Sarah Evins
Professor Scarlatos
HON 301
March 25, 2012

Abstract: This report seeks to clarify the current state of nanotechnology as it enables new innovations in solar technology. The report first defines the role of the unique field of nanotechnology as transformative. Then, a description of all solar cell devices puts the role of nanotechnology into perspective. An explanation of the mechanisms of solar nanostructures follows, framed through the lens of photosynthesis. An index of various applications of these mechanisms then illustrates current and potential products that result from these scientific innovations. Finally, the report attempts to discuss the impending growth of solar nanotechnology by assessing prospective developers and inhibitors of solar nanotechnology.

Table of Contents

1. Introduction

The continued development of nanotechnology to improve solar technology may be the key to making solar energy cost efficient. This research paper approaches the idea of solar nanotechnology using a top-down approach. I will begin by describing ideas fundamental to research in all of nanotechnology. I will then explain the mechanisms of nanotechnology being used for solar cells. Then I will explain how these nano-scale mechanisms are being applied in different types of solar technologies; this will include a description of both current second generation and developing third generation solar cell technologies. Finally, I will describe the factors that influence the future development of nanotechnology.

2. The Nanotechnology field

2.1: Definition of nanotechnology

Nanotechnology encompasses a broad field that aims to study and use structures between one and one hundred nanometers in size. The implications of this definition are as follows: (1) the size of nanotechnology requires materials and tools that operate at the nanoscale, (2) at the nanoscale, materials behave in unusual or useful ways, and (3) researchers may be able to "harness" these unexpected behaviors to create new technologies ("What is Nanotechnology?").

2.2: History of nanotechnology

Before the modern era, nanostructured materials were the products of craftsmen. Craftsmen, using high heat, produced products with dichroic glass, luster glazes, stained glass windows, and swords. The exploration of nanoscaled materials began with Erwin Müller's field emission microscope in 1936 and the theory for growing these nanomaterials was founded by Victor La Mer and Robert Dinegar in 1950. tIn 1974, Tokyo Science University originated the term "nanotechnology" to describe the creation and application of nano-sized materials. Since that time, different nanostructures and new technologies purposed to manipulate these structures have been developed to be used for a wide array of radically new and transformative applications ("Nanotechnology Timeline").

2.3: Nanostructures

Different nanostructures have different properties and behaviors that enable them to perform different functions.

2.3.1: Fullerenes

A fullerene is any nanostructure that is composed entirely out of carbon. A fullerene can be a sphere, ellipsoid or tube. A spherical fullerene is called a buckyball and a cylindrical fullerene is called a carbon nanotube or buckytube ("The Future of Nanotechnology"). These structures are extremely strong; their strength is derived from the special characteristics of carbon bonds at the nanoscale ("Introduction to Nanotechnology").

2.3.2: Nanorods or nanowires

Nanorods can be made of of carbon, silicon, other semiconductors and metals. They are made using solution chemistry methods and can then self-assemble into larger nanoscale structures

(Ratner 55). They are shaped like long sticks or dowels and have a diameter in the nanoscale and a long length (Ratner 174). Nanorods not made out of carbon are usually called nanowires, especially those made of silicon. They exhibit special physical and electrical properties including a tensile strength stronger than steel, flexibility, ability to act as a superconductor, and very little production of waste heat as electrons flow through (Ratner 56-57).

2.3.3: Quantum dots

Composed of a hundred to a thousand atoms, quantum dots are small particles made of semiconductor materials about a nanometer in size. The size of a quantum dot influences its appearance; as particle size decreases, its color moves through the colors of the rainbow (“Quantum Dots and Nanoparticles”). Quantum dots display several unusual properties. They emit light if excited—the smaller the particle the higher the energy of light it emits. They are also capable of “Multiple Exciton Generation,” allowing for the production of an unusually a high amount of electrical energy after absorbing light (NREL: “Quantum Dots”).

