THE PRINCIPLE OF OPERATION OF SOLAR CELLS AND THE POSSIBILITY OF INCREASING EFFICIENCY BY APPLYING QUANTUM DOTS

[1]Milovan Paunic, [2]Marko Filijovic

[1]Faculty of Mechanical Engineering, University of Belgrade, Serbia

[2]Athens Institute for Education and Research – ATINER, Athens, Greece

milovan.paunic@gmail.com

Abstract

A solar or photovoltaic cell is a semiconductor device that converts the Sun's light energy into electricity, which occurs due to the photoelectric effect. The world market is dominated by silicon solar cells. The solar panel is only able to absorb the photons of a certain wavelength and this ability is directly impacted by the type of material from which the solar panel is made. This limitation results in certain shortcomings that are noticed during energy conversion and it is these shortcomings that represent opportunities for the improvement and application of quantum dots in solar systems.

This paper intends to review the theoretical explanation of the functioning of silicon solar cells and to present the possibilities of quantum dots application that arise from their unique properties. Due to their ability to absorb different wavelengths, quantum dots are capable of absorbing more photons from the solar spectrum, which theoretically increases their efficiency in relation to silicon solar cells.

In the case of quantum dots application, transmission and reflection are significantly reduced, so quantum dots can be used as a kind of coating for silicon solar cells.

The application of new quantum-dot-based tools provides broad scientific opportunities for the advancement and further development of nanotechnologies.

Keywords: *solar energy, photovoltaic cell, quantum dots, nanotechnology*

INTRODUCTION

The use of solar energy enables the gradual abandonment of the traditional use of fossil fuels in order to obtain an environmentally sustainable energy system (Hassanien, Li, Dong Lin, 2016, pp. 989-1001). Further growth of the need for devices that generate clean energy is completely expected, as the energy needs of humanity are constantly growing (Filijović, 2015, pp. 304-306).

In the past few decades, the most commoN-type of solar cells has been silicon solar cells that can have a solar energy conversion efficiency of over 20% while at the same time maintaining more than 80% of the initial conversion rate even after long-term use of about 20 to 30 years (Savin et al., 2015, pp. 624-628).

When it comes to silicon solar panels, it is necessary to consider another important aspect, which is the possibility of recycling. Most solar panels that are currently in widespread use aim for performance, reliability and cost-effectiveness, but putting effort into the simplification of recycling is bypassed. This is an extremely important factor that makes it possible for the entire solar panel lifecycle to become a closed process that can be called a clean and renewable energy source in the true sense (Tao et al., 2020, pp. 1-12).

It was found that a material that has a band gap of 1.1 eV can absorb about 77% of sunlight. Silicon semiconductor materials have a band gap greater than 2 eV and can theoretically absorb approximately 30% of solar energy (Nunzi, 2002, pp. 523-542). Unlike silicon semiconductors, quantum dots have the ability to fine-tune the size of the band gap by changing size. Thanks to this characteristic, it is theoretically possible to absorb a larger number of photons of different wavelengths and thus increase the conversion efficiency.

SEMICONDUCTORS – SOLAR CELLS

Semiconductor materials are structures that under certain conditions can become conductors. Figure 1a shows the bands where electrons can be found.

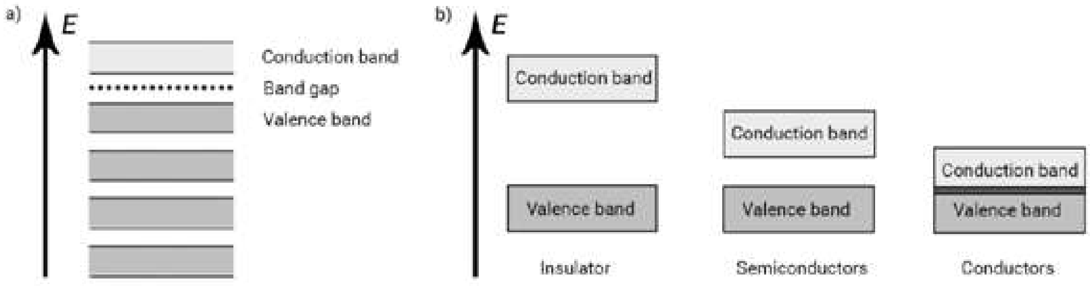

Figure 1. Schematic representation of a) energy bands layout, b) size of the forbidden zone in the case of insulators, semiconductors and conductors

The electrical conductivity depends on the possibility of electron flow from the valence level to the conduction band. In order for valence electrons to reach the conduction band, it is necessary for them to "jump over" the band gap (excited state) which occurs in cases when they absorb energy larger than the band gap size.

