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High efficiency solar cells for space applications

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The present paper is a review of the current situation in high efficiency solar cell for production of energy for special applications. The comparison of the most popular Si, GaAs, InGaP and InP solar cells, as well as their parameter variation with increasing temperature, radiation treatments and improving design have been analyzed. The conditions of the solar cell operation in the space and the requirements for modern advanced devices are discussed as well.

Keywords: III-V solar cells; Solar cell efficiency; Solar cell design

1. Introduction

Starting from the 1953 - year when the semiconductor solar cell (SC) was invented, - SCs were mainly applied in the space satellite energy systems. Up to 1990 the solar cells were created on the base of single crystal, poly-crystal and amorphous Si. Mainly caused by the comparatively high efficiency of these solar cells (η=12-17%) and relatively cheap technology. The price of GaAs SC was around ten times higher than the price of Si SC. In 1990 when the GaAs SC technology moved into volume production the price of GaAs SC dropped to five times of Si SC price.

Sharp rise of GaAs SC volume production was connected with the revolution in the satellite industry [1,2]. It was caused by the improvements in III-V solar cell design, coupled with the demand for satellites with more on-board power and longer life period on the orbits. Actually the figures 1, 2 and 3 present the change during last 20 years in parameters such as: the satellite life-time, named End of life (EOL) on the orbits (Fig.1), as well as the power of photoelectric batteries on satellites (fig.2) and power density per kilogram (fig.3) [2].

Single crystal silicon solar cells (SC) working under non-concentrated solar radiation with efficiency η=17-18% had the most spread application in space solar energy devices. Despite on some shortages (brittle, high density) GaAs single crystals have essential advantages in comparison with Si. GaAs has a greater band gap (1.40 eV) and as a result it will not absorb the sun light with wavelength > 0.9 μm. It is the reason of the low reverse excess saturation current $J_{rev} = 10^{-9} - 10^{-10}$ A/cm^2 in GaAs SC in comparison with Si SC, were $J_{rev} = 10^{-6} - 10^{-7}$ A/cm^2 ; as well as the higher value for open circuit voltage and the low coefficient for the change in efficiency with temperature for GaAs SC [3,4]. It was discovered that AlGaAs/GaAs interface is characterized by a small density of extended defects and recombination centers due to practically the same lattice parameters at epitaxial growth temperature. This effect allows that solar cells based on AlGaAs/GaAs structures have a low surface recombination velocity (S) and two sides carriers collection with high efficiency η=20-25%. The most popular GaAs SC were created on the base of p-AlGaAs - p-GaAs - n-GaAs heterostructures.

For solar concentrator application the dependence of the conversion efficiency of these cells on sun concentration shows that maximum efficiencies of about 25%, 22,5% and 22,5% for AlGaAs/GaAs, Si/Si and Si/SiGe concentrator devices could be achieved without including the possible enhancement due to geometry optimization and surface passivation [5].

Sun radiation, electron and proton particles from Earth radiation belts, vacuum and thermo-cycling affect on the photovoltaic (PV) battery on space orbits [1,2,6,7]. With the aim to decrease of radiation influence the PV batteries as a rule are covered by a radiation protective glass. The efficiency of the glass protection depends on glass thickness. The latter could be changed from 0,1mm up to 0,5mm for different space orbits. One of the negative factor affecting on PV battery is a charging due to radiation. The protective glass on the PV battery surface can accumulate the electric charges. At one specific value of these charges the glass electrical breakdown could be initiated.

Application of solar concentrators can be used not only to increase SC output electric power, but also in the some degree for radiation protection as well. Thus radiation and thermo cycles are the most important factors, which affect the efficiency of PV battery solar cells, used on the space

Table 1. Radiation effects on space orbits [8].

