INVESTIGATIONS IN THE FIELD OF SOLAR CELLS
AT YEREVAN STATE UNIVERSITY

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Results obtained in Armenia in last years are presented together with achievements in the world

1. Introduction

First Heliolaboratory in Armenia was organized at the Institute of Energetics, then it was re-organized in Armenian Branch of VNIIT-Kvant (Shirimanian, Albert Vardanyan). Main directions of activity of the Branch were investigations and manufacture of Collectors (Solar Heaters), concentrators of solar energy (including holographic), solar furnace, etc. (A. Vardanyan, V. Afyan, T. Vardapetyan, Yu. Avakian, et al.). Solar collectors were investigated, manufactured and installed later also by other new organizations (Solaren, SEUA, YSU, etc). Some silicon solar cells and panels produced in VNIIT were periodically tested in Soviet period here, in Armenian Branch.

One of leading positions in world in the field of photoelectrochemical conversion of solar energy in hydrogen has Yerevan State University. This activity does not reported here (see, for example, the review papers: V.M. Aroutiounian, V.M. Arakelyan, and G.E. Shahnazaryan, Solar Energy 78, 5, pp. 581–592, 2005; V.M. Aroutiounian, Сб. Фотокаталит. Преобразование солнечной энергии, Гетерогенные, гомогенные и молекулярные структурно-организованные системы, с. 228–294, 1991 г.; Успехи физических наук, 158, 2, с. 255–291, 1989 г.; Сб. Фотоприемники и фотопреобразователи, Ленинград, с. 253-287, 1986 г., which are cited many ten times).

Fantastic growth (80% in 2008) of photovoltaic solar modules and panels in world and their rapid decrease in cost continue. Regretfully, Armenia was not among producers of solar cells, but we have some achievements in the field, which are shortly discussed in this report.

Antireflection coatings for silicon solar cells

One of the crucial problems in solar cells is that a significant part of the incoming radiation is reflected, which limits the efficiency of such devices. One of important ways of minimizing this detrimental effect and subsequently improving the conversion efficiency of solar cells is a reduction of the reflectance using an appropriate antireflection coating (ARC). Application of the ARC is especially important for Si-based solar cells because Si reflects approximately 30% of the incident light in the spectral range where Si is photosensitive.
It is well known that the conversion efficiency of solar irradiation is proportional to \((1 - R)\), where \(R\) is the reflection coefficient. Therefore, the ARC must be designed in such a way which can provide low reflectance in the wide range of wavelengths of solar irradiation and especially in the wavelength region where the solar irradiation maximum place. For these purposes, the most widely used technique in the industrial solar cells’ technology is a combination of chemical texturization and deposition of ARCs. The following materials and combination of some of them usually are used as single or multilayer ARCs: ZnS, Al\(_2\)O\(_3\), Ta\(_2\)O\(_5\) layers as a single-layer ARC, SiO\(_2\)/TiO\(_2\), MgF\(_2\)/ZnS and MgF\(_2\)/CeO\(_2\) as double-layer ARC, and MgF\(_2\)/Al\(_2\)O\(_3\)/ZnS as triple-layer ARC. However, these materials are not suitable for the following reason: some of them are relatively soft and easily damaged and eroded by rain, wind and particle impact, have poor resistance to corrosive environments. The three disadvantages of using SiO\(_2\) are firstly, its low refractive index \((n=1.46)\); second, necessity in extended periods at high temperatures required to grow the dense 350 nm-thick ARC layer; and third, it is required an etch-back step.

Record laboratory efficiencies for silicon solar cell were obtained using extremely complex processing of inverted pyramids and high temperature passivation. Probably, such fabrication process may not be suitable for a cost-effective large-scale production of solar cell. Therefore, it is necessary to design such ARCs which price and preparation technology have to satisfy low-cost requirements for the large-scale production of silicon solar cells.

