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Tandem GaInP/Ga(In)As structures for triple-junction hybrid GaInP/Ga(In)As//Si solar cells

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The external quantum efficiency spectra for GaInP-, Ga(In)As- and Si-subcells of hybrid GaInP/Ga(In)As//Si solar cells for space applications have been calculated. It has been found that decreasing the thickness of the photoactive layers of the GaInP-subcell from 550 nm to 290 nm and the Ga(In)As-subcell from 3100 nm to 550 nm allows matching the photogenerated currents at a level of $\sim 14.5\,\mathrm{mA/cm^2}$, while replacing the Ga(In)As- with a 600 nm thick GaAs-subcell ensures matching at a level of $\sim 14.9\,\mathrm{mA/cm^2}$. It has been shown that replacing the middle and bottom subcells in the GaInP/Ga(In)As/Ge- structure with GaAs and Si, respectively, will increase the efficiency from 29.4 to 30.8 % (AM0, 1 sun) while simultaneously improving the energy-mass parameters and the active exploitation time of space solar batteries.

Keywords: multijunction solar cell, MOCVD, efficiency, spectral characteristics, mathematical modeling.

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Solar cells (SCs), which are the main source of energy for spacecraft, have been used in space for more than 60 years [1]. Space solar batteries (SBs) have evolved from silicon-based single-junction SCs with a low conversion efficiency [2] to highly efficient multi-junction (MJ) SCs based on semiconductor A^3B^5 compounds [3]. The engineering of space SBs is focused on solving the following key issues: increasing the efficiency of solar energy conversion, improving the energy-mass parameters, and enhancing the radiation resistance. The current best laboratory efficiency values corresponding to space conditions (AM0 spectrum) are 33.7 % for inverted monolithic MJ SCs [4] and 35.8 % for five-junction SCs fabricated by wafer gluing („bonding") [5]. Although MJ SCs have demonstrated high efficiency levels in laboratory conditions, GaInP/Ga(In)As/Ge SCs based on a lattice-matched three-junction heterostructure are the ones used most often at present in serial production. Such SCs have an efficiency of $\sim 30{-}31\,\%$ (AMO, 1 sun) and demonstrate fine energy delivery performance and long-term reliability in space missions [6–8].

In a GaInP/Ga(In)As/Ge structure, the band gaps of each subcell are 1.9, 1.42, and 0.67 eV, respectively, and the layer thicknesses are chosen in such a way as to ensure controlled mismatch of photogenerated currents (PGCs) of these subcells. This is dictated by the need to ensure the required level of radiation resistance of MJ SCs. However, since complete PGC matching is infeasible (the lower germanium-based subcell generates a current that is almost 2 times greater), it is hard to raise the efficiency of such SCs further [9]. The solution to this problem lies in new MJ SC designs and structures: metamorphic heterostructures [10], mechanical stacking of SCs [11], and the technique of wafer „bonding" [12].

Efficient types of „bonding" of two-junction GaInP/GaAs and GaInP/GaInAsP tandem structures with a single-junction Si SC via mutual interdiffusion of semiconductor surfaces and van der Waals forces have recently been demonstrated in [13,14] in the configuration for the AM1.5G terrestrial solar spectrum. Having a band gap wider than the one of germanium, a silicon subcell generates a significantly higher open-circuit voltage $V_{oc} \approx 0.72{-}0.75\,\mathrm{V}$ (germanium has $V_{oc} \approx 0.25\,\mathrm{V}$) in comparable illumination conditions (one solar constant) [15]. Coupled with optimization of the GaInP/GaInAsP heterostructure, this made it possible to raise the SC efficiency to 36.1 % for the AM1.5G terrestrial spectrum [14].

If we consider a hybrid GaInP/Ga(In)As//Si SC in the context of its application in space SBs, the potential advantages of this design lie primarily in the improved energy-mass parameters of solar panels, since the density of silicon is 2 times lower than the density of germanium.

The present study is focused on calculations of spectral characteristics of hybrid GaInP/Ga(In)As//Si SCs aimed at optimizing their structure and PGC matching. Mathematical modeling of the spectral characteristics of the GaInP/Ga(In)As tandem and the Si-subcell was performed using the technique detailed in [16] with the propagation of light in a layered medium taken into account.