Orbit altitude, (km)	**Electron dose** (rad)	**Proton dose** (rad)
700 (98 grad)	3.9×10^5 (3 years)	9×10^5 (3 years)
1400 (63 grad)	9.6×10^6 (3 years)	1×10^6 (3 years)
2000 (51 grad)	1.5×10^7 (3 years)	4.3×10^6 (3 years)
36000 (0 grad)	4×10^8 (5 years)	7×10^6 (5 years)

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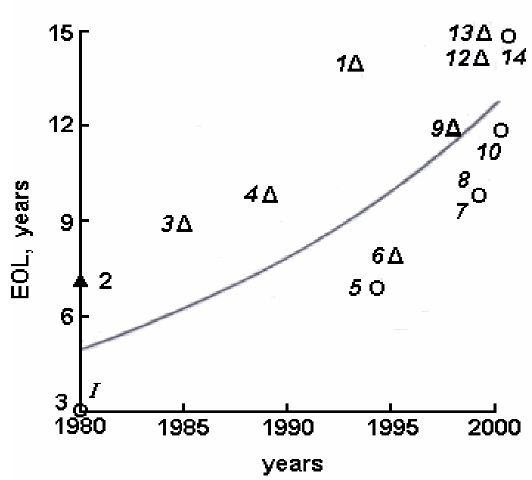

Figure 1. End of life period for different satellites: 1-Gorizon, 2-Intelsat, 3-Morelos-1, 4-ICSAT-1, 5-Gals, 6-Galaxy-X, 7-Yamal-100, 8-Navstar-2R, 9-Galaxy-X, 10-Yamal-200, 11-Solidaridad-1, 12-ICSAT-6, 13-Galaxy-XI, 14-Express K-2. [2].

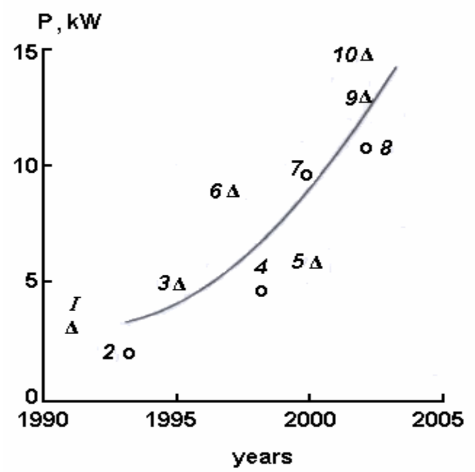

Figure 2. Electrical power on the board of different satellites: 1-Astra, 2-Gorizont, 3-Arabsat, 4-Yamal-100, 5-HS-601, 6-A-2000, 7-Yamal-200, 8-Express-2000, 9-HS-702, 10-Spacebus [2].

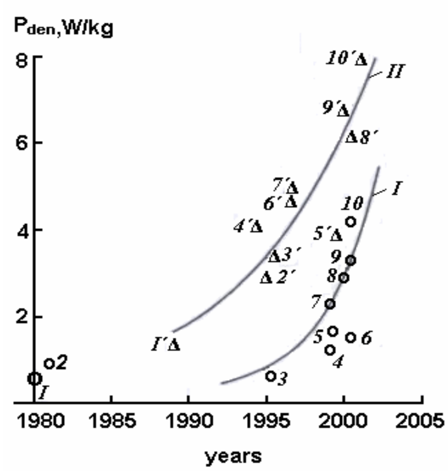

Figure 3. Electrical power density per kilogram for Russian (I) and International(II) satellites: (I) 1-Gorizont, 2-Molnia, 3-Express, 4-Express-M, 5-Yamal-100, 6-Mayak, 7-SESAT, 8-Yamal-200, 9-Express-2000, 10-Express K-2. (II) 1-ICSAT-1, 2-Galaxy-R, 3-ICSAT-4, 4-A-2100A, 5-TELESTAR, 6-A-2100AX, 7-Galaxy-VIII-I, 8-Anik-F1, 9-XM-1, 10-A-2100(modern) [2].

orbits.