**Armenia:** The advantages of porous silicon (PS), such as the possibility of broadening of the bandgap, large active area for the light-semiconductor interaction, decrease in reflection losses, the specific character of its absorption spectrum, etc., make PS a promising material for use in the solar cell technology. We in Yerevan State University (Dept. Physics of Semiconductors and Research Center of Semiconductor Devices and Nanotechnologies-DPS&NT) have manufactured a PS layer as the ARC on common (industrial) solar cells instead of conventional ZnS ARC and compared their parameters. Our investigations have shown that the reflection from the porous silicon layers remained less even after degradation during 6 months, compared with samples with ZnS ARC and those without ARC [Adamian Z.N., Hakhoyan A.P., Aroutiounian V.M., Barseghian R.S., Touryan K. Solar Energy Materials and Solar Cells, 64 (2000), pp. 347-351; Proc. SPIE on Solar and Switching Materials, 4458 (2001) pp. 1-9].

In particular, we found theoretically and experimentally that the covering of porous silicon by other resistive to surrounding media dramatically decreases the reflectance of solar irradiation from silicon solar cells and make PS remarkably more stable in time. We took into account that diamond-like carbon (DLC) films have a high hardness, a high stability in hostile environments such as in aggressive chemical attacks, under irradiation or under ambient condition fluctuations. In addition, by changing the growth parameters, it is possible to change the refractive index of such a material from 1.5 to 3.1. Furthermore, due to a large band gap, DLC has a high transparency in the UV region, making it especially promising in solar cells for space applications. We realized technology of the DLC film growth using CVD from hydrocarbon precursors such as a toluene and sputtering of a graphite target. Note also that the deposition of DLC layers occurs at low temperatures (in some technologies, it does not exceed 300°C), which provides no changes in the properties of silicon solar cells.

We calculated the reflectance of a multilayer coating made of the DLC/PS double layers. The calculations were carried out for several values of refractive indices and thickness of the layers. As a result of simulations, we selected the following case: \( n_{DLC} = 1.5; \) \( n_{PS} = 2.9; \) and \( d_{DLC} = 88 \text{ nm}; \) \( d_{PS} = 46 \text{ nm}. \) The result is shown in Fig.1 where the reflectance spectrum of \( \text{SiO}_2/\text{TiO}_2 \) and single-layer DLC ARCs reflectance spectrum is given for the comparison. It is evident that the use of such a double layer DLC/PS structure will be better in comparison to one-layer DLC ARC and effective, because it is possible not only to preserve the low reflectance in the IR and visible regions, but also enlarged it towards the short-wave region (up to 400 nm). Such double-layer ARC is much stable in time and at different environments than the PS ARC. The enlargement of range with almost zero reflectance leads to a large increase in the absorbed part of the solar irradiation (this value can rise up to 60%), leading to an increase in solar cell efficiency.

**Fig. 1.** Reflectance spectrum of single-layer DLC (dashed line), double-layer \( \text{SiO}_2/\text{TiO}_2 \) (dash-dotted line) and double-layer DLC/PS (solid line) ARCs
We calculated also the reflectance spectrum of the SiOxNy/PS double layer ARCs for several parameters and values of the indices and thicknesses of each layer. The simulation results indicate that the smallest reflectance is achieved for the following parameters of the PS and SiOxNy layers including (i) the refractive indices $n_{\text{SiOxNy}} = 1.5$ and $n_{\text{PS}} = 2.9$ and (ii) the thicknesses of the layers $d_{\text{SiOxNy}} = 92$ nm and $d_{\text{PS}} = 48$ nm for SiOxNy and PS, respectively, double layer ARC with those of a DLC/PS double layer [Aroutiounian V., Martirosyan Kh., Soukiassian P., J. Phys. D: Appl. Phys. 39, pp. 1623–1625, 2006; Aroutiounian V.M., Martirosyan Kh.S., Hovhannisyan A.S., Soukiassian P.G., Proc. SPIE, Nanoengineering 6327 (2006) 63270T-1-63270T-10].

