Nanotechnology for a Brighter and More Sustainable Future

by Professor Javier Garcia-Martínez

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Nanotechnology, with its unprecedented control over the structure of materials, can provide us with superior materials that will unlock tremendous potential of many energy technologies currently at the discovery phase. The quest for more sustainable energy technologies is not only a scientific endeavor that can inspire a whole generation of scientists, but the best way to establish a new economy based on innovation, better paid jobs, and care for the environment[1,2].

Solar Energy: Nanotechnology to Capture the Energy of the Sun

According to the IEA Energy Statistics[3], the renewable energy accounted for around 13.1% of the fuel share of world's total primary energy supply energy in 2004, where photovoltaic technology represented only the 0.04%. Thus even if solar energy is free and abundant, we are still far away of an energetic system based on this technology.

Besides, the Alternative Policy Scenario presented in 2006 World Energy Outlook[4] has predicted an increase of photovoltaics of around 60 times from 2004 to 2030 year. In fact, the evolution of photovoltaic technology has provoked that its price has fallen down to a tenth in the last 20 years (from 2.00 $/kWh in 1980 to 0.20-0.30 $/kWh in 2003). Independent studies suggest that the costs will continue to fall and that it is plausible to envisage costs of around 0.06 $/kWh by 2020.

The application of nanotechnology in PV cells is already producing some significant advantages to increase the efficiency/cost ratio by using materials with different bandgaps, i.e., multilayers of ultra-thin nanocrystalline materials, new dyes or quantum dots, among others. For example, the ability to control the energy bandgap provides flexibility and inter-changeability. Also, nanostructured materials enhance the effective optical path and significantly decrease the probability of charge recombination. Quantum well devices such as quantum dots and quantum wires, as well as devices incorporating carbon nanotubes, are being studied for space applications with a potential efficiency up to 45%.

Nanocrystal quantum dots (NQDs)[5] are nanometer-scale single crystalline particles of semiconductors. Due to the quantum confinement effect, their light absorption and emission wavelengths can be controlled by tailoring the size of NQDs. Nowadays, conventional solar cells are mostly built on silicon (Figure 1). Because the cost of silicon keeps growing, this technology will not be the one to bring down the cost of solar generated electricity below1 $/kWh. In contrast, as an example of their attractive future as more efficient solar cells, analogous nanocrystalline quantum dots have close to 40% efficiency.

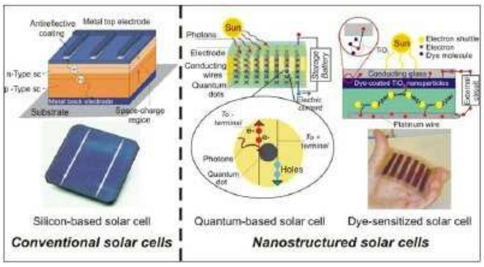

Figure 1. Evolution of PV technology: from conventional (silicon-based solar cells) to nanostructured solar cells (quantum-based and dye-sensitized solar cells)[1]

The use of nanocrystalline materials in thin-film multilayered cells also help achieve a regular crystalline structure, which further enhances the energy conversion efficiency. An example of nanostructured layers in thin-film solar cells has been recently reported by Singh et al.[6] Nanocrystalline CdTe and CdS films on ITO-coated glass (indium tin oxide) substrates have been synthesized as potential n-type window layers in p-n homo(hetero)junction thin-film CdTe solar cells. CdTe nanocrystals of around 12 nm in diameter exhibit an effective band gap of 2.8 eV, an obvious blue shift from the 1.5 eV of bulk CdTe (Figure 2).

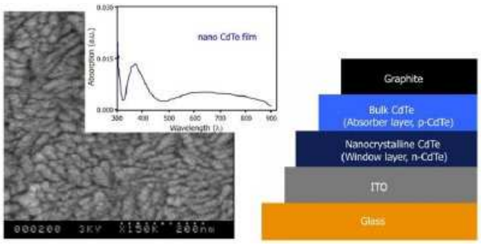

Figure 2. Example of nanomaterials for photovoltaic cells fabrication. Left part: FE-SEM image of a nanocrystalline CdTe film on ITO-coated glass substrate. The inset shows the absorption spectrum of a nanocrystalline CdTe film on ITO-coated glass substrate. Right part: Device configuration of a Glass/ITO/n-Nano-CdTe/p-bulk CdTe/graphite solar cell. Adapted with permission from ref.6. Copyright 2004, Elsevier

Another alternative offered by nanotechnology to conventional silicon-based solar cells is the use of dye-sensitized solar cells. Dye-sensitized photoelectrochemical solar cells (PES or Grätzel cells) represent a relatively new class of low-cost thin-film solar cells[7]. Nano-structured TiO_2, CeO_2, CdS and CsTe are of great interests as the windowing and light absorbing layers[8,9]. These dye-sensitized nanostructured solar cells, which comprise devices such as nanocrystal solar cells, photoelectrochemical cells and polymer solar cells, are being studied for terrestrial applications and represent the third generation of photovoltaics.

