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REVIEW ON THE CHALLENGES AND THE FUTURE OF SOLAR CELL FOR SPACE APPLICATIONS

N.I. Babashova [1] **N.F. Rajabli** [1] **R.B. Rustamov** [2]

1. Linnaeus University, Vaxjo, Sweden, nazrin.i.babashova@hotmail.com, nijat.rajabli@gmail.com
2. Laboratory of Modern Method of Applied Electrodynamics, Institute of Physics, Azerbaijan National Academy of Sciences, Baku, Azerbaijan, r_rustamov@hotmail.com

Abstract- Solar power systems are one of the major energy sources for spacecrafts and satellites. The first ever satellite was supplied by electricity generated via silicon based solar cells. Thus, solar arrays play integral role for space environment applications. However, space industry encounters various difficulties related to solar cells, and the main challenge is impact of radiation on the performance of solar units. Destructive nature of radiation has adverse effect on solar power systems causing certain damages leading to loss of efficiency and other negative consequences. In addition, there are other issues such as temperature and vacuum environment causing degradation of solar cells which also should be paid particular attention. In this paper, the physics of semiconductors, the history and importance of solar photovoltaics in space industry, the effect of radiation and techniques which can help to reduce or fix the negative impact of radiation, other challenges related to solar power systems, and the future of solar cells are reviewed.

Keywords: Solar Cell, Solar Power System, Radiation, Challenges, Space Environment, Space Applications.

1. INTRODUCTION

Solar photovoltaic energy conversion is based on transformation of light energy which includes infrared, visible, and ultraviolet to electrical energy. For conversion to happen, several stages should take place. Foremost, the light should be absorbed by a material where the transition from ground state to excited state occurs (Fonash, 2010). The physics behind the process is built on the concepts of quantum theory. Photons, which are energy portions of light, strike the surface of material transferring sufficient energy to electrons which, afterwards, move to higher energy levels. Gaining energy, electrons are able to jump the gap from the valence band into the conduction band leading to electron-hole pairs occurrence. Free-negative and free-positive charge carrier pairs start to move in opposite directions to external circuit. The potential difference occurs which pushes electrons through load in order to perform electrical work (Nelson, 2003).

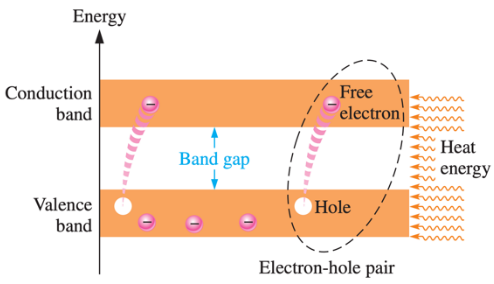

Figure 1. Energy diagram of silicon (Floyd, 2008)

The solar photovoltaic is consisted of numerous solar cells. Nowadays, silicon based solar cells are the most common type of technologies used for solar PV occupying almost 95% of the photovoltaic market in 2017 (Philips & Warmuth, 2019). The typical Si-based solar cell comprises following elements: front contact, antireflection coating which minimizes the loss of the light, emitter or n-type silicon with negative charge carriers, base or p-type silicon with positive charge carriers, back surface field, and back contact. The front and back contacts are necessary for making an electrical circuit.

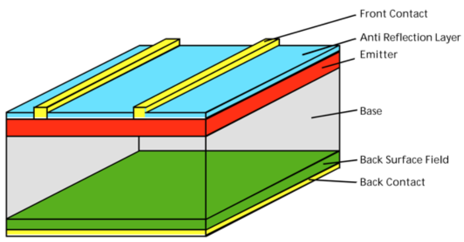

Figure 2. Schematic representation of Si-based solar cell (Goetzberger, 2005)

The area of a single solar cell is around 100 cm^2, and a DC voltage generated by the cell is between 0.5 and 1 Volt. However, such voltage is too low, and numerous solar cells connected together in series making a module are needed to obtain desired voltage. The module usually is comprised of 28 to 36 cells, which makes it possible to produce an output of 12 V in standard illumination conditions (Nelson, 2003).

Nowadays, commercially available solar panels have 15-20% efficiency. However, the best silicon elements can reach up to 24-25% efficiency under non-concentrated sunlight which is almost close to the theoretical efficiency of 29% (Blakers, Zin, McIntosh, & Fong, 2013).

2. SOLAR POWER SYSTEMS IN SPACE

Solar cells were first implemented in satellites and spacecraft in the late 1950s since solar panels are reliable and do not require constant maintenance (Jha, 2009). Made from silicon, solar cells supplied power to Vanguard satellite, the first US Earth orbiting satellite, which was launched on March 17, 1958. For over two decades, space industry was the main field where Si-based solar cells were applied (Walters, 2017). Later, in 1956, RCA Laboratories invented the solar cell based on GaAs with 6% efficiency (Jenny, Loferski, & Rappaport, 1956).