As can be seen in Figure 2(b), the reflectance for the latter extends to a somewhat broader spectral range compared with the former, from 400 nm to 860 nm wavelength for a reflectance remaining below 2%, with two minima at about 0.5% for 420 and 700 nm wavelengths. We focused our attention on the 450–600 nm spectral range which corresponds to the maximum intensity of solar irradiation. As compared to the DLC/PS (and SiO2/TiO2 double layer ARC), the SiOxNy/PS double layer ARC is characterized by a smaller reflectance precisely in this
useful range, which could contribute very significantly to further improvements in the performance of solar cells.

Finally, the advantages of a double layer coating compared with a single layer one for the case of SiO\textsubscript{x}N\textsubscript{y} can be traced in Fig. 3. Indeed, one can clearly see that the reflectance of the single layer SiO\textsubscript{x}N\textsubscript{y} remains well above the reflectance obtained for the double layer ARC with a minimum centered at 500 nm wavelength.

![Fig. 3. Comparison of reflectance spectra of SiO\textsubscript{x}N\textsubscript{y}/PS (——) double layer and SiO\textsubscript{x}N\textsubscript{y} (·······) single layer ARCs.](image)

Similar experimental investigations carried out in State Engineering University of Armenia (J. R. Panosyan et al.) for standard Si SCs covered directly by DLC (without PS layer).

Note that results of investigations in YSU of double-layer ARC for Si solar cells are covered by two France Patents and published in above mentioned papers. Paper in J. Phys: D Appl. Physics in 2004 had more than 1300 downloads and announced as one of highlight papers, published in 2004 in this Journal having the highest Impact Factor among journals in the field of Appl. Physics.

**Theory of Bifacial Sunlit Silicon Solar Cells**

One of the promising possibilities to make solar cells more effective and cheaper in design and manufacture is to illuminate them from both sides, under one-sun conditions (i.e., through the use of high-reflection, white-painted surrounding, or using very low-cost reflectors) [Gasparyan F. V., Aroutiounian V. M. Proc. SPIE on Solar and Switching Materials, 4458 (2000) p. 77–86, etc]. We showed that the short-circuit current under bifacial illumination is higher than the sum of the currents obtained under the alternate illumination of the front and rear surfaces, thus leading to an inherently better bifacial cells. The cell illuminated from p-side shows higher current at any voltage than the cell illuminated from n\textsuperscript{+}-side. The dependences of \(V_{OC}\), \(j_{SC}\) and \(\eta\) on the resistivity \(\rho\) are presented in our paper.
Existing thin-film technologies

Thin-film solar cells are deposited today directly on large area substrates. Thin-film photovoltaic (PV) cell has an inherent low-cost potential because its manufacture requires only a small amount of active (high cost) materials. The highest efficiencies have been achieved for multijunction solar cells, increasing at a rate of almost 1% per year in recent years. Multijunction cell efficiencies have the potential to approach 50% in the coming years.

There are three major inorganic thin-film technologies, all of which have been manufactured at pilot scale (1-2 MWp) and are being or have been transferred to high volume production (10 MWp to over 50 MWp). The three technologies are amorphous/micro-crystalline silicon (TF Si – 13% efficiency), and the polycrystalline semiconductors CdTe (16.5% efficiency), and CIGSS (an abbreviation of Cu (In, Ga) (S, Se) 2 – 19.5% efficiency).

Historic summary of champion cell efficiencies for various photovoltaic technologies.

They share a number of common features. Each technology requires only small amounts of semiconductor material: the film thickness is typically 1 μm. They have all shown long-term stability under outdoor conditions. Thin-film PV has a very high potential for cost reduction if materials and manufacturing can be improved by intensive and effective R&D on the fundamental science and production technology. Table 1 lists today’s’ level of module efficiency [K. Touryan, unpublished].
Table 1: Module Efficiency from survey of manufacturers’ websites and Performance Ratios