Figure 1 presents the spectral characteristics of the external quantum efficiency (EQE) of subcells of the GaInP/Ga(In)As/Ge three-junction SC (curves *1–3*, respectively) with an efficiency of 29.4 % (AM0, 1 sun). The het-

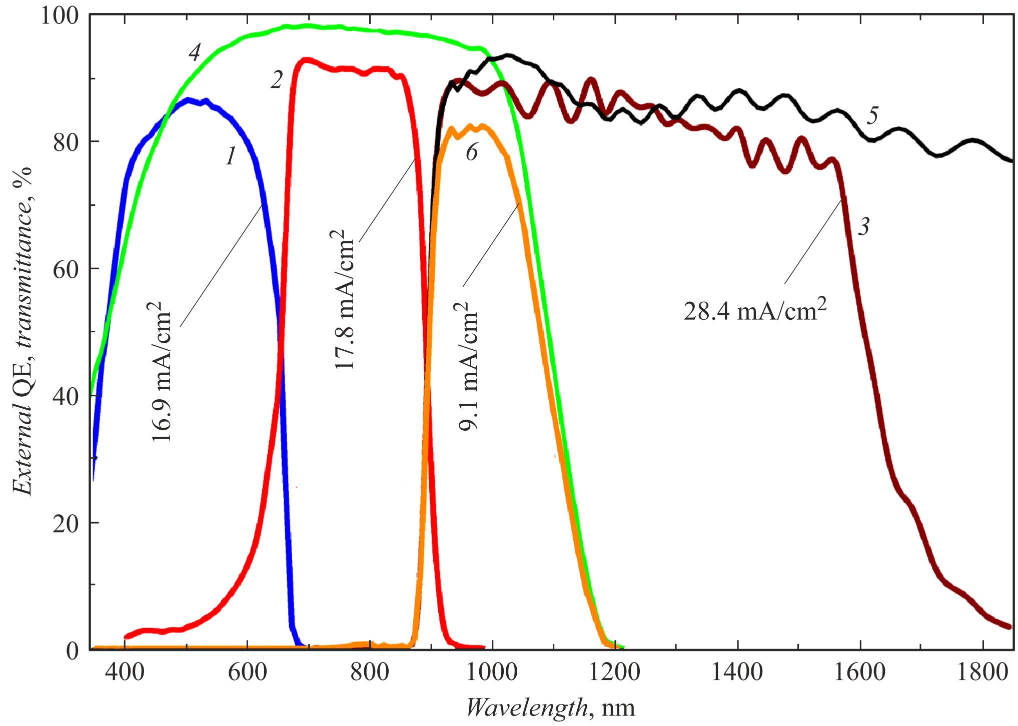

Figure 1. Measured external quantum efficiency spectra for the GaInP- (curve *1*), Ga(In)As- (curve *2*), and Ge-subcells (curve *3*) of the GaInP/Ga(In)As/Ge SC and for the Si solar cell (curve *4*), calculated transmittance spectra for the GaInP/Ga(In)As tandem structure (curve *5*), and calculated external quantum efficiency spectrum for the Si-subcell (curve *6*) of the hybrid GaInP/Ga(In)As//Si SC. The thicknesses of photoactive layers are as follows: GaInP — 550 nm, Ga(In)As — 3100 nm.