3. Solar cell genealogy

3.1: First generation solar cells

The first generation of solar cells is the traditional model for a photovoltaic cell and is currently dominating the commercial market. The cell is made by doping—modifying a substance’s electrical properties—a semiconductor like silicon or germanium with phosphorus and boron. This doping forms a p-n junction, where the electronic action of the solar cell occurs (Lund). The resulting cell is a flat plate panel made of bulk materials with a relatively high energy conversion efficiency (“Solar Voltaic Technology Basics”) (Lund). Unfortunately, because the cell requires pure silicon and is difficult to manufacture, its high production cost is not in proportion with its power output (Lund).

3.2: Second generation solar cells

Second generation solar cells are also called thin-film solar cells. They use layers of semiconductor materials only a few micrometers thick and are of composed of nanocrystals. Their flexibility allows for multi-functionality, as roof shingles, tiles, building facades or skylight glazings (“Solar Voltaic Technology Basics”). There are four basic types of thin-film solar cells: amorphous silicon cells, polycrystalline silicon on a low cost substrate, Copper indium diSelenide (CIS or CIGS), and Cadmium Telluride cells. These cells have a lower efficiency than first generation solar cells, but are much cheaper to produce. They are thus more cost efficient in that the cost per watt produced is lower than that of the first generation (Lund).

3.3: Third generation solar cells

Still in its research phases, these solar cells are being developed with the objective to increase efficiency and lower production cost (Lund). These third generation solar cells include: solar inks with printing press technologies, solar dyes, conductive plastics, and quantum dots (“Solar Voltaic Technology Basics”) (Lund).

4. Light capture in solar nanotechnologies

4.1 Understanding light capture in photosynthesis

The photosynthetic apparatus is incredibly complex and made up of a host of interacting nanostructures. There are three major nanostructures that compose the natural photosynthesis apparatus: the antenna, reaction center and membrane charge management structure (Ratner 123).

The antenna is made up of molecular light absorbing centers. These centers absorb energy from sunlight and move the energy into a collecting station called the light harvesting complex. This light-harvesting complex is made of rings of molecules that exchange energy until it is ready to be transferred to the reaction center (Ratner 123).

The reaction center is where the energy is used to separate charges. An electron is separated from its positively charged hole by more than 2 nanometers to be captured by another nanostructure. When this transferred charge is finally brought to the charge management structure, a complex system of membrane-bound structures allow for charge recombination. Through this process, ATP is formed (Ratner 123, 124).

4.2 Applying knowledge of light-capture to nanostructures

The role of nanostructures in natural photosynthesis helps scientists understand energy capture at the nanolevel. Energy capture is the result of three functions: (1) sunlight is captured, (2) sunlight is used to separate positive and negative charges, (3) these separated charges are then recombined in such a way that allows for the creation of a useful energy source (Ratner 124).

Nanotechnology incorporates this understanding of the photosynthetic apparatus into the technology. Work with semiconductors in first and second generation solar cells has provided an understanding of materials science that optimizes the application of various nanomaterials. Understanding the unique behavior of these structures at a nanolevel allows these nanomaterials to be applied into a useful photovoltaic apparatus . Thus, solar nanotechnology imitates parts of the photosynthetic apparatus (Ratner 125).

5. Kinds of solar nanotechnologies

5.2: Current products: second generation solar cells

5.2.1: Amorphous silicon cells

A thin layer of silicon in grown on a base material, usually metal or glass, to create this solar cell (Lund). Growing the semiconductor silicon in a thin layer of nanocrystals is much less expensive than buying pure silicon as raw material, as is done with traditional solar cells. Furthermore, it uses 300 times less active material. However, while these cells are much cheaper to manufacture, their efficiency is also much less—less than 10% compared to 15% in first generation silicon solar cells. It is currently being used for pocket calculators (Malsch).