<table>
<thead>
<tr>
<th>Eff.</th>
<th>Module/Country</th>
<th>Temperature. coeff. (power)</th>
<th>Technology</th>
<th>Performance Ratio cell/module</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.0</td>
<td>WurthSolar WS 11007/80 (Germany)</td>
<td>-0.36 %/C</td>
<td>CIGS</td>
<td>55%</td>
</tr>
<tr>
<td>10.4</td>
<td>First Solar FS-275 (Int’l)</td>
<td>-0.25 %/C</td>
<td>CdTe</td>
<td>63%</td>
</tr>
<tr>
<td>8.5</td>
<td>Sharp NA-901-WP (Japan)</td>
<td>-0.24 %/C</td>
<td>a-Si/nc-Si</td>
<td>70%</td>
</tr>
<tr>
<td>8.1</td>
<td>GSE Solar GSE 120-W (USA)</td>
<td>-0.5 %/C</td>
<td>CIGS</td>
<td>41%</td>
</tr>
<tr>
<td>6.3</td>
<td>Mitsubishi Heavy MA 100 (Japan)</td>
<td>-0.2 %/C</td>
<td>a-Si, single-junction</td>
<td>66%</td>
</tr>
</tbody>
</table>

At present, the market share of thin-film PV within total PV production is below 10%, but might grow to 20% in 2010 and beyond 30% in the long term. Thin-film technology has a great potential for cost reduction. The global production capacity of thin films is expected to reach 1 GW p/year in 2010 and 2 GW p/year in 2012. It is being installed mainly in Japan, USA and Europe. Europe already has excellent thin-film R&D infrastructure and a number of thin-film factories. Total manufacturing costs are expected 1-1.5 €/W p in 2010, below 0.75 €/W p in 2020 and 0.5 €/W p by 2030.

**Thin Film Silicon Modules**

TF Si modules are based on amorphous silicon (a-Si) or silicon-germanium (a-SiGe) alloys, microcrystalline Si (μc-Si), and on processes involving the large-scale recrystalization of Si. A promising concept is the a-Si/μc-Si tandem cell. The best typical stabilized laboratory conversion efficiencies are currently in the range of 9.5% (a-Si), 12% (tandem a-Si: /μc-Si) and 13% (triple junction using SiGe alloys). This translates into commercial module efficiencies of 6.5, 8.5 and 7%, respectively, but large area module efficiencies up to 11% have been demonstrated at the prototype scale. TF Si cells with stabilized efficiencies above 15%, and, at the module scale, over 12% were demonstrated. In the long term, higher stabilized cell efficiencies should be above 17% by 2020. Analyses suggest that within the next two or three years production costs in the range 1.3-1.6 €/W p should be achievable for a-Si modules (efficiencies of 6.5 to 7.5 %), and for “micromorph” modules (efficiencies 8 to 9%) using production equipment that has recently become available. The target for 2013 is an efficiency increase to above 10%, with production costs below 1 €/W p on rigid substrates. The corresponding targets for flexible substrates are 9% and 0.75 €/W p, respectively. The targets assume production lines of 100 MW p/year for glass substrates and 50 MW p/year for flexible substrates. To meet these goals, cost-effective deposition of microcrystalline Si on large area (> 1 m²) must be achieved.
Copper-indium/gallium-diselenide/disulphide and related I-III-VI compounds (CIGSS)

Main of such materials has the absorption coefficient of phonons higher in comparison to silicon, which leads to decrease in thickness of active semiconductor layer. CIGSS technology currently exhibits the highest cell and module efficiencies of all inorganic thin film technologies (cells of 19.5%; commercial modules of 12%; prototype modules of 13-14% for areas of 0.35-0.7m²). Large-scale manufacturing (mainly in Europe) of the first generation of CIGSS modules has begun. New non-vacuum techniques for the deposition of device layers (like nanoparticle printing and electrodepositing) as well as the use of substrates other than glass (e.g. flexible metal and polymer foils) and low-cost encapsulation (using barrier coatings, transparent polymers) could reduce cost. A main challenge specifically facing CIGSS thin-film technology is the reduction of the material costs; high cost materials (In, Ga) should be replaced with, for example Al (a challenge that will become more pressing as CIGSS production increases to the very large scale), less material should be wasted during manufacture, active layer thicknesses should be reduced, and tolerance to impurity in the materials should be increased. We will expect the production modules at costs of much less than 1 €/Wp and module efficiencies well above 15%.