Experiencing more and more development, GaAs solar cells became far more efficient than Si solar units. In addition, GaAs solar cells showed higher resistance to radiation which is essential feature for space sector (Curtis & Anspaugh, 1991). Therefore, Si-based solar cells were slowly replaced with GaAs. Nevertheless, further improvement took place, and a switch from single-junction to multi-junction solar cells occurred. According to Henry, several p-n junctions of different semiconductors grown in a stack where the uppermost semiconductor has the highest band gap can be more efficient rather than single-junction solar cell (Henry, 1980). Afterwards, dual-junction, and then triple-junction solar cells were developed.

The first application of multi-junction solar cell in space was in 1997 which implies that it took almost 40 years for enhancement of solar cell technology since its first space implementation. Nevertheless, despite considerable progress, there are still various challenges which solar industry faces nowadays. For instance, even though more radiation-resistant solar cells were designed, the issue of radiation remains relevant. Different types of particles existing in space environment damage solar cells and decrease the lifetime of solar panels (Wang & Wang, 2014). In order to demonstrate adverse impact of radiation, the failure of Telstar satellite caused by Starfish nuclear test taking place in 1962 will be reviewed.

The nuclear weapon of 1.4 megaton strength was exploded at high altitude which was approximately equal to 400 km above Johnston Island in the Pacific Ocean. The explosion resulted in production of beta particles with an artificial radiation belt formation. The Telstar was the first satellite which failed due to subjection to the dose which was 100 times larger than expected. In addition, the nuclear test destroyed other six satellites within 7 months, and one of the main reasons behind the failure was destruction of solar cells (Stassinopoulos, 2015). This case demonstrates the role of solar units in space industry and importance of solar cell protection from external factors such as radiation. In following chapters, the problem of radiation will be examined in greater depth.

3. SPACE RADIATION AND ADDRESSING OF THE DAMAGE

Various types of charged particles with wide energy range present in space environment such as electrons, protons and heavy ions. Location of solar units in space, the solar cycle, and other parameters determine a vulnerability of solar power system to radiation. For earth-orbiting systems and devices located near the Earth, the main source of aforementioned particles is Van Allen belts which are donut-shaped clouds containing high-energy particle. Another source of such particles is CME or coronal mass ejection occurring during high solar activity. Radiation can lead to ionization, and in the case of high-energy electrons and protons it can result in displacement damage. Ionization is the generation of free-negative and free-positive charge pairs in the material that causes radiation effects. Lattice displacement is the dislocation of atoms from their initial position in the lattice, creating a point defect in the system (Wang & Wang, 2014).

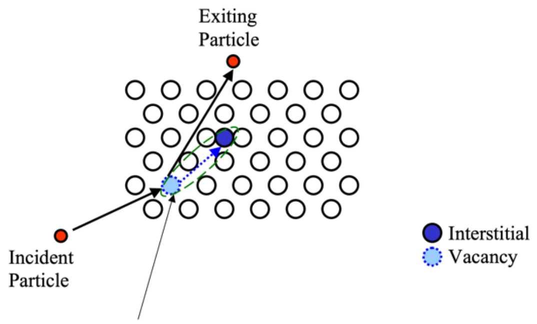

Figure 3. Displacement damage caused by radiation (Holbert, 2007)

These damages may cause serious complications such as formation of energy levels within the forbidden gap of the material with traps preventing an ability of electron to move and interrupting the flow of current. There are five main mechanisms affecting mobility of charges in semiconductors: generation, recombination, trapping, compensation and tunneling. Generation results in the increase of dark IV characteristics causing the photovoltage degradation. In the case of recombination, electron-hole pair recombines at the damaged site. Due to the fact that free-negative and free-positive charge carrier pairs are responsible for the current flow, recombination leads to degradation of the photocurrent. Trapping is the seizing of free charge carriers inside the defect. Compensation decreases the density of charge carrier due to the permanent placement of the carrier. Tunnelling decreases the tunnelling potential: an ability of charge carrier to pass through the energy barrier (Walters, 2017).

Even though it is not possible to avoid the damage caused by radiation, there are numerous ways to decrease or fix destructive effects of radiation on solar power systems. For instance, according to Yamaguchi and his colleagues, thermal annealing under room temperature helped to partially recover InP solar units properties (Yamaguchi, Itoh, & Ando, 1984). Higher resistance to radiation of solar cells while being under light illumination is another observation made by Yamaguchi (Yamaguchi & Ando, 1988).