5.2.2: Copper indium selenide and cadmium telluride cells

These are a direct bandgap photovoltaic cells that use the compounds copper indium selenide ($CuInSe_2$) and cadmium telluride (CdTe) in the form of nanocrystals as a semiconductor. Photons that strike the panel get absorbed by a thin absorber layer in a highly efficient manner upon reaching less than 1µm into the material. These semiconductive nanocrystals can be grown upon a metal, glass, or flexible plastic substrate or made into an ink that can be printed onto aluminum for production (Lund). These two types of cells are the most popular thin-films solar cell commercially, but only account for about 9% of total solar energy sales. Although lab tests have seen efficiencies as high as 30%, manufactured and commercial cells are at highest 10-12%, less than that of the traditional solar cell. Cadium causes some environmental concern because it is a toxic material when swallowed or inhaled (Malsch).

5.2.4: Graetzel cells

Unlike other second generation solar cells, the apparatus is made of organic dye molecules are absorbed into pores between titanium dioxide particles and surrounded by an electrolyte fluid (Malsch). A dye molecule absorbs light and separates charge, passing an electron to the titanium dioxide nanocrystal. When separated charges then recombine through a series of electrochemical reactions, a fraction of the energy captured from the sun is released as an electrical current into an external circuit (Ratner 69). These organic dye sensitive solar cells can convert low light intensities into electricity, which allows the cells to work indoors. They can have efficiencies of 7-8%, which is much lower than that of other commercial solar panels (Malsch). The solar panels have found a niche market in solar clocks and watches and educational kits (Ratner 69) (Malsch).

5.3: Potential products: Third Generation Solar Cells

5.3.1: Quantum dot solar cells:

Most solar cells are confined to a theoretical upper limit of 31% conversion efficiency, called the Shockley-Queisser Limit, which is defined by a certain range of sunlight wavelengths. Sunlight photons below or above a certain energy are unable to excite electrons or produce heat rather than electricity, respectively. However, quantum dots exhibit at the nanoscale behavior called “multiple exciton generation” (MEG) that allows quantum dot solar cells to surpass the the Shockley-Queisser Limit (Bessel).

In MEG, when a single photon of light of a sufficiently high energy is absorbed by a quantum dot, it produces more than one exciton, a bound electron hole pair. The exact mechanism of this behavior is unknown, but it can be understood as “quantum confinement”: an electron must exist in a confined space, allowing very high energy photons to transfer energy in a way that creates multiple excitons (Bessel) (NREL: “Quantum Dots”). Thus, while non-quantum-dot cells can only achieve a quantum efficiency—the proportion of photons that produce an electron output—of up to 80 or 90%the quantum dot solar cell has a quantum efficiency of up to 114 percent. Scientists predict that further research may be able to produce solar cells with a light conversion efficiency of up to 66%, more than twice that of the most efficient solar cells currently available.

5.3.2: Silicon wire arrays

A new generation of thin-film technology, this solar cell “surpasses the conventional light-trapping limit for absorbing materials,” according to researcher Harry Atwater (Oliwenstein). These silicon wire arrays are composed of silicon nanowires which work as semiconductors, silicon nanoparticles to scatter and trap light and a flexible and transparent polymer with a reflective backing. Nanoparticles that scatter and redirect are able to trap light in a thin film cell for an extended period which allows more photons to be absorbed by the silicon nanowires. With this approach, the cell has a lab tested quantum efficiency of 95%, more than that of traditional solar cells (Glynn). The array distributes the silicon nanowires sparsely; this effective optical concentration means that only 2% of the entire cell is made of silicon (Oliwenstein). Thus, highly efficient light absorption is achieved with only 1% of the silicon needed in an amorphous silicon cell or 0.003% of the silicon needed for traditional solar cells (Glynn).

5.3.3 Nanoantennas

Nanoantennas combine nanorod structures with rectifier antennas. Because of the size of these nanoantennas, they can absorb the infrared part of the spectrum. This means that even after the sun sets nanoantennas will be able to absorb solar energy in the form of infrared radiation. While the nanoantennas have a quantum efficiency comparable to first and second generation solar cells, their ability to absorb sunlight after the sun has set is unmatched. Furthermore, the nanoantennas are made of less expensive carbon materials and can be printed on thin and flexible plastic, allowing for cheaper materials and production costs ("Harvesting the Sun's Energy with Antennas").