The last advances in photovoltaic technology are based on the preparation of nanocomposites based on the mix of nanoparticles with conductive polymers or mesoporous metal oxides with high surface areas thus increasing internal reflections and, consequently, having a single multispectrum layer.

Advanced Nanomaterials for Fast and Efficient Energy Storage

Many of the clean energy alternatives produce (e.g. PV solar cells, wind) or require (e.g. hydrogen production, water splitting) electricity. Therefore, a more novel and efficient way to store electricity is needed. Energy storage systems include batteries, and among them Li-ion batteries are specially attractive because they lead to an increase of 100-150% on storage capability of energy per unit weight and volume as compared with the more traditional aqueous batteries. Nevertheless, some disadvantages arise, related to low energy and power density, large volume change on reaction, safety and costs.

Nanotechnology is already producing some very specific solutions to the field of rechargeable batteries. Electrolyte conductivity increases up to six times by introducing nanoparticles of alumina, silicon or zirconium to non-aqueous liquid electrolytes. Most efforts have been focused on solid state electrolytes, solid polymer electrolytes (SPE).

Poly(ethylene oxide)-based (PEO-based) SPE received most attention since PEO is safe, green and lead to flexible films. Nevertheless, polymers usually have low conductivity at room temperature and, depending on SPE compositions, their interfacial activity and mechanical stability are not high enough.

In this sense, nanocomposite polymer electrolytes could aid in the fabrication of highly efficient, safe and green batteries. For example, the introduction of ceramic nanomaterials as separators in polymer electrolytes increases the electrical conductivity of these materials at room temperature from 10 to 100 times compared with the corresponding undispersed SPE system. TiO_2, Al_2O_3 and SiO_2 and S-ZrO_2 (sulphate-promoted superacid zirconia) have been used for this purpose and results reveal that the introduction of S-ZrO_2 led to the best performance[6].

Other Opportunities for a Brighter Future

There are many other examples of the use of nanotechnology to make energy production, storage and use more efficient, like the use of nanostructured electrodes in supercapacitors[10], novel hierarchical porous catalysts for advanced chemical processing or nanostructured catalytic electrodes for fuel cell applications. For example, nanostructured carbon materials with different structures has been synthesized in our laboratory via supramolecular templating obtaining cabon nanofoams with high surface area and good electrical conductivity, excellent chemical, mechanical, and thermal stabilities (Figure 3)[10].

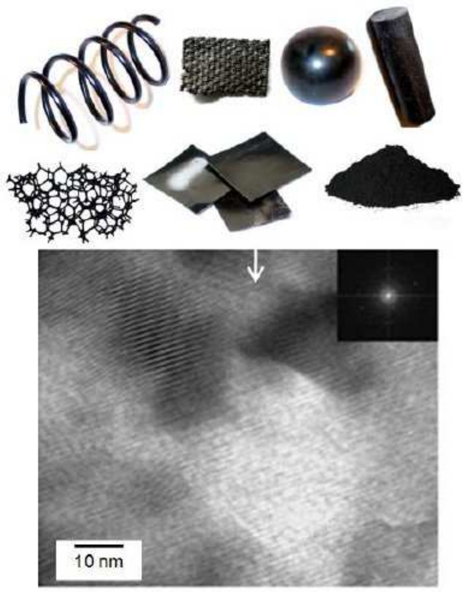

Figure 3. Nanostructured carbon materials with different structures prepared via supramolecular templating and TEM image for nanostructured carbon thin films. Adapted with permission from ref. 10. Copyright 2008, Wiley Interscience.

These materials were tested by cyclic voltammetry as supercapacitor electrodes and these materials exhibit specific capacitances over 120 F A/g or 100 F A/cm^3, powder densities of 10 kW A/kg and energy densities of 10 Wh A/kg. But there are many other opportunities, like light nanocomposites for more energy efficient transportation, the use of nanomaterials in construction and nanoporous adsorbents for CO_2 capture[11].

Nanotechnology unprecedented control over the size, structure, and organization of matter is providing very tangible examples of how better materials are contributing to the well-being of present and future generations by proving alternative cleaner ways to produce and use energy.

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Date Added: Jun 7, 2010

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