Armenia: Scientists in Armenia (Department of Physics of Semiconductors and Microelectronics and Research Center of Semiconductor Devices and Nanotechnologies in YSU (DPS&M) worked in the second part of 80s on the manufacture of thin CuInSe₂ (CIS) films and development of sensors for the control of the evaporation of each components of such a compound material and grown first good-quality thin films. We had good contacts with Solar Energy Research Institute (now Renewable Energy National Laboratory) in Golden (Colorado) and Arco Solar Inc. in California. Last company was larger producer in the world that time. We made the proposal to organize in Armenia the production of thin solar cells made of a-silicon and CIS with the help of Arco Solar Inc. Proposal was accepted, but terrible earthquake in 1988 in Armenia and destroy of the Soviet Union did not allow to realize this project.

Cadmium telluride (CdTe)

The attractive features of CdTe are its chemical simplicity and stability. The band gap of CdTe corresponds to maximum of the Sun spectrum. Because of its highly ionic nature, the surfaces and grain boundaries tend to passivated and do not contain significant defects. The efficiency of CdTe cells depends on how the CdTe layers are grown, the temperature at which the layers are deposited and the substrate on which they are deposited. The CdTe layers grown at high temperatures (~600 °C) on “alkali-free” glass cells have up to 16.5% efficiency. There is a large gap between the theoretically achievable efficiency (>25%) and efficiency reached in practice (16.5%). CdTe thin-film modules are already being produced in both Europe and the USA at capacities of
roughly 100–200 MWp/year. Module efficiencies of 9% have been reached and manufacturing costs already seem to be competitive with c-Si.

Emerging PV technologies

There are 4 sub-categories within the “Emerging PV technologies” category, all of which essentially aim at very low production costs with efficiencies around 15%.

Organic solar cells

For all of the approaches in this sub-category, the active layer consists at least partially of an organic dye, small, volatile organic molecules or polymers suitable for liquid process-sing. One is the hybrid approach in which organic solar cells retain an inorganic component (e.g. the Graetzel cell). The other is full-organic approaches (e.g. bulk donor-acceptor heterojunction solar cells). Organic solar cells offer the prospect of very low cost active layer material, low-cost substrates, low energy input and easy up-scaling. The efficiency and stability of organic solar cells are low today.

Armenia: Only Dr. T. Paronyan in the Institute for Physical Research of NAN, Armenia in Ashtarak, and Dr. H. Matnishyan in the Armenian Institute of Optical Researches, Yerevan, are working now in this field.

Thermophotovoltaics (TPV)

Such cells could be used in concentrating solar thermal power applications (CSP). Within Europe there are several low band gap cell types being investigated for TPV ranging from germanium-based cells to advanced ternary and quaternary alloys incorporating the elements gallium, antimony, indium, arsenic and aluminum. Although some R&D is still needed on the individual components of a TPV system (cell, monolithic module integration, emitter, filters), the main challenges are to integrated the components in a system, boost reliability and the demonstrate electricity costs less than 0.1€/kWh and a system efficiency of 15%. Photovoltaic devices developed for most TPV applications have bandgaps ranging from 0.5eV to 0.75eV. Most works on TPV devices have concentrated on III-V semiconductors InGaAs on InP (typically $E_g = 0.5–0.73$ eV, but are limited by lattice mismatch to the high band-gap ranges) or InGaAsSb on GaSb (limited to $E_g > 0.5$ eV by the miscibility gap). Meanwhile a maximum efficiency and maximum power density can be achieved with bandgaps between 0.2–0.5 eV for black body sources temperature in the range of 1200K to 2500K. This band-gaps range is considerably lower than almost all conventional TPV cells. Thus, there is a need for significant development in both new materials used for TPVs and in processing, to produce high performance TPV converters with lower band gaps.

Armenia: An alternative to InGaAs on InP, and InGaAsSb on GaSb substrate are less developed epitaxial InAsSbP lattice-matched structures on InAs or GaSb substrates. Lattice-matched InAs/InAsSbP TPV cells have variable bandgaps ranging from 0.3 to 0.5 eV, that displaces the
spectral response to the long-wavelength range, which is impossible to cover by GaSb-based materials.


