III-V HETEROSTRUCTURE PHOTOVOLTAICS IN RUSSIA

Honorary Lecture by the Becquerel Prize Winner

Viacheslav M. Andreev
IOFFE Physico-Technical Institute, St.Petersburg, Russia

Mr Chairman, Ladies and Gentlemen, Dear Friends,

I am greatly honoured to accept the prestigious Alexandre Becquerel prize on behalf of all colleagues from Russia, and other countries who have carried out the investigations with me in the field of photovoltaics during the last thirty five years. I thank the Becquerel Prize committee for recognition the achievements of my co-workers at the IOFFE Physico-Technical Institute who have made so much to receive the results we had. I also thank Antonio Luque for the kind and friendly words in his laudatory speech.

The investigations in the field of solar energy conversion in Russian were initiated by A.F.Ioffe in the 1930s. But at that time, the solar cell efficiency did not exceed 1%. In the decades that followed, their efficiency was increased up to 30% and higher owing to intensive work in the physics and technology of solar cells all over the world including the investigations, which have been carried out at the IOFFE Institute in the field of III-V heterostructure solar cells. These investigations were stimulated and supported by ambitions program of Space investigations in the USSR. Since the first solar-powered satellites “Vanguard-1” and “Sputnik-3” were launched in the spring of 1958, solar arrays based on single crystal silicon were the main source of energy on the spacecrafts.

In the beginning of 1960s, it was found that single-junction GaAs based solar cells ensured the better temperature stability and higher radiation resistance. The first applications of single-junction GaAs solar cells were on the Russian spacecrafts “Venera-2” and “Venera-3” launched in November 1965 to the “hot” planet Venus. The area of each GaAs solar array fabricated by the Enterprise KVANT on these space crafts was 2 m^2. Then the Russian moon-cars with GaAs 4 m^2 solar arrays were launched in 1970 (“Lunokhod-1”) and 1972 (“Lunokhod-2”). The operating temperature of these arrays on the illuminated surface of the moon was about 130 ^oC. Therefore silicon based solar cells could not operate at these conditions. GaAs solar arrays have shown enough high efficiency of 11% and have provided the energy supply during the all life-time of these moon-cars.

AlGaAs/GaAs heterostructures were received at first in the IOFFE Institute in 1967. Due to these developments, solar cells based on AlGaAs/GaAs heterostructures were created in the Institute in 1970. Owing to higher efficiency and improved radiation hardness of the developed solar cells, this technology has been utilized by KVANT and high scale production of AlGaAs/GaAs space arrays have been organized for the spacecrafts launched in 1970s-90s. Heterostructure solar array with a total area of 70 m^2 was installed in the Space station MIR launched in 1986. During the 15 years on the orbit, the array degradation has been lesser than 30% under difficult conditions of its operation, of appreciable shadowing, effects of numerous docking and ambient environment of the station. At that time, it was the high-scaleest demonstration of AlGaAs/GaAs solar cells advantages for space applications.

Several types of high-efficiency single junction and tandem solar cells for space and terrestrial applications were developed in 1980s-90s. The developed in IOFFE Institute a low-temperature liquid-phase epitaxy modification for the growth of AlGaAs/GaAs structures has yielded solar cells with confirmed efficiency of 24.7% (AM0, 100 suns), 27.5% (AM1.5D, 140 suns), 25-26% at 2000-1700 suns and 23% at 5800 suns, which are among the highest value for single junctions cells measured in these conditions.

The MOCVD method is now the main one for preparation of multilayer AlGaAs/GaAs and GaInP/GaAs solar cell heterostructures. This method provides a good crystal quality of epitaxial structures, high productivity and reproductivity of the fabrication technology. High-efficient radiation-stable AlGaAs/GaAs solar cells with internal Bragg reflector were developed at the IOFFE Institute in 1990s by the MOCVD method. The main reason for the photocurrent and efficiency degradation of solar cells in space conditions is a reduction of the minority carrier diffusion length at electron and proton irradiation. Bragg reflector made of multilayer AlGaAs/GaAs heterostructures selectively reflects unabsorbed photons with energy a little higher than GaAs bandgap providing the second pass of these photons through the photoactive region thereby increasing the photocurrent and improving the cell irradiation hardness.

Last decade, mechanically stacked and monolithic multijunction (MJ) solar cells based on III-V heterostructures were developed for space and terrestrial applications. Efficiencies exceeding 28% (AM0) and 32% (AM1.5D) have been achieved (Boeing, IOFFE Institute, NREL, FhG-ISE) in mechanically stacked concentrator GaAs/GaSb and GaAs/InGaAs tandems. Monolithic multijunction GaInP/GaAs/Ge solar cells with efficiency of more than 25%(AM0) and 30% (AM1.5D, 100-1000 suns) were developed at first by NREL and then by the others teams. Today, monolithic MJ solar cells achieve efficiencies of more than 27% AM0 and exceed 32% at concentrated AM1.5D sunlight.