Figure 1b shows that the band gap size is large for insulators and small for semiconductors. In the case of conductors, the conductive and valence bands overlap. In the case of semiconductors, with relatively low energy absorption, it is possible to send a valence electron to the conduction band. A solar cell is essentially a semiconductor that has a small gap between the valence and conduction zones. This distance is short enough to cause the excited state of the electron by the mere action of sunlight. Figure 2 schematically shows a typical silicon solar cell composed of two types of semiconductors that differ only in the doping type.

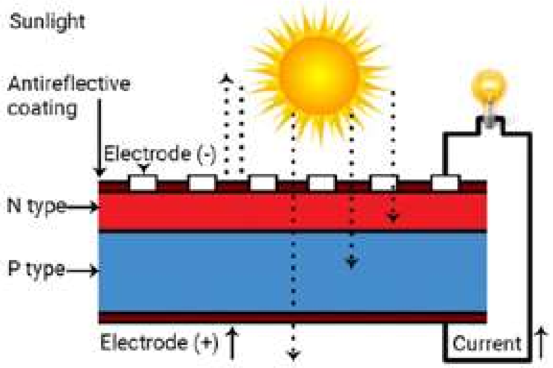

Figure 2. Schematic representation of a silicon solar cell

Since quantum dots will be discussed in the continuation of the paper, it should be pointed out that from a quantum point of view, light can be viewed in two ways - as a wave and as a particle. A photon is an elementary particle that represents a quantum of electromagnetic radiation. Sunlight photons hit the solar panel and then absorption, reflection or transmission occurs (Figure 2). The absorption of the photon causes the valence electrons to be excited by a quantum of energy that is large enough to let them jump over the band gap between the PN junctions of the semiconductor. The structure of the semiconductor significantly affects the performance characteristics which is why impurities such as boron and phosphorus are added to silicon. The addition of boron to silicon is called P-type doping while the addition of phosphorus is referred to as N-type doping.

Figure 3 shows that in the case of P-type semiconductors, the holes represent the majority of the electric charge carrier while the free electrons represent a minority - for the N-type, the reverse is true.

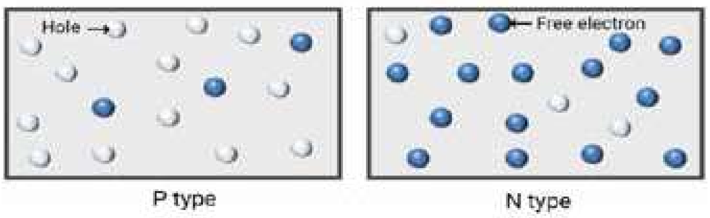

Figure 3. Schematic representation of N and P-type semiconductors

The N and P-type semiconductors are combined into a PN junction which is a semiconductor crystal structure with a preserved lattice at the junction between the P and N layers. By connecting P and N-type semiconductors (Figure 4), the exchange of charges in the contact zone occurs. Electrons from N-type semiconductors migrate to P-type semiconductors, while holes move in the opposite direction. When such electrons, moving from N to P-type semiconductors, merge with holes in P-type semiconductors, atoms in that zone have a higher number of electrons compared to the number of protons, so the charge is negative. An electron leaving an N-type semiconductor now makes its atom have more protons than electrons and we now have a case of a positive ion. A potential barrier (field) is created between the positive and negative contact charges, which prevents further movement of free electrons and holes so there is no movement of current through the semiconductor.

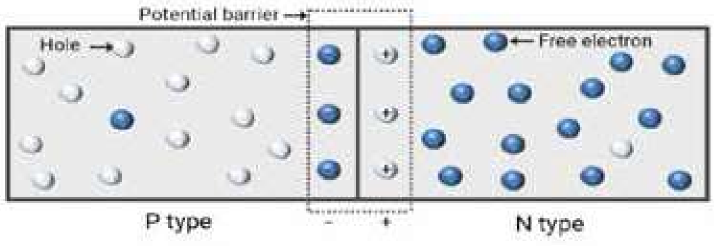

Figure 4. Schematic representation of N and P-type semiconductors

When sunlight reaches the contact band between the PN junction, energy absorption creates new electron-hole pairs. Due to the field action of the potential barrier, the free electrons start moving towards the N-type of semiconductor, while the holes move towards the P-type of the semiconductor. In this case, the accumulation of free electrons in the N-type and the accumulation of holes in the P-type of the semiconductor occur simultaneously. At some point, a large enough potential difference will be created between these two layers. By connecting a conductor, the electron charge will move from N-type to P-type of semiconductor. Once electrons reach type P semiconductors, the electron-hole recombination will occur.