In LPEE technique we used a growth cell consisting of the growth solution and two separate liquid-sources of grown layer components. This version of LPEE was realized in a horizontal liquid-phase electroepitaxial reactor, equipped with a specially modified slider-type boat to permit the usage of two additional channels and reservoirs for liquid-source solutions under a Pd-diffused H₂ flow. Epitaxial growth of InAsSbP quaternary layers were grown on n-InAs (100) substrates at constant temperature and electric current. The thickness of epilayers grown by LPE and LPEE was 3–5 μm. The investigations of cross-sectional area of p-n heterojunctions, morphology of layers surface and InAsSbP alloys composition have been carried out using SEM-EDX and Scanning Electron Microscope “Zeiss DSM 962” equipped with Oxford Instrument EDX equipment.

n-InAs/InAs₁₋ₓ₋ᵧₓSbₓPy (x=0.08; y=0.14) TPV cells have grown in a horizontal atmosphere pressure reactor. This TPV structure consists of an sulfur-doped InAs (with concentration n~2×10¹⁸cm⁻³) substrate, a 7-8 μm thick undoped InAs “buffer” layer and 1 μm thick p-type Zndoped InAs₀.₂₇ₐ₀₀₂₃ₚ₀₅ cladding layer. The spectral response of n⁺-InAs/n⁰-InAs/p⁺-InAs₀.₂₇ₐ₀₀₂₃ₚ₀₅ TPV diode heterostructure is presented in Fig.4. The monochromatic current maximum of sensitivity at the wavelengths 3.1–3.4 μm is 1.4-1.6 A/W which corresponds to a quantum efficiency of 0.5-0.6 without any antireflection coating. The presence of wide band-gap InAs₀.₂₇ₐ₀₀₂₃ₚ₀₅ emitter layer due to the “window” effect results to increasing the range of spectral sensitivity. As seen from Fig.7, the n⁺-InAs/n⁰-InAs/p⁺-InAs₀.₂₇ₐ₀₀₂₃ₚ₀₅ TPV diode heterostructure has a constant spectral sensitivity in enough wide region from 3.6 μm up to 2.6 μm and the spectral sensitivity at half-maximum sensitivity from 3.6 to 2.2 μm. Note that the wavelength 2.6 μm corresponds to the energy of photons 0.56eV.
The current-voltage characteristics, transmission spectra and optical response of n-InAs/p-InAs$_{1-x-y}$Sb$_x$P$_y$ TPV cells were measured and investigated. The maximum photoresponse is observed near the wavelength of 3.4 μm, which corresponds to the optimum efficiency of TPV cells [K. Gambaryan, V. Aroutiounian, T. Boeck, and M. Schulze, Physica Status Solidi 6, N 6, pp. 1456-1459, 2009].

**Novel active layers with reduced dimensionality. Tailoring the solar spectrum to boost existing cell technologies**

Nanotechnology allows introducing quantum wells, quantum wires and quantum dots in the active layer. There are three different approaches using these features. The first aims at obtaining a more favorable combination of output current and output voltage of the device. Both parameters are related to the band gap of the semiconductor used, but with opposite dependence. Selecting the optimum material thus implies making the best trade-off between current and voltage. By introducing quantum wells or quantum dots consisting of a low-band gap semiconductor within a host semiconductor with wider band gap, the current might be increased while retaining (part of) the higher output voltage of the host semiconductor. A second approach aims at using the quantum confinement effect to obtain a material with a higher band gap. The third approach aims at the collection of excited carriers before them thermals to the bottom of the concerned energy band (e.g. hot carrier cells). The reduced dimensionality of quantum-dot material tends to reduce the number of allowable phonon modes through which this thermalization takes place and increases the probability of harvesting the full energy of the excited carrier.