The calculated doses of the radiation exposition on the satellites, worked during 3-5 years on low earth orbits (LEO) with altitude H = 700-2000km or on geosynchronous Earth orbits (GEO) with H = 36000 km , are presented in table 1 [8]. . As can be seen GEO are attractive for commercial reasons, but are extremely challenging for satellite designers because of particle radiation

The satellite flying around Earth is exposed to a cycle of dark and sun exposition. This cycling will enhance the thermo-cycling variation of the PV battery temperatures. For example, the space orbits with H=2000 km are characterized by a temperature variation from -55 ^{o}C up to 60 C. On Soviet lunar landing automatic station the temperature fluctuation changes from 200 C up to -200 C. The strong PV battery temperature fluctuation is a extremely challenging for SC parameter thermo stability.

The studies connected with the research of radiation impact, high level solar exposition and temperature on SC parameters, as a rule, will impact on SC design improvement [4, 6-9]. It was shown, for example, that SC radiation degradation essentially depends on the p-n junction depth and the quality of the semiconductor structures [6,9].

Laboratory test results for variation of output parameters for Si and GaAs SC´s at electron beam radiation and temperature changes are presented in Table 2 [1].

As can be seen GaAs based SC’s are characterized by the lowest values of efficiency variation with temperature and better radiation stability, than Si SC’s. The above mentioned effect in GaAs based SC’s could be explained by recombination enhanced annihilation of radiative point defects. Both of these aspects contribute to explain the low degradation velocity of GaAs SC’s parameters and the long life-time (up to 15 years) on space orbits.

The main ways to improvement of solar cell efficiency include [8]: the expansion of spectral photosensitivity range; the reduction of p-n junction depth; the increases of the minority carriers diffusion length in base layer and the reduction of the reverse p-n junction saturation current; the use of additional homo-junction barriers and p-n junctions; the decrease of surface recombination velocity on photosensitive surface; the optimization of contacts and other.

The expansion of spectral photosensitivity range of p-AlGaAs - p-GaAs - n-GaAs SC’s at the first was achieved by the application of $AlxGa1_{-x}As$ alloys. It is essential that $Al_xGa_{1-x}As$ band gap increasing with x content is not accompanied by a surface recombination velocity increment on the photosensitive surface. The later is consequence of the indirect band gap for solid solution $Al_xGa_{1-x}As$ with x>0,34. The creation of the isotope potential barrier in hetero-structures is used for reverse saturation current reduction [9-10].

As a rule in GaAs SC’s the AlGaAs solid solution is used for wide gap windows. However the AlGaAs solid solution is characterized by a great oxidation velocity, as

Table 2. Comparison of different SC performances on temperature and radiation [1].

Type	**Efficiency**(%)	**Power** (W)		**Power** (W)			
SC materials		Un-Irradiated		1MeV Electron Fluence			
				3 $x10^{14}e/cm^2$		$1x10^{15}$ e/cm^2	
		28 °C	50 °C	28 °C	50 °C	28°C	50 °C
Silicon	14.8	170.9	149.5	129.0	112.2	113.0	98.8
GaAs/Ge	18.5	218.1	208.2	188.1	179.6	166.8	159.3
GaInP/GaAs/Ge	21.5	253	242.8	223.0	211.9	192.7	183.0

well as the relatively low radiation resistance. During last five years a lot of attempts were made for replacement the AlGaAs solid solution by more stable compound such as InGaP. The heterostructures of InGaP/GaAs, InGaAP/InP and InP/Si are considered now as the photoelectric materials with most perspective [1, 7-10].

The highest efficiency of InGaP/GaAs SC's is consequence of two reasons: i) The wider band gap of InGaP materials in comparison with the band gap of AlGaAs alloys give the possibility for expansion of the spectral photosensitive range. ii) The AlGaAs/GaAs heterojunction is characterized by the essential conduction band discontinuity, as well as for InGaP/GaAs heterojunction the larger band discontinuity observed for valence-band. As result the more mobile carriers - electrons - are better separated by the p-n junction electric field [8].