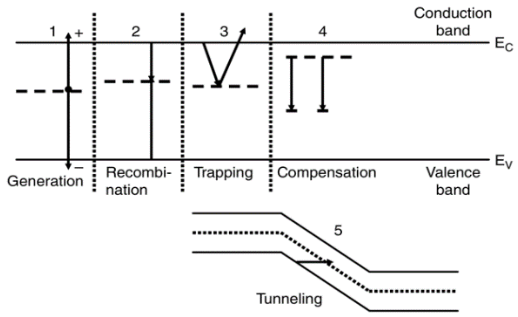

Figure 4. Illustration of the mechanisms affecting transportation of the current in semiconductor (Walters, 2017)

In addition, it has been discovered that forward-bias injection has positive effect on power recovery of solar cells (Yamaguchi, Ando, Yamamoto, & Uemura, 1984). Coating may also reduce the negative impact of radiation on solar units. It was reported that diamond-like carbon films (DLC) both improve efficiency of Si-based solar cells and have higher stability against effects of gamma-irradiation (Klyui et al., 2011). Other studies such as GaAs solar cells with back mirror contact (Bauhuis et al., 2005) and nanophotonic light trapping (Mellor et al., 2017) also showed positive results in the improvement of radiation hardness.

However, radiation is not the only problem which has devastating impact on solar cells: other issues such as ultraviolet darkening, meteoroids and orbital debris, temperature and vacuum cause slow degradation of solar arrays in space (Fernandez Lisbona, 2017). In the following chapter, both problems and advantages of solar power systems in space environment will be reviewed.

4. PROBLEMS AND ADVANTAGES OF SPACE SOLAR CELLS

Solar cells are reliable source of energy for satellites and spacecrafts. National Aeronautics and Space Administration (NASA) spent around $41 million to develop solar technologies for space applications between 1966 and 1973. Despite the fact that more money was invested in nuclear energy for space purposes ($120 million), NASA came to conclusion that solar power is more preferable energy source for space devices (Etzkowitz, 1984).

In addition, nuclear energy has higher risk of failure compared to the solar one. However, solar power systems are not suitable for outer planet missions. *"The solar irradiance at Jupiter (5.1 AU) is 3.7% of that at 1 AU. At Saturn (9.5 AU) it is 1.1%, at Uranus (19.2 AU) it is 0.28%, and at Neptune (30 AU) it is 0.1%"* (Surampudi et al., 2017). Due to the low solar intensities, outer planet missions would require solar power systems with high power capability. Also, taking into consideration the dusty environment of Mars (Mazumder et al., 2003) and high radiations of Jupiter, solar cells should be less vulnerable to harsh space conditions. Furthermore, the mass and volume of solar arrays are other challenges for long-distance missions, and in order to be able to deploy solar power systems for outer planet missions, considerable progress in solar cell features should be made (Surampudi et al., 2017).

As it was mentioned in previous chapter, other space conditions such as temperature, presence of meteoroids, and vacuum environment decrease the output power of solar power systems. For instance, UV radiation can darken particular types of solar cell cover glass leading to the decline of the sunlight transmission to the solar cells and increasing temperature of solar power systems which results in poorer electric performance (Goodelle, Brooks, & Mosher, 1975). Another phenomenon causing degradation of solar cell cover glass is micrometeoroids. ATOX, or atomic oxygen, is one more problem in space environment resulting in erosion of silver interconnectors in solar cells (Gerlach & Lothar, 1986). Vacuum has several negative impacts: it affects both metals of solar power systems such as Mg, Cd, and Zn evaporating them, and volatile substances like adhesives (Fernandez Lisbona, 2017). Thermal cycles have also detrimental impact on solar arrays: being subjected to a wide range of temperatures (from +150 °C to -180 °C), certain parts of solar power systems such as wires and insulators experience cracking (Schneider, Vaughn, Wright, & Phillips, 2015).

However, the problems may arise not only in space environment: there can be physical damages during manufacturing processes, handling, and transportation. The long period of storage may cause corrosion due to humidity. During the launch of solar power system to space there are vibrations, shocks, acceleration causing mechanical stress leading to physical damages (Fernandez Lisbona, 2017).

Taking into consideration all aforementioned facts, it can be implied that despite all advances and developments of solar photovoltaics properties, there are still various problems which should be tackled. In the next chapter, the future of solar cells for space applications will be studied.

5. FUTURE OF SOLAR POWER FOR SPACE TECHNOLOGIES

In this section, several applications of solar cells for space use will be reviewed. First, the period of 2023-2032 with four major planetary missions will be addressed, namely outer planets, inner planets, Mars, and small bodies. In addition, future possible inventions in solar photovoltaic technologies will be revised.