The theoretical limits of the efficiencies of these devices are as high as 50-60%. Research in novel active layers should be conducted in concert with concentrator system research, since it is highly probable that this technology will perform best under high intensity illumination.
The incoming solar spectrum for maximum conversion to electricity in the active semiconductor layer relies on up- and down-conversion layers and plasmonic effects. Nanotechnology might again play an important role here. Surface plasmons generated through the interaction between photons and metallic nanoparticles have been proposed as a means to increase the photoconversion efficiency in solar cells by shifting the wavelength of the incoming light towards the wavelengths at which the collection efficiency is maximal or by increasing the absorbance by enhancing the local field intensity. The application of such effects in photovoltaics is definitely still at a very early stage, but the fact that they can be ‘bolted-on’ to conventional solar cell technologies (crystalline silicon, thin films) may reduce their time-to-market considerably. An improvement of at least 10% (relative) of the performance of existing solar cell technologies thanks to up- or down-convertors or the exploitation of plasmonic effects should be demonstrated in the coming decade. With proofs-of-concept available, practical low-cost synthesis routes for these layers and manufacturing processes to introduce these layers into existing solar cell technologies should be developed (expected 2015-2025).

ARMENIA: Quantum Dot Solar Cells

The concept of a new device, namely the quantum dot (QD) solar cell, which provides a novel direction to the high-efficiency solar cell problem, was proposed and developed in Dept. of Physics of Semiconductors and Microelectronics at Yerevan State University in 2000 [V. Aroutiounian, S. Petrosyan, A. Khachatryan, K. Touryan, J. Appl. Physics 89(2001)2268]. At first, a theoretical model is presented for a practical p-i-n QD solar cell built on the base of the self-organized $\text{InAs}/\text{GaAs}$ system. We studied the advantages of the use of QDs in active region for photon absorption in the long-wavelength part of spectrum and increase the power convention efficiency.

The model proposed is based on a p’-i-n’ cell structure included multi-quantum-dot layers in the intrinsic region of the structure to enhance the photocurrent. The effective band gap for absorption will be determined by the lowest confined states of QDs. The internal quantum efficiency for the collection of charge carriers’ photoexcited in the QD can be enhanced using, for example, the phenomena of the resonant tunneling. High-density array of uniform QDs can be fabricated using the epitaxy technique. Usually, the strain fields of the lower QDs layer extended into the barrier material cause the vertical alignment of QDs. Due to the strong vertical coupling between QDs, electronic states can acquire a wire-like character. Therefore, high internal quantum efficiency for the collection of carriers’ photoexcited in the QDs can occur as a result of channeling the electrons and holes through the coupling between aligned QDs. This effect allows one to separate and inject the generated electrons and holes in QDs, into an adjacent p- and n-regions with high efficiency. By changing the deposition mode one can change the size and shape of the $\text{InAs}$ islands. Our model for the calculation of the power converting efficiency includes realistic estimates.
for the light absorption and photocurrent generation in p- and n-type region and QDs i-region, surface and volume minority-carrier recombination and junction thermal generation and recombination currents.

We calculated the photocurrent by solving the minority carrier transport equation at room temperature in uniform p-type and n-type regions. Taking into account detailed balance between the incident and emitted radiation in thermal equilibrium we obtained the expression for the thermal generation current in i-region and calculated the cell power conversion efficiency at the maximum power point. The calculations show that the inclusion of the QDs in the intrinsic region does indeed enhance short-circuits current without significant losses in the open-circuit voltage and results in significantly improved cell efficiency (up to 50% higher).

Later we continued our investigations taking into account that our paper in J. Applied Physics was cited more than 40 times in world literature. Moreover, QD solar cells were realized by A. Alguno in Japan [Appl. Phys. Lett. 83(2003)1258]. Usually the QDs should be placed together as close as possible in order to provide absorption coefficient as high as possible. Depending on QD spacing (dot density) they can play role of additional generation-recombination centers or they can form the intermediate band originated from the overlap between the electron confined states in dots. The incorporation of the QDs has two counteracting effects: the short-circuit current is increased because of the additional absorption of the subbandgap photons in the lower band-gap quantum dots; and the open circuit voltage is decreased because of the increase in the recombination of the photocarriers trapped in the QDs. To provide the additional photocurrent and improve the conversion efficiency photogenerated carriers in QDs need to escape and be swept by the built-in electric field under steady-state conditions. We made corresponding calculations and determined an optimal number of stacked QD layers which can produce the maximum photocurrent and increased a list of materials by Si-Ge and others for the manufacture of QD solar cells [V. Aroutiounian, S. Petrosyan, A. Khachatryan, Solar Energy Materials and Solar Cells 89(2005)165].