APPLICATION OF QUANTUM POINTS IN SOLAR SYSTEMS

Nanotechnology is a branch of science that studies the characteristics of materials and phenomena that occur on a nanometer-scale - the size of atoms. The aim is to create new materials with unique characteristics that would be adapted for specific applications (Ouyang et al., 2004, p. 918).

In the early 1960s, the consideration of quantum dots as a new structure of semiconductor material began. In 1985, Louis Brus developed a quantum model of a spherical quantum dot (Brus, 1986, pp. 2555-2560). Work on the commercial production of quantum dots lasted for more than a decade, and in the late 1990s, this became possible. The work of Schaller and Klimov (2004, pp. 186601-186614) showed that quantum dots are able to emit up to three electrons for each absorbed photon (*multiple exciton generation*), which was revolutionary as standard semiconductors always emit one electron per each quantum of energy received.

By applying nanotechnologies, it is possible to improve silicon solar cells. Black silicon, or nanostructured silicon material, has promising properties to reduce the percentage of reflection of solar cells without the need to use the usual anti-reflection coating. In the work of Savin et al. it was assumed that the use of black silicon can simultaneously lead to cheaper production while increasing the efficiency of conversion (usability) of solar energy. The conversion efficiency was soon proven as black silicon led to an increase in the generated energy by 3% in relation to the reference cell (reference cell) (Savin et al., 2015, pp. 624-628). Moreover, according to Rasid et al (2020, pp. 105-113), it was found that at a wavelength of 600nm, black silicon, that is, its nanostructure, leads to reflection reduction from 9.9% to 6.5%, while the reduction becomes even more significant as we move towards larger wavelengths.

In addition, hybrid structures of silicon and aluminum nanocoating were observed. In the initial part of the infrared spectrum, in the range of 700-1600 nm, it was determined that the average absorption of the hybrid structure is 5 times higher in relation to the silicon cell (Zaman, Hossain, 2020, pp. 3082-3093).

As in the case of silicon solar panels, the safety aspect due to the use of toxic substances must not be left unmentioned. The most commonly used type of quantum dots in solar systems contains highly toxic elements such as cadmium (Cd), lead (Pb) and other harmful substances that can cause fatal consequences for human health and the environment (Fiandra et al., 2019, pp. 91 -101). However, success has been noted in this field due to the ability of quantum dots to adapt and overcome obstacles. The research of Meinardi et al. (2015, pp. 878-885) found that there is a way to produce solar panels based on quantum dots such that there is no need to use substances that are toxic and dangerous to the environment, while the group of authors led with You went a step further. Namely, not only was it established that there is a possibility for completely ecologically acceptable panels, but the use of such new technologies in semi-transparent panels that could replace windows on smart buildings in the future was considered (You et al., 2019, p. 1801967).

Quantum dots can be described as nanometer-sized crystals that have the ability to transport electrons. Such particles can be created to emit or absorb a specific wavelength of the light spectrum. Unlike silicon semiconductors, quantum dots have the ability to adjust the size of the band gap by changing the diameter which can be set precisely in the manufacturing process. If a photon that has less energy than the band gap of silicon comes to the silicon semiconductor, the photon will be transmitted through the material. In case the photon energy is higher than the band gap, an electron will be excited and it will "jump" over the band gap, but this excess energy (thermal loss) will be released immediately and the electron will go down to the lowest excited state. Only in the case that the wavelength of light is such that the energy of the photon exactly corresponds to the value of the band gap, the ideal excitation of the electron occurs without any losses.

Having all the above in mind, it should be pointed out that a quantum dot should be small enough so that quantum laws apply. Thanks to these laws, it is possible to establish a relationship between the diameter of a quantum dot and the size of the band gap for that quantum dot. If the diameter of the quantum dot increases, the band gap decreases, and vice versa (Figure 5a).

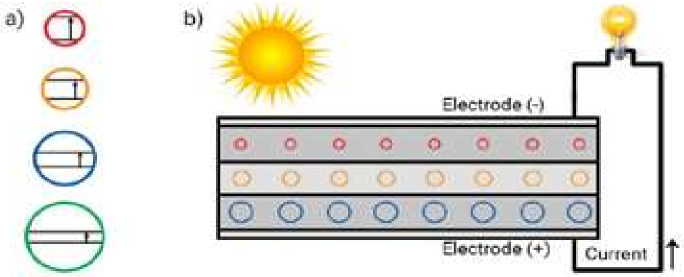

Figure 5. Schematic representation: a) dependence of the size of the band gap on the diameter of the quantum dot, b) quantum solar cells made of quantum dots of different sizes

A schematic representation of a solar cell based on quantum dots can be seen in Figure 5b where quantum dots of different diameters are placed in several different layers. The basic idea is to reduce the number of unused photons that the silicon cell cannot absorb (transmission and thermal loss). Each absorbed photon will excite an electron and generate an electron-hole pair.

