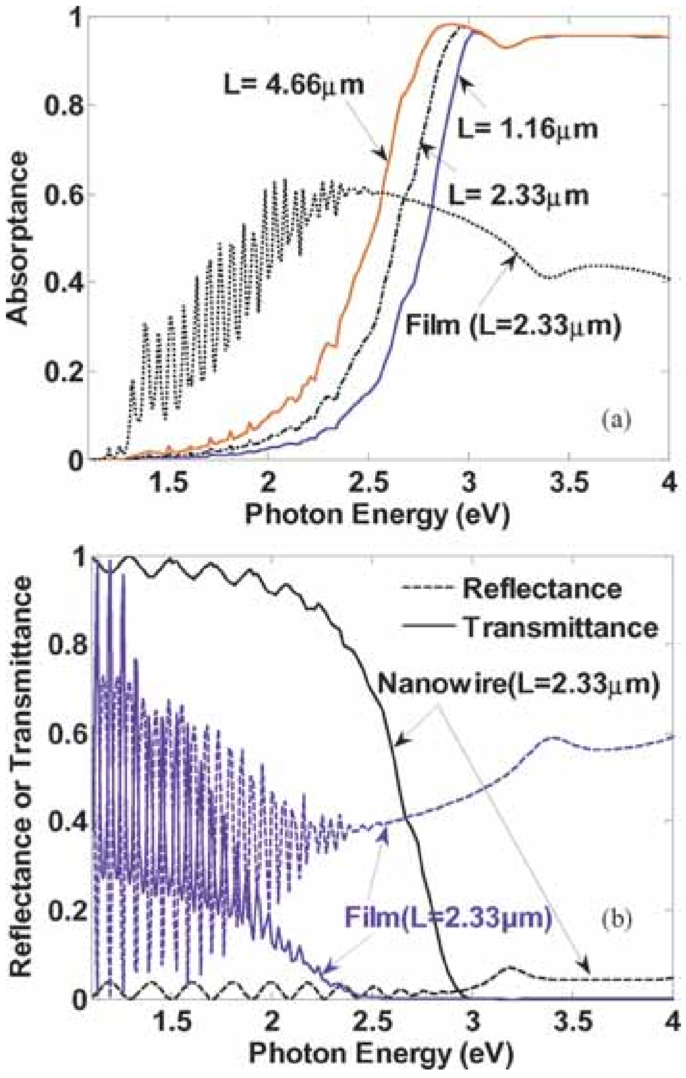

Figure 2. *Radiative properties of nanowire structures of various thickness. L is the wire length. (a) Absorptance of nanowires with L = 1.16, 2.33, and 4.66μm (diameter = 50nm, wire spacing = 100nm). The absorptance of a thin film is included for reference. (b) Reflectance of nanowires and the thin film. (Adapted with permission, copyright American Chemical Society, 2007.*[3]*)*

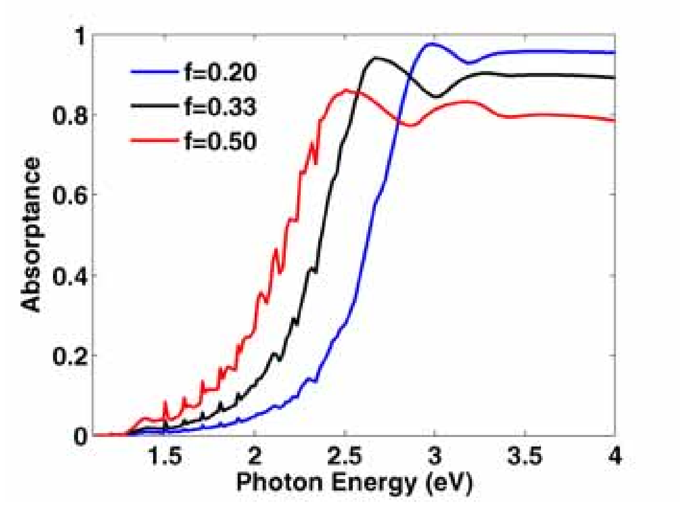

Figure 3. *Reflectance of nanowire structures with various filling ratios where f is the filling ratio.*

The total absorptance of the nanowire structure is determined by the reflectance and transmittance of light. To understand the trend of absorptance in nanowire arrays, in Figure 2(b) we plot the reflectance and transmittance for a nanowire structure and a thin film. It is interesting to note that reflectance of the nanowires is significantly lower than that of the thin film across the entire spectrum. In the thin-film solar cell, such a small reflectance can only be achieved by applying special antireflection coatings. It is the combined effect of the small reflectance and zero transmittance in the high-frequency regime that causes higher absorptance in the nanowires than in thin films. In the low-frequency regime, Figure 2 shows that the transmittance of the nanowire structure is higher than that of the thin film. The higher transmittance cannot be compensated by the low reflectance, leading to insufficient absorption of low-energy photons in the nanowire structure.

Figure 3 shows the absorptance of nanowire structures with different filling ratios. All structures have a fixed wire spacing of 100nm and wire length of 2.33μm, but the wire diameter varies. The figure shows that larger filling ratios give higher absorption in the low-frequency regime, while in the high-frequency regime nanowires with smaller filling ratios can absorb more light. By changing the filling ratios, a nanowire structure can have an overall absorption efficiency close to that of thin film.

In summary, our analysis demonstrates that nanowire structures have the advantage of small reflectance across a wide spectrum and can be achieved without specially designed antireflection coatings. This small reflectance improves optical absorption significantly in the high-frequency regime, while in the low-frequency regime a similar improvement cannot be achieved because of the small extinction coefficient of silicon, which is the light lost to scattering and absorption. However, the less-optimal absorption in the low-frequency regime can be overcome by using longer wires or light trapping.

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