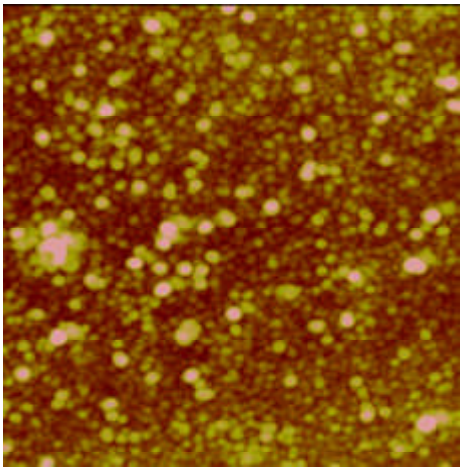
Nanostructured Materials Developed for Solar Cells

There has been considerable investigation recently regarding the potential for the use of nanomaterials and nanostructures to increase the efficiency of photovoltaic devices. Efforts at the NASA Glenn Research Center have involved the development and use of quantum dots and carbon nanotubes to enhance inorganic and organic cell efficiencies. Theoretical results have shown that a photovoltaic device with a single intermediate band of states resulting from the introduction of quantum dots offers a potential efficiency of 63.2 percent. A recent publication extended the intermediate band theory to two intermediate bands and calculated a limiting efficiency of 71.7 percent. The enhanced efficiency results from converting photons of energy less than the band gap of the cell by an intermediate band. The intermediate band provides a mechanism for low-energy photons to excite carriers across the energy gap by a two-step process.

Quantum dots offer the potential to control the intermediate band energies since the individual quantum energy levels associated with isolated quantum dots are a function of their size and material composition. Placing the appropriate quantum dot material of the necessary size into an organized matrix within an ordinary *p-i-n* structure solar cell should result in the formation of accessible energy levels within what would normally be the forbidden band of the device.



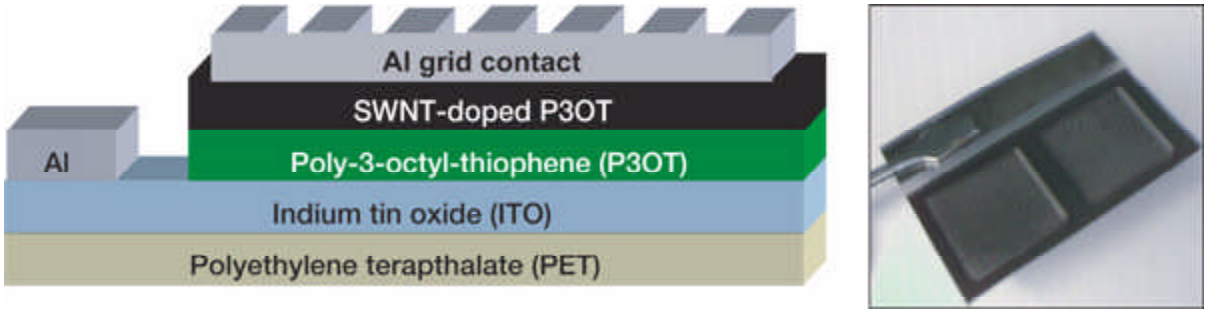
1- by 1-µm tapping-mode atomic force microscope image of colloidal $CuInS_2$ (mercaptoacetic acid) quantum dots on glass.

In preparation for their insertion into a *p-i-n* amorphous silicon cell structure, we have been investigating depositing quantum dots of $CuInS_2$ and $CuInSe_2$. $CuInS_2$ quantum dots were coated with hexanethiol and a sequential exchange of the hexanethiol coating by triocytlphosphine oxide (TOPO), pyridine, and mercaptoacetic acid was performed to render the dots dispersible in water. The preceding figure shows tapping mode atomic force microscope (AFM) of these dots arrayed on a glass substrate by electrostatic layer-by-layer assembly. The remaining issues regarding the best procedure for introducing these

dots into a *p-i-n* amorphous silicon cell structure are currently being addressed.

Thin-film polymeric solar cells may also benefit from the introduction of quantum dots. Solar cells that utilize conjugated polymers such as poly-3-octyl-thiophene (P3OT) or poly-3-hexyl-thiophene (P3HT) making junctions with indium tin oxide (ITO) have suffered from low conversion efficiencies because of the low transport mobility of the photogenerated carriers. The light that is absorbed in the conjugated polymers creates excitons or bound electron/hole pairs. Before these charges can contribute to any photocurrent, they must first be separated. It has been shown that semiconducting quantum dots introduced into the polymeric matrix will serve as disassociation centers and improve overall device efficiency. However, even with the disassociation of the carriers, their mobility in these materials is still quite low. This can be addressed to a certain extent by the use of nanorods instead of the spheroidal quantum dots.

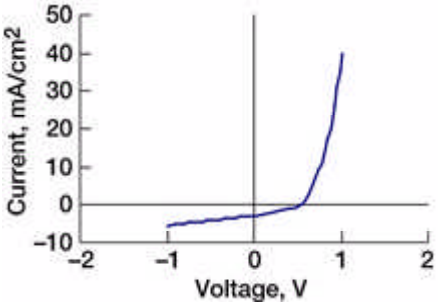
The problem of low carrier mobility in thin-film polymeric solar cells may be addressed through the use of single-walled carbon nanotubes (SWNTs). It has been demonstrated that even a small weight percent doping of SWNTs in a polymeric thin film can dramatically improve the film's electrical conductivity. In addition, SWNTs can themselves be semiconducting and are very good absorbers in the visible range. They may serve a similar role to that of the quantum dots when introduced into the conjugated polymers used in photovoltaic development.



Carbon nanotube polymeric solar cell.
Photograph and diagram showing cell layers (top to bottom) of aluminum grid contact, SWNT-doped Poly-3-octyl-thiophene (P3OT), aluminum and P3OT, indium tin oxide (ITO), and polyethylene teraphthalate (PET).

Photovoltaic devices have been constructed at Glenn using P3OT doped with high-purity SWNTs produced by laser vaporization. The composite solution (1 wt% SWNTs in P3OT) was applied to ITO-coated glass substrates. The cell structure can be seen in the preceding photograph. A simple 1.0-µm-thick Al grid contact was deposited onto the P3OT surface via thermal evaporation. The SWNT-P3OT diode response produced an open-circuit voltage V_{oc} in the range of 0.7 to 0.9 V, and the short-circuit current I_{sc} was observed to double for the composite solar cells in comparison to those that contained P3OT without the SWNTs. It is typically the case that the work function difference between Al and ITO (i.e., 4.3 and 4.7 eV, respectively) is responsible for determining the V_{oc} in these types of devices. However, the relatively higher V_{oc} measured here is presumably due to the influence of the SWNTs. We suggest that for an MIM-type junction

the ITO-polymer-SWNTs account for the measured potential.



Current-versus-voltage response of an SWNT-doped P3OT/ITO solar cell.

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