Recently we reported our first efforts for the growth of InAsSbP-based diode heterostructures with (and without) quantum dots (QDs) on InAs (100) substrates as a new material for TPV application. The following three lat-tike matched diode heterostructures have been grown and investigated: I – n-InAs/p-InAs\textsubscript{1-x-y}Sb\textsubscript{1-x-y}P\textsubscript{1-x-y} \textsubscript{x} \textsubscript{y}, II – n-InAs / undoped-n-InAs\textsubscript{1-x-y}Sb\textsubscript{1-x-y}P\textsubscript{1-x-y} / p-InAs\textsubscript{1-x-y}Sb\textsubscript{1-x-y}P\textsubscript{1-x-y} and III – n-InAs / p-InAs\textsubscript{1-x-y}Sb\textsubscript{1-x-y}P\textsubscript{1-x-y} with the quaternary composition QDs inside p-n junction spatial charge region (Figure 5).
For the fabrication of self-assembled strain-induced QDs and the growth of lattice matched quaternary InAsSbP emitter cap layer the conventional and “step-cooling” versions of liquid phase epitaxy have been employed. The values of $x=0.08$ and $y=0.178$ for p-type emitter layers have been chosen and measured for all three structures. The corresponding band gap energy of these alloys was equal to $\sim 0.4$ eV. The investigations of cross-sectional area of p-n heterojunctions, morphology of layers surface and calculations of quaternary InAsPSb alloys composition have been carried out using SEM–EDXA (FEI Nova 600–Dual Beam) equipment. The morphology, dimensions and distribution density of QDs were investigated by AFM technique (AFM–TM Microscopes–Autoprobe CP). The average density of the QDs was equal to $(5–7)\times10^9$ cm$^{-2}$, with dimensions of 0.7–12 nm in height and 20–80 nm in width. The Gaussian distribution of QD’s amount versus their average diameter has been also detected [K. M. Gambaryan, V. M. Aroutiounian, T. Boeck, M. Schulze and P. G. Soukiassian, J. Phys. D: Appl. Phys. 41 (2008) 162004; Armenian Journal of Physics 1, N 1, pp. 28-37, 2008].

The EDAX measurements on the top and bottom’s angles of InAsSbP quaternary pyramids as well as the lattice mismatch ratio calculations have been carried out. The compositions of quaternary InAs$_{1-x-y}$Sb$_x$P$_y$ pyramids with the values of $x < 4$ at. % and $y < 2$ at. % were measured. The good symmetry of compositions and lattice mismatch ratio values in the both angles of cut off pyramid’s base has been detected. Investigations showed that the strength on the top of pyramids was less than on the bottom’s angles and that the size of islands becomes smaller when the lattice mismatch decreases. The average density of the QDs was equal $(5–7)\times10^9$ cm$^{-2}$, with dimensions of 0.7–12 nm in height and 20–80 nm in width. The Gaussian distribution of QDs amount versus to their average diameter has been also detected. The critical size ($L_{\text{Critical}} \sim 500$ nm) of InAsSbP-based strain induced pyramid’s shape transformation to globe was determined.

Note that proposed and fabricated InAsSbP-based diode heterostructures with and without QDs inside p–n junction spatial charge region provide the optimum bandgap for high efficiency of
TPV cell, decrease the temperature of heat source–emitter and displace the spectral response to the long-wavelength region. These structures can be also useful for other mid-infrared applications.

Conclusion

Activity of Armenian scientist in previous years correspond World standards for investigation in the field of solar cells.