The development of single (SQW) and multi-quantum well (MQW) growth technologies, as well as super-lattice creations in p-n hetero-junctions and in base layers caused a revolution in solar cell technology based on hetero-structures. Really the creation of SQW and delta - doped layer enhance the reverse SC saturation current reduction [10,11] as well as MQW insertion in I-layer of SC p-i-n junction to stimulate the efficiency rise [12,13]. The latter effect was achieved by the expansion of the photosensitivity spectrum and photocurrent increase (40%) due to the best separation of photo-carriers in quantum wells at practically the constant value of open circuit voltage (the variation no more then 0,03V).

The efficiency of the best GaAs solar cells (27%) with accuracy near 10% is in conformance with the theoretically predicted value (30%) for GaAs SC's with single p-n junction. Practically the unique possibility to improvement these type devices consist in creation of tandem (cascade) converter. This advantage is based on the more effective use of solar radiation energy which has a wide wavelength range (visible, near infrared and infrared). Creation of cascade SC is one of the main directions for the increasing of the photoelectric conversion efficiency. In cascade devices the SCs are placed one after another with decreasing band gaps on beam spreading. The upper wide gap element of such cascade converts the short wave part of solar spectrum with minimum losses of photon energy. The lower narrow gap SC allows using a considerable part of long wavelength solar radiation. In the case of using the adequate quantity of semiconductor layers the efficiency in solar energy conversion can approach to 60% (theoretical value). The III-V compounds are the most promising materials which best of all satisfy to above mentioned conditions.

There are a lot of articles connected with theoretical optimization of two p-n junction tandem converter parameters. The typical design of such two element tandem SC based on InGaP and GaAs p-n junctions is presented in figure 4 [14]. The comparative analysis of the radiation response for InP/Si, InGaP and tandem InGaP/GaAs space solar cells under both electron and proton irradiation is presented in [15]. The kinetics of parameter changes during

Table 3. The best world results for the efficiency of tandem solar cells

Structure	**Efficiency**	**Production firms**
InGaP /InGaAs/ Ge	29-30% (AMO) 31-32% (AM1.5)	Toyota Technological Inst Japan Energy Corporation [17].
InGaP / GaAs / Ge	32.3% Concentrator solar cell	Spectrolab, USA Nation. Renew. Energy Lab. [18].
GaAs / GaSb	31.4% C=100, AM 1.5 at 25°C	Fraunhofer Inst. of Solar Energy Systems, Germany [2].
InGaP / GaAs	30.28% (AM1.5) 25.7% (AMO)	Jap. Energy Corporation [21].
GaAs / InGaAs	28% (AM1.5)	Sumitomo Electric Ind. Ltd. Japan [19].

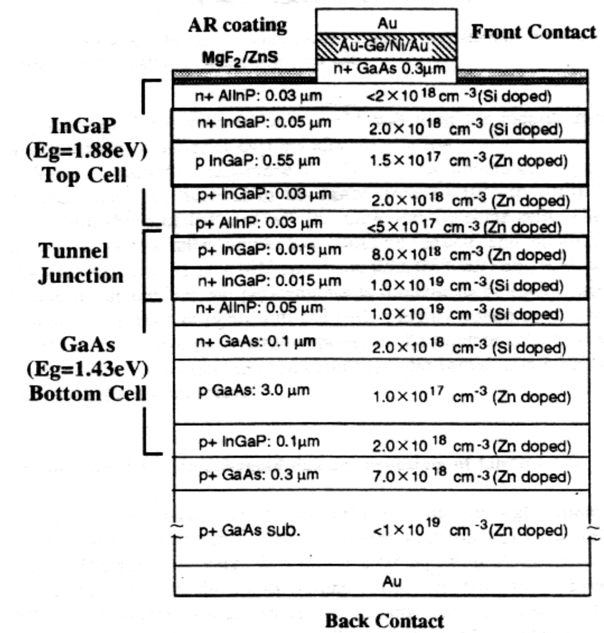

Figure 4. Schematic diagram of an InGaP/GaAs tandem cell [14].

radiation degradation is used for prediction of the end-of-life (EOL) performance of such solar panels on Earth orbit. It has been shown [15], that tandem InGaP/GaAs SC´s on orbits outside of the Earth radiation belts (H < 2000km) provide the highest EOL specific power. However, on the orbits which pass through the radiation belts (2000km < H> 20000km), the InP/Si SC´s provide the highest power on more than 30% (Fig.5). Table 3 presents recent world results for tandem solar cell efficiency, which were received in last five years.