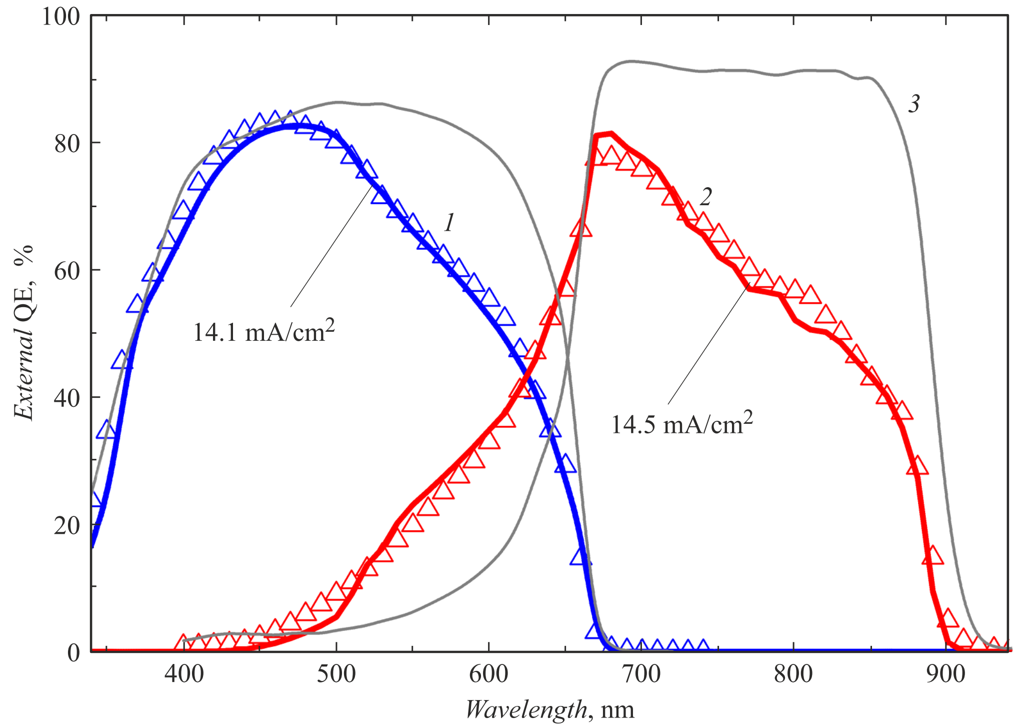

Figure 2. Variation of external quantum efficiency spectra for the GaInP (symbols and curve *1*) and Ga(In)As (symbols and curve *2*) subcells of the GaInP/Ga(In)As/Ge SC (curves and symbols represent calculated and experimental data, respectively) induced by a reduction in their thickness (GaInP: from 550 to 290 nm; Ga(In)As: from 3100 to 550 nm) relative to the SC with its EQE spectra shown in Fig. 1 (curves *3*).

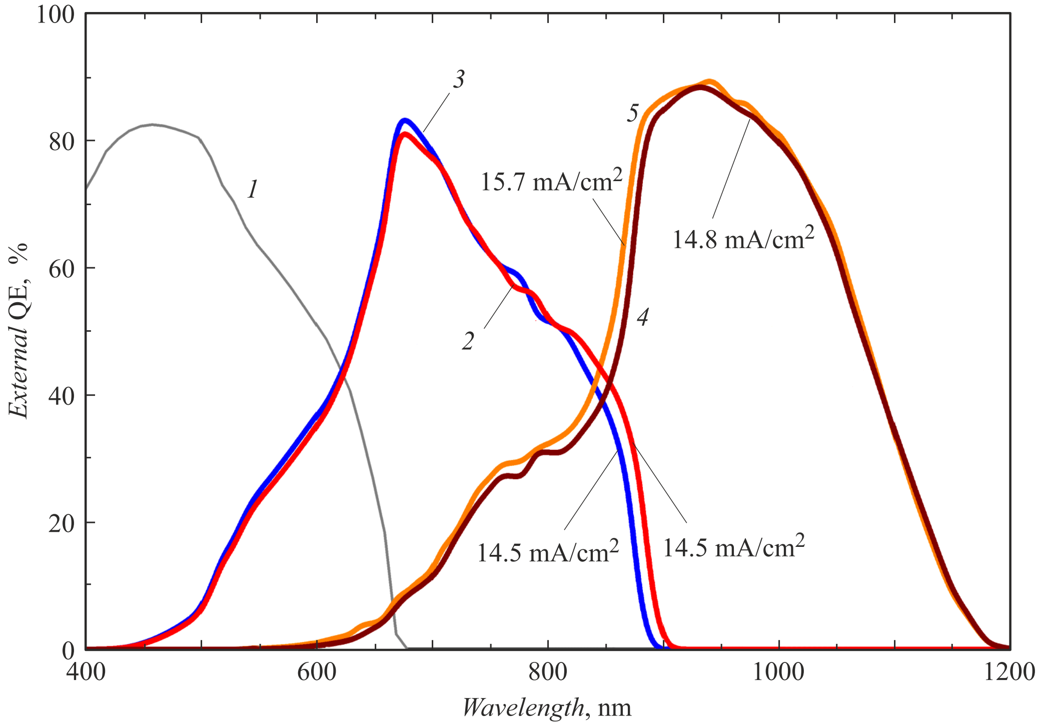

Figure 3. Calculated external quantum efficiency spectra for the GaInP- (curve *1*), Ga(In)As- (curve *2*), and GaAs-subcells (curve *3*) and Si-based subcells of the hybrid GaInP/Ga(In)As//Si SC (curve *4*) and the hybrid GaInP/GaAs//Si SC (curve *5*). The thicknesses of photoactive layers of the GaInP/GaAs//Si SC subcells are as follows: GaInP — 290 nm; GaAs — 600 nm.

erostructure of this SC was grown by metalorganic chemical vapor deposition in an industrial horizontal planetary-type reactor. The PGCs of the GaInP/Ga(In)As/Ge SC subcells for the AM0 spectrum are 16.9, 17.8, and 28.4 mA/cm^2, respectively. Since the subcells in the monolithic structure are connected in series, the total PGC of the MJ SC is equal to the smallest of the subcell currents, while the total voltage is the sum of the subcell voltages. Thus, one may raise the MJ SC voltage without sacrificing the PGC by increasing the band gap of the lower subcell.