Similar to traditional solar cells, by accumulating charges on the electrodes (electrons and holes), a potential difference will be created. Another interesting effect that is possible in such quantum systems is *multiple exciton generation* (MEG) (Beard, 2011, pp. 1282-1288). The basic characteristic of this effect is that one photon can excite two or more electron-hole pairs. This differs significantly from the classical silicon semiconductor where one photon always excites exactly one pair of electron-hole. This effect arouses great interest among scientists because if something like this were produced for commercial use, this discovery would be extremely important for humanity. That way, a significant reduction in the consumption of fossil fuels that harm the environment would be achieved.

CONCLUSION

With the use of solar energy, it is already possible to replace the traditional use of fossil fuels in order to obtain an energy system that is environmentally sustainable. Further growth in the need for devices that generate clean energy is completely expected, as the energy needs of humanity are constantly growing. The application of new technologies based on quantum dots provides ample opportunity for the improvement and further development of solar systems. Quantum dots can still be considered young technology and it is expected that each new experiment may change previous knowledge and create new theories and principles on which future generations of solar systems can be developed.

In this regard, the essential task remains to increase the efficiency of solar energy conversion, but also to reduce the cost of the production process. The road to the commercialization of quantum dot solar panels is still thorny. However, having in mind the wide interest in this field as well as current research, the expectations that something like this will happen in the near future are quite realistic.

REFERENCES

Beard MC., (2011). "Multiple Exciton Generation in Semiconductor Quantum Dots", *J Phys Chem Lett*. 2(11):1282-8. doi: 10.1021/jz200166y.

Brus L. E. (1986). "Electronic wave functions in semiconductor clusters: experiment and theory", *J. Phys. Chem*. 2555-2560.

Fiandra V., Sannino L., Andreozzi C., Graditi G., (2019). "End-of-life of silicon PV panels: A sustainable materials recovery process", *Waste Management,* 84 91–101

Filijović, M., (2015). "Trka za resursima u astroprostoru: Šta nam donosi budućnost", *Međunarodni Problemi*, Vol. 67 Issue 4, pp. 304-327., UDK:620.91:341.229, Biblid: 0025-8555, 67(2015)., DOI:10.2298/MEDJP1504304F

Hassanien R. H. E., Li M., Dong Lin W., "Advanced applications of solar energy in agricultural greenhouses", *Renewable and Sustainable Energy Reviews*, Elsevier, vol. 54(C), pages 989-1001.

Meinardi, F., McDaniel H., Carulli F., Colombo A., Velizhanin K. A., Makarov N. S., Simonutti R., Klimov V. I., Brovelli S., (2015). "Highly Efficient Large-Area Colourless Luminescent Solar Concentrators Using Heavy-Metal-Free Colloidal Quantum Dots", *Nat. Nanotechnol. 10*, 878– 885

Nunzi J., (2002). „Organic photovoltaic materials and devices", *C R Phys 3* 523–542

Ouyang J., Chu C., Szmanda C., Ma L., Yang Y., (2004)." Programmable polymer thin film and non-volatile memory device", *Nature Materials*, vol 3, 918-922.

Rashid M., Ahmed N., Noor N.A., Pakhuruddin M.Z., (2020). "Silicon quantum dot/black silicon hybrid nanostructure for broadband reflection reduction", *Materials Science in Semiconductor Processing*,Volume 115, 105-113, ISSN 1369-8001.

Savin H., Repo P., Von Gastrow G., Ortega P., Calle E., Garin M., Alcubilla R., (2015). "Black silicon solar cells with interdigitated back-contacts achieve 22.1% efficiency", *Nat. Nanotechnol*., 10, 624-630

Schaller R.D., and Klimov V.I., (2004). "High Efficiency Carrier Multiplication in PbSe Nanocrystals: Implications for Solar Energy Conversion", *Phys. Rev. Letts,* vol. 92. 186601-4

Tao M., Fthenakis V., Ebin B., Steenari B., Butler E., Sinha P., Corkish R., Wambach K., Simon E., (2020). "Major challenges and opportunities in silicon solar module recycling", *Prog Photovolt Res Appl*. 1–12

You Y., Tong X., Wang W., Sun J., Yu P., Ji H., Niu X., Wang ZM., (2019). "Eco-Friendly Colloidal Quantum Dot-Based Luminescent Solar Concentrators", *Adv Sci (Weinh)*, 6(9):1801967. doi: 10.1002/advs.201801967.

Zaman S., Hossain M., (2020). "Broadband light absorption by metal nanoparticle or quantum dot-coated silicon nanostructures for solar cell applications", *OSA Continuum*, Vol. 3, 3082-3093