6. The future

6.1: Research development

The U.S. Department of Energy, Office of Science has founded a program called Energy Frontier Research Centers. The program give 46 research centers between $2 and $5 million dollars a year to accelerate the development of "radically new technologies [that] arise from disruptive advances at the science frontiers." These research centers involve universities, national laboratories, nonprofit organizations, and manufacturers and focus on solving "grand challenges" (U.S. Department of Energy). At the hub of all of these research centers, the National Renewable Energy Laboratory, the sole national laboratory dedicated to advancing renewable energy, help determine problem-solving areas of research (NREL). The ultimate objective of the program is to discover scientific advancements that create a "fundamentally new U.S. energy economy (U.S. Department of Energy).

6.2: Adaptability for mass production

First generation solar cells require a bulk amount of pure silicon to be shaved into a thin wafer, a process that is expensive, wasteful of materials and energy-intensive. Current thin-film technologies are able to print nanocrystals onto rigid and flexible panels ("Nanotechnology in Solar Cells"). The ability to use flexible panels allows for a production process called "roll-by-roll" printing, a rapid process that automates production and results in more output.

Additionally, the growth of nanomaterials continues to be researched from laboratory to manufacturing scales. With the guidance of the National Renewable Energy Laboratory, research for commercial viability is integrated into the approach for developing nanotechnologies (NREL: Quantum Dots).

6.3: Possible harmful effects on the environment

Because nanotechnology applications are still in their infancy, many of its long term effects are unknown. The concern that nanotechnology could have significant toxic effects on the environment continues to be monitored and disproved by research (Seller 2). The toxicity of the nanostructure depends on the toxicity of the material from which it is made. Furthermore, the amount material is nano-sized, it poses a much smaller risk for exposure than bulk materials (Seller 176). Without exposure, there is no risk; therefore, as long as toxic nanomaterials handled properly and contained, hazards are negligible (Seller 175). If mishandled, nanoparticles would not biomagnify. Because nanomaterials tend to aggregate and sorb onto environmental media, they are unlikely to accumulate and biomagnify, or disburse from organism to organism, through the food chain (Seller 177). Solar nanotechnology is thus much more likely to help rather than hurt the environment.

7. Conclusion

This report has described the current applications of nanotechnology in solar cells as well as prospective applications. A fundamental understanding of nanotechnology as it applies to solar power is the scientific foundation of current second generation solar cells. Aided by nanotechnology research, companies are able to manufacture thin-films which minimize production cost but are yet to rival the efficiency of first generation solar cells. Another branch of nanotechnology explores third generation solar cells, whose product applications remain on the horizon. In theory, using principles derived at the nano-scale, these potential products will meet or surpass the capabilities of both first and second generation solar cells. Government funding and corporate viability continue to facilitate as well as accelerate the continued development of solar nanotechnology. And with the knowledge that this radically new technology will not lead to disastrous environmental consequences, it is clear that nanotechnology will improve energy consumption problems by eventually turning solar power into an efficient and financially-incentivized source of energy.

Works Cited

Bessel, Carol, and Patrick Glynn. "Enhancing the Energy Harvest." *Stories of Discovery and Innovation*. U.S. Department of Energy: Office of Science, 1 Feb. 2012. Web. 16 Mar. 2012. <http://science.energy.gov/stories-of-discovery-and-innovation/127026/>.

"The Future of Nanotechnology." *Future of Nanotechnology*. Future for All. Web. 17 Mar. 2012. <http://futureforall.org/nanotechnology/nanotechnology.htm>.

Glynn, Patrick. "Trapping the Light Fantastic." *Stories of Discovery and Innovation*. U.S. Department of Energy: Office of Science, 19 Sept. 2011. Web. 17 Mar. 2012. <http://science.energy.gov/stories-of-discovery-and-innovation/127018/>.

"Harvesting the Sun's Energy with Antennas." *The Energy of Innovation*. Idaho National Laboratory, 17 Dec. 2007. Web. 23 Mar. 2012. <https://inlportal.inl.gov/portal/server.pt/community/newsroom/257/feature_story_details/1269?featurestory=DA_101047>.