In the considered hybrid GaInP/Ga(In)As//Si SC design, the GaInP/Ga(In)As tandem structure should be fabricated by inverted growth (layers are grown in reverse order) with a „sacrificial“ AlGaAs layer between the growth substrate and the GaInP/Ga(In)As heterostructure. The technique of pressure „bonding“ with subsequent removal of the GaAs growth substrate and the „sacrificial“ AlGaAs layer is used to stack GaInP/Ga(In)As and Si-structures. To simulate the EQE spectra of the lower (Si) subcell, the transmittance spectra of the GaInP/Ga(In)As tandem without a substrate were calculated (Fig. 1, curve *5*), and the obtained spectra were then multiplied by the EQE spectrum of the silicon SC.

Silicon heterojunction SCs Si-HJT (Silicon HeteroJunction Technology [15]), which convert photons with a wavelength up to 1200 nm (Fig. 1, curve *4*), are the best suited for fabrication of hybrid GaInP/Ga(In)As//Si SCs. The results of EQE modeling with Si-HJT used as the lower subcell of the hybrid GaInP/Ga(In)As//Si SC (Fig. 1, curve *6*) revealed that the PGCs of subcells cannot be matched if the upper tandem absorbs all photons with an energy greater than the band gap of Ga(In)As, and the Si-subcell current (9.1 mA/cm^2) turns out to be 2 times lower than the currents of subcells of the wide-gap pair.

It is evident that the use of a thin Ga(In)As-subcell partially transparent within the wavelength range of 700−900 nm will allow a greater number of photons of the solar spectrum to reach the Si-subcell. The corresponding optimization of thicknesses of photoactive layers should also include the GaInP-subcell to ensure matching of PGCs of all three subcells of the designed hybrid GaInP/Ga(In)As//Si CE.

A GaInP/Ga(In)As tandem structure with reduced thicknesses of photoactive layers of the subcells (GaInP: from 550 to 290 nm; Ga(In)As: from 3100 to 550 nm) was proposed as a result of modeling. The PGCs of the GaInP and Ga(In)As-subcells of experimental samples fabricated from the thinned GaInP/Ga(In)As/Ge structure were 14.1 and 14.5 mA/cm^2 (AM0 spectrum), respectively. These values agree fairly closely with the model estimates (Fig. 2). The calculated transmittance spectra of the thin GaInP/Ga(In)As tandem predicted a PGC of the Si-subcell at the level of 14.8 mA/cm^2 (Fig. 3).

„Bonding“ may introduce additional optical losses for radiation propagating through the GaInP/Ga(In)As tandem to the Si-subcell. One may raise the PGC of the silicon subcell by using a GaInP/GaAs tandem that may be grown on GaAs substrates pseudomorphically, which means that the lattice parameter is preserved (in contrast, the GaInP/Ga(In)As tandem is matched with Ge by adding 1% of indium to Ga(In)As and GaInP). The calculated PGCs for the hybrid GaInP/GaAs//Si SC design with thin GaInP (290 nm) and GaAs (600 nm) subcells were 14.4/14.5//15.7 mA/cm^2, respectively (Fig. 3).

Since the SC efficiency is directly proportional to the product of PGC and V_{oc}, the efficiency of the designed hybrid SC was estimated. The experimental value of V_{oc} of the GaInP/Ga(In)As/Ge SC at 1 sun is ~ 2.69 V. The substitution of Ge with Si will add 0.47 V to the open-circuit voltage. An increase in the band gap of photoactive layers of the upper tandem will provide another 40 mV of added voltage. Thus, the expected V_{oc} in the GaInP/GaAs//Si SC is 3.21 V, and the PGC with complete matching of subcells is 14.9 mA/cm^2 (this value was calculated as the arithmetic mean of PGCs of subcells). This translates into a predicted hybrid SC efficiency of ~ 30.8% (AMO, 1 sun) with simultaneous improvement of the energy-mass parameters of the device.

It is important to note that the degradation of space SCs under irradiation is caused by shortening of the diffusion lengths of minority carriers in photoactive layers of SC subcells and, consequently, a reduction in PGC of subcells due to impaired collection of photogenerated carriers. In addition to improving the efficiency and energy-mass parameters, the significant reduction in thickness of the photoactive layers in the proposed design of hybrid GaInP/GaAs//Si SCs should contribute to the enhancement of radiation resistance of such SCs and the service life of SBs based on them.

Conflict of interest

The authors declare that they have no conflict of interest.

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