Nanostructured silicon for alternative energy devices

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Nanoscale materials promise better thermoelectrics and solar cells through gains in efficiency and lower cost.

The United States uses approximately 3.5TW of electric power in one year. More than 85% of that amount is supplied by mechanical heat engines that burn fossil fuels. Unfortunately, these fuels are limited and pollute the atmosphere. The rising costs of and demand for energy products, and the alarming rate of global warming, have served to focus research efforts onto alternative forms of renewable energy. The sun is one such source that has a nearly infinite lifetime (over one billion years) and does not pollute. However, devices that directly convert sunlight to electricity account for less than 1% of all power-generating sources. Thermoelectrics and photovoltaics (solar cells) are two types of renewable energy-producing devices. Both currently find limited use due to their low efficiencies and high cost. Here, I review the potential of nanoscale materials to transform thermoelectric and solar cell devices into low-cost yet efficient renewable energy devices.

A thermoelectric material can generate electric power anywhere waste heat is found. Temperature differences from the heat cause the diffusion of electrons from the hot end of the material to the cold end, creating a voltage. Accordingly, the thermal conductivity of the material is an important parameter in determining power efficiency. For high efficiency, thermal conductivity should be low so that the material can maintain a temperature difference. In semiconductors, heat transport is dominated mostly by phonons (atomic vibrations). If left undisrupted, phonons can efficiently transfer heat, which results in a large degree of thermal conductivity. However, if the phonons are allowed to scatter, which can occur with a reduction in size of a thermoelectric material, thermal conductivity decreases. For example, phonons scatter more frequently when the lateral dimension of a material is made smaller than the mean free path of a phonon mode. In many materials, the mean free path is usually on the order of tens to hundreds of nanometers. Thus, nanoscale materials offer substantial promise in this field.

Figure 1. A scanning electron microscope image of a silicon nanowire thermoelectric device. The silicon nanowires, colored in green, exhibit ZT values approaching 1 (inset). ZT: A dimensionless number that measures the efficiency of a thermoelectric material.

In our recent research on silicon nanowires, we measured thermal conductivity using a microfabricated device with built-in heaters and resistive thermometers. The entire device was suspended to minimize any parasitic heat loss. The thermal conductivity was determined by the joule heat dissipated in the heater (red winding electrodes), and the temperature difference using the two inner yellow electrodes (see Figure 1). We found that thermal conductivity was reduced by a factor of 100 over bulk silicon, primarily because of enhanced phonon scattering from the nanowire surface. As a result, efficiency was increased to almost 10% (see Figure 1, inset).

A major consideration in the quest for practical photovoltaics is cost. Crystalline silicon represents over 90% of the solar cell market, but it is expensive. One reason is the effort required to convert metallurgical-grade silicon (99.99% pure) to solar-grade silicon (99.99999% pure), which accounts for over 40% of the
completed cell cost. If solar cells are to become commercially competitive, they need to achieve $1/W. Being able to manufacture radial p-n junction solar cells from metallurgical-grade silicon would go a long way to achieving this goal.

Metallurgical-grade silicon is raw, unpurified silicon (e.g., containing aluminum, copper, and titanium) that is reduced from quartz in an arc furnace. It costs ~$1/kg, making it almost 100 times less expensive than solar-grade silicon. Now, in a standard, planar p-n junction solar cell, light absorption occurs in the same direction as carrier collection. Photogenerated electron-hole (charge-carrying) pairs outside of the p-n junction are collected only if they are within a diffusion length away from the junction. Consequently, large diffusion lengths necessitate the use of high-purity silicon materials to keep trap densities low.

In radial p-n junctions, carrier collection is orthogonal to light collection. This means that shorter carrier collection distances (< 1 μm) are possible, which in turn enables relaxation of purity requirements. We diffused copper into a p-type silicon wafer at high temperature. Radial p-n junctions were prepared by drilling deep holes into the wafer using reactive-ion etching. The holes were then filled with an n-type spin-on dopant and then annealed, forming the radial p-n junctions. We found that, for silicon samples contaminated with copper, the radial p-n junction solar cell devices have efficiencies two to three times larger than their planar counterparts.

In conclusion, we have shown that nanostructured silicon materials have the potential to improve alternative energy devices, such as thermoelectrics and photovoltaics. Heat transport is radically altered at the nanoscale for silicon thermoelectrics, which results in increased efficiency. Photovoltaics can also take advantage of nanostructured geometries where charge carriers can be efficiently collected in impure materials. Future work will focus on the challenges inherent in manufacturing practical nanoscale devices.

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References