Evidently, for the achievement of the cascade SC efficiency predicted by theory a further improvement in the SC production technology and design is needed. Right now the creation of 40% efficient, multijunction laboratory cells under 500 light concentrations is a reasonable, important near-term goal for the photovoltaic program [16].

III-V material solar cell advantages mentioned above were completely confirmed with the GaAs solar battery operation in Soviet "Lunokhod-1, -2" and American "Apollo-14, -15" automated stations in lunar surface missions. GaAs solar batteries at T=130-140 C on the lunar surface generated an electrical power more than 2 times biggest that calculated power for Si battery in that conditions.

Starting from 1980 GaAs solar battery actively was flight tested and in 1990 began to be board used in commercial satellites: ESA: UOSAT (January 1990), TUBSAT (June 1991), STRV-1A (June1994), UPM/LB Sat (February 1995). ASI: ASGA on EURECA (July 1992). ASI-CNES COOPERATION: ARSENE (May 1993). ASI-CONAE-NASA COOPERATION: SAC-B (1996). Commercial minisatellites: OERSTED (1997), MINISAT (1996), UNAMSAT (1996), SUPERBIRDS-1-4 (1998-2000).
The telecommunication satellites as a rule are intended for a geosynchronous orbit, where it can arrange connection with 1/3 of the Earth's surface. But as can be seen from

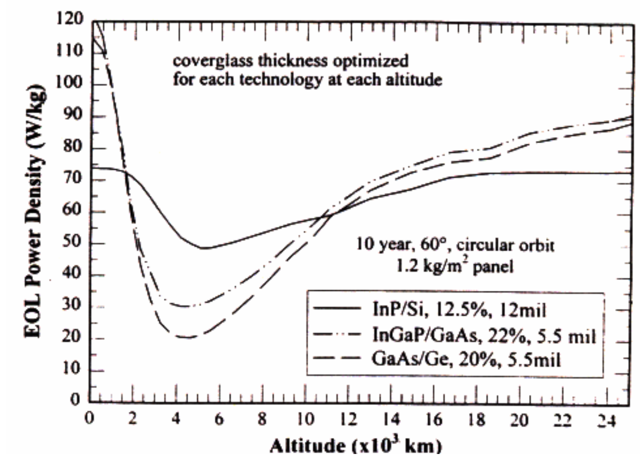

Figure 5. Calculation of the EOL power density of a solar panel in Earth orbit [15].

table 1, GEO is characterized by a high particle radiation and therefore very demanding operation regimes.

The current space projects are directed to the development of new class of telecommunication system, so-called "satellite network". It is a chain of interlinked small satellites which are situated into low Earth orbits. A satellite into the LEO cover a smaller earth's surface, but the time required to transmit data is also reduced. The latter is a positive factor for broadband communications, although the more satellites are needed in that case. It is essential also that for LEO the influence of a particle radiation on the satellite reduces and it´s exploitation time rises. Experts estimate that nearly 50-70% of all commercial satellites now under construction will be equipped with III-V solar cells [1].

2. Conclusions

1. The advantages of GaAs based SCs in comparison with Si SCs, listed below, make GaAs SCs more attractive for space applications:
   - output power per square unit 30% higher for the same sun light exposition,
   - radiation reliability 20% higher under the same operation conditions,
   - lower (2 times) coefficient of efficiency change with temperature,
   - life-time on the orbits longer than 40-60%,
   - over 20-25% higher the efficiency in energy conversion.
2. The high radiation exposition on GEO orbits requires SCs with higher radiation stability. In this case InP based SCs provide the highest power more than 30% in comparison with GaAS based SCs.

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