As it was noted in previous chapter, current solar cells are not appropriate for outer planets mission due to severe environment of distant planets and low solar irradiance. Solar power systems for the inner planets mission such as Venus and Mercury, on the contrary, will be exposed to the high solar irradiance since they will operate close to the Sun. For Venus orbital operations, current solar technologies can be applied without major modifications since environment is almost similar to the one of Earth orbital missions. Nevertheless, for Venus aerial missions at low altitudes, solar arrays which are capable to operate under low solar intensities (50-300 W/m^2), high temperatures (200-350 °C), and corrosive conditions will be required. For Mercury missions, solar cells should be improved as well due to extremely high solar irradiance (1000–14000 W/m^2) and high-temperature (~270 °C).

Despite the fact Mars has dusty environment as it was mentioned before, existing solar power systems are suitable for short-duration missions. Nevertheless, improved configurations of solar arrays such as higher efficiency and lower mass will be more beneficial for future Mars missions. In the case of small bodies mission including asteroids, comets, and dwarf planets, there is one main concern: for small bodies beyond 3 AU, environmental conditions are the same to outer planet ones. Therefore, present solar power systems will degrade relatively soon under extreme environment implying that today's solar arrays are not suitable and should be upgraded. Nevertheless, solar power systems for small bodies which are closer will still need some advances such as high voltage (>100 V), high power (20-100 kW at 1 AU), low mass and low stowage volume.

Touching upon the topic of solar properties, it is forecasted that solar panels will achieve around 38% efficiency at 1 AU by the mid-2020s. With the help of DoD, commercial funding and NASA, different types of solar power systems such as flexible fold-out systems, flexible roll-out systems, concentrator and solar power systems for harsh environmental conditions are in the development stage. In the near future, the performance of solar photovoltaics will achieve 150–200 W/kg, and in a longer time frame it may reach up to 250 W/kg (Surampudi et al., 2017).

6. CONCLUSION

In this paper, the working principle of semiconductors which are the major materials in solar cells, the history of solar cell for space environment applications, the problems of solar photovoltaic and its future were studied. The subject of radiation is of high importance and was carefully examined in the project. Two major damages, namely ionization and displacement damage with five main mechanisms (generation, recombination, trapping, compensation and tunneling) were reviewed. In addition, several measures helping to recover properties of solar cells or decrease adverse impact of radiation on solar power systems were mentioned such as thermal annealing, high-resistance coating and nanophotonic light trapping. Other issues such as thermal cycles, effects of vacuum on the components of solar array, possible physical damages during manufacture, transportation, storage and launching were addressed. Referring to the future applications of solar power systems for space environment, certain improvements and properties enhancement are projected in the near term.

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BIOGRAPHIES

Nazrin I. Babashova was born in Baku, Azerbaijan on December 4, 1996. She has completed her Bachelor degree in Chemical Engineering at Khazar University, Baku, Azerbaijan in 2018. She is Master of Science in Sustainable Energy Processes and Systems at Linnaeus University, Vaxjo, Sweden. As a member of "Network for Future Global Leaders" established by Swedish University, she organizes events and workshops regarding green energy and environmentally sound technologies. She has experience in renewable energy field and contributed her skills to World Bioenergy Association.

Nijat F. Rajabli was born in Gakh, Azerbaijan on January 30, 1997. He has completed his Bachelor degree in Computer Engineering at Khazar University, Baku, Azerbaijan in 2018. He is Master of Science in Software Technology at Linnaeus University, Vaxjo, Sweden. He has experience in solar car project and applications of self-adaptive systems in renewable energy sector.

Rustam B. Rustamov was born in Ali Bayramli, Azerbaijan, on May 25, 1955. He is an independent expert on Space Science and Technology. In the past, he was in charging of the Azerbaijan National Aerospace Agency activities as an Acting Director General. He has mainly specialized in space instrumentation and remote sensing and GIS technology. He has graduated Ph.D. at the Russian Physical-Technical Institute, S. Petersburg, Russia. He was invited for the work at the European Space Agency within the Framework of the United Nations Program on Space Applications at the European Space Research and Technology Center, The Netherlands. He has appointed for the United Nations Office for Outer Space Affairs Action Teams (member, Vienna, Austria), United Nations Economical and Social Commission for Asia and the Pacific (national focal point, Thailand), International Astronautically Federation (Federation's contact, France), Resent Advances in Space Technologies International Conference Program Committee (member, Turkey). He is an author of 11 books published by the European and United States famous publishers and more than 100 scientific papers.