"Introduction to Nanotechnology." *Understanding Nano*. Present Hawk's Perch Technical Writing, LLC, 2007. Web. 17 Mar. 2012. <http://www.understandingnano.com/introduction.html>.

Lawrence Berkley National Laboratory. “Sunny Future for Nanocrystal Solar Cells.” *Science Daily*, 23 Oct. 2005. 14 Mar. 2012.

Lund, H., R. Nielsen, O. Salomatova, D. Skare, and E. Riisem. "Different Generations of Solar Cells." *Solar Cells*. Norwegian University of Science and Technology, 2008. Web. 25 Mar. 2012. <http://org.ntnu.no/solarcells/pages/generations.php>.

Malsch, Ineke. "Nanotechnology Helps Solve the World's Energy Problems." *Nanotechnology Now*. 7thWave, Inc., 16 Apr. 2003. Web. 17 Mar. 2012. <http://www.nanotech-now.com/Ineke-Malsch/IMalsch-energy-paper.htm>.

"Nanotechnology in Solar Cells." *Understanding Nano*. Present Hawk's Perch Technical Writing,
LLC, 2007. Web. 19 Mar. 2012. <http://www.understandingnano.com/solarcells.html>.

“Nanotechnology Timeline.” United States of America. US Department of Energy. National Nanotechnology Initiative. *Nano*. United States National Nanotechnology Initiative. Web. 15 Mar. 2012. <http://www.nano.gov/timeline>.

National Renewable Energy Laboratory. *NREL Certifies First All-Quantum-Dot Photovoltaic Cell; Demonstrates Stability, Performance*. *NREL: Highlights*. U.S. Department of Energy, February 2011. Web. 17 Mar. 2012. <http://www.nrel.gov/science_technology/pdfs/50855.pdf>.

National Renewable Energy Laboratory. *NREL Researchers Demonstrate External Quantum*

Efficiency Surpassing 100% in a Quantum Dot Solar Cell. *NREL: Highlights*. U.S. Department of Energy, December 2011. Web. 17 Mar. 2012. <http://www.nrel.gov/science_technology/pdfs/53258.pdf>.

National Renewable Energy Laboratory. *Quantum Dots Promise to Significantly Boost Photovoltaic Efficiencies*. *NREL: Innovation*. U.S. Department of Energy, June 2010. Web. 17 Mar. 2012. <http://www.nrel.gov/innovation/pdfs/47571.pdf>.

Oliwenstein, Lori. "Caltech Researchers Create Highly Absorbing, Flexible Solar Cells with Silicon Wire Arrays." *Caltech Media Relations*. California Institute of Technology, 16 Feb. 2012. Web. 17 Mar. 2012. <http://media.caltech.edu/press_releases/13325>.

“Quantum Dots and Nanoparticles” *Exploring the Nanoworld*. National Science Foundation, 2008. Web. 16 Mar. 2012. <https://mrsec.wisc.edu/Edetc/nanotech/index.html>.

Ratner, Mark A., and Daniel Ratner. *Nanotechnology: A Gentle Introduction to the Next Big Idea*. Upper Saddle River, NJ: Prentice Hall, 2003. Print.

Sellers, Kathleen. *Nanotechnology and the Environment*. Boca Raton: CRC, 2009. Print.

"Solar Photovoltaic Technology Basics." *NREL: Learning* -. 21 Mar. 2012. Web. 19 Mar. 2012. <http://www.nrel.gov/learning/re_photovoltaics.html>.

U.S. Department of Energy: Office of Science. U.S. Department of Energy: Office of Science. *Energy Frontier Research Centers*. U.S. Department of Energy, 14 Aug. 2011. Web. 22 Mar. 2012. <http://science.energy.gov/>.

“What Is Nanotechnology?” *Exploring the Nanoworld*. National Science Foundation, 2008. Web. 16 Mar. 2012. <https://mrsec.wisc.edu/Edetc/nanotech/index.html>.