The cost of III-V cells exceeds the cost of monocrystalline silicon solar cells. Consequently, an application of the MJ solar cells without sunlight concentration is only justified for space power systems, in which the cost increase of generated electricity is compensated by the higher efficiency and better radiation stability of these cells. For terrestrial conditions an application of the MJ solar cells in modules without sunlight concentration might result in higher costs per Watt, if compare to modules made of silicon solar cells. Accordingly, for terrestrial applications the MJ solar cells should be used in combination with concentrators of sunlight made of cheap materials (e.g. Fresnel lenses). The area of the solar cells necessary to obtain an equivalent electric power decreases in these concentrator modules roughly by the factor of 500-1000. Therefore, an essential cost reduction of electric power produced by power installations equipped with MJ solar cells and concentrators is expected.

Some problems arise in the practical realization of techniques for conversion of concentrated sunlight. First, as sunlight density increases, the density of photocurrent generated by a solar cell grows proportionally, which complicates the cell design in order to decrease resistive losses. Second, the temperature of solar cells increases, requiring an efficient heat removal system. Third, it is necessary to design highly efficient and cheap sunlight concentrators. Fourth, we must have precise Sun tracking, which adds complexity to the installation design and its performance. At the same time, owing to the application of concentrators, it is possible to use expensive semiconductor materials, for example, III-V cascade solar cells for the fabrication of high-efficiency, thermally stable, and high power solar cells. Concentrator cells are more efficient than one-sun cells and also permit the use of the combined thermal, photon and injection annealing effect to remove radiation defects arising during the cell operation in space. Since comparatively small-area cells are used in this case, a better protection from adverse environmental factors can be provided, owing, in particular, to the screening action of concentrators and heat removal systems.

Further progress in concentrated sunlight conversion primarily relies on whether we can achieve maximum efficiencies of light concentrators and, hence, of solar cells. This enhances the importance of the subjective factor, hampering the improvement of the method. Indeed, the world's practice can give examples of specialists in optics acting as the principal designers of concentrator cells and recruiting semiconductor experts as co-executors, or vice versa. The crucial factor of motivation in each case is whether a particular new design or technology concerns the concentrator or the cell. In either case, it is necessary for various specialists to cooperate and to become cross-informed about both the fundamentals and the latest developments in relevant sciences. It seems obvious that the information should be presented in such a way as to be able to break the conventional stereotypes of non-specialists, who may consider concentrator designing as being too simple and self-evident while the operation principles of semiconductor cells as being sophisticated and requiring too much effort for comprehension.

Terrestrial concentrator photovoltaics was initiated in the Soviet Union in 1965-1967, when the first installations with sunlight concentrators and silicon solar cells were developed. Since that time, a lot of concentrator photovoltaic installations have been fabricated over the whole world. The concentrator installations designed and fabricated in the IOFFE Institute in beginning of 1980s consisted of parabolic mirrors or Fresnel lenses with area of about 0.1 m^2 and AlGaAs/GaAs concentrator solar cells with output electric power of about 10-15 W. The main disadvantage of these installations with large sizes of concentrators was the overheating the high-power solar cells. The other problem was a poor stability of tradition polymer materials which have been used for fabrication of Fresnel lenses at that time.

Recently, the concentrator mini-modules based on silicone-glass Fresnel lenses with area of about 10-20 cm^2 and concentrator solar cells with area of 0.04-0.1 cm^2 have been developed in the IOFFE Institute. A silicate glass is used as a superstrate and a very thin profile made of transparent silicone in the refractive Fresnel structure. In this case, the front glass surface of the module is flat and therefore, resistant to the influence of abrasive particles. Silicone is known as a high-transparent polymer material resistant to UV irradiation. Also, it is characterized by the good elastic and thermal properties. Being polymerized directly on the glass surface (using a special intermediate adhesive layer) silicone remains in strong contact with the glass superstrate at any variation of temperature and other conditions. The long-term outdoor monitoring has shown high stability of the modules with these lenses that makes them very perspective for high scale terrestrial photovoltaics. Estimations show the possibility to reduce the price to \$ 1/Wp of concentrator modules based on high-efficient, high concentrator (500-1000x) multijunction III-V solar cells and developed composite Fresnel lenses.

In conclusion, I should like to say that main received results were obtained due to close co-operation between photovoltaic specialists in Russia and other countries. More than thirty years fruitful co-operation consolidated our team with Dr. M.Kagan and colleagues from Enterprise KVANT.

Recent progress in the field of high-efficient high concentrator solar cells was achieved under the sponsorship of the EC in the frame of the HERCULES project with Instituto de Energia Solar, Madrid, headed by Prof. A.Luque and with Dr. G.Smekens team from Brussels.

Concentrator modules of the last generation based on composite Fresnel lenses were designed and fabricated in the frame of INTAS project with Dr. A.Bett and colleagues from Fraunhofer Institute for Solar Energy Systems, Freiburg.

The advanced space concentrator modules have been developed in co-operation with Dr. K. Bogus and colleagues from ESTEC of European Space Agency. A long-term project has been carried out in the field of space photovoltaics in co-operation with Dr. D.Flood and colleagues from Photovoltaic Branch of NASA Glenn Research Center.

There were also close contacts and joint projects with Italy, Japan, China, India and other countries.

I hope to continue the work in this very interesting and important area in co-operation with all my friends.

Thank you for your attention.