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Multijunction Solar Cell With Intermediate IR Reflector

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Abstract: In the present work, for a system with the sunlight spectrum splitting, a multilayer mirror built-in into the GaInP/Ga(In)As/Ge TJ SC structure is proposed as a selective optical mirror. The function of such a mirror is to extract the IR part of the radiation in the wavelength range of 900-1100 nm from the SC structure for its following utilization by a SC based on Si or InGaAs. Being located between the middle GaAs and the bottom Ge subcells, the mirror based on doubled Bragg reflector (2BR) decreases controllably the portion of IR radiation incident on the Ge subcell and creating conditions for matching the Ge subcell photocurrent with the photocurrents of two other subcells in a TJ SC. The merit of the proposed approach is the entire absence of additional radiation losses in the ranges of the top GaInP and middle GaAs subcells sensitivity (usually resulting from diffraction effects in dichroic mirrors), which conserves their photocurrent at the maximum achievable level without violation of the current matching conditions. Thus, the efficiency of a TJ SC with 2BRs remains practically unchangeable compared with that of a conventional cell structure. The efficiency of 36.6% is demonstrated for a pair of cells: GaInP/Ga(In)As/2BR/Ge TJ (32.6%) and Si SJ (4%) the latter being operated under the radiation reflected by a 2BR.

Keywords: Optical beam splitters, Bragg reflector, multijunction solar cells
PACS: 42.79.Fm, 42.79.Dj, 88.40.jp.

INTRODUCTION

In recent years, great interest was aroused in development and creation of systems with spectral and spatial separation of the sunlight with following photovoltaic conversion of the formed light fluxes by several solar cells (SCs). The converter can consist of several either single-junction or dual-junction SCs accord to the optical scheme design and characteristics of dichroic mirrors used for the solar spectrum splitting. The efficiency of the system based on SCs with the total number of p-n junctions of up to six can exceed 55% at conversion practically of the whole sunlight spectrum [1].

The common disadvantage for the designs using the principle of the light flux spectral splitting is a quite high complexity of the multielement optical system including a set of dichroic mirrors and secondary optical elements [2-4].

The partial absorption of radiation in multilayer dicroic mirrors and the high order interferential effects result in reduction of the portion of radiation incident on SCs, which decreases their photocurrent and the system efficiency in the whole. Also problematic is the insurance of the long-term reliability of dichroic mirrors and holding their high optical characteristics at long operation.

In turn, the most effective solar cells based on monolithic triple-junction (TJ) structures with the efficiency of higher than 40% have not yet found practical application in the photovoltaic (PV) systems with spectral splitting of the light flux.

A specific feature of the TJ SCs is that the Ge subcell photocurrent is higher than the photocurrent of other two subcells at operation in the mode of the sunlight conversion. At their series connection in the structure, the common operating cell photocurrent is determined by the minimum one of three. So, the energy of photons creating the excess photocurrent of the germanium subcell is used rather ineffectively due to losses on thermalization.

In the work [5], an attempt has been made to separate a part of the IR radiation from the Ge subcell spectral sensitivity range by means of a dichroic mirror for its following conversion by a silicon SC. Thus, the TJ SC falls into the regime of the total current matching, and the excess radiation is used for photovoltaic conversion by a separate SC, which raises the sunlight conversion efficiency in the whole. However, even in this case the optical system remains quite complicated including the large number of elements.

In the present work, it is proposed to reject the use of the complicated optics based on dichroic mirrors and to perform the sunlight spectral splitting directly in the TJ SC structure itself. For this purpose, a multilayer epitaxial structure is grown as a part of a cell, which includes one or several Bragg reflectors (BRs) and plays a role of a mirror reflecting selectively and expelling from the structure the radiation in the spectral range of 900-1050 nm for its following conversion by SCs based on Si or InGaAs (Fig. 1). Such reflectors are successfully used by us in recent years in the structures of single and multi-junction SCs intended

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for space application, allowing increasing their efficiency and radiation tolerance [6, 7].

The BRs being located between the middle GaAs and bottom Ge subcells decrease controllably (according to their optical properties) the portion of IR radiation by narrowing the spectral range of the sunlight incident on the Ge subcell and create conditions for approaching the value of the photocurrent generated by it to the photocurrents of the two top subcells. Thus, the TJ SC appears to be transferred to the regime of the practically complete current matching.

An advantage of the proposed approach is the absence of additional losses of radiation within the sensitivity ranges of the top GaInP and middle GaAs subcells (usually arising at splitting of the light flux by dichroic mirrors), which retains their photocurrents at the maximally achievable level, and the efficiency of the TJ SC with a built-in BRs appears to be close to that of a cell having traditional multijunction structure.

An optical mirror necessary for spectral and spatial splitting of the light flux is fabricated in one and the same technological process during growth of the TJ SC multilayer structure by the MOVPE technique. Giving the use of intermediate multilayer selective optical elements up makes the system to be technically simple for fabrication and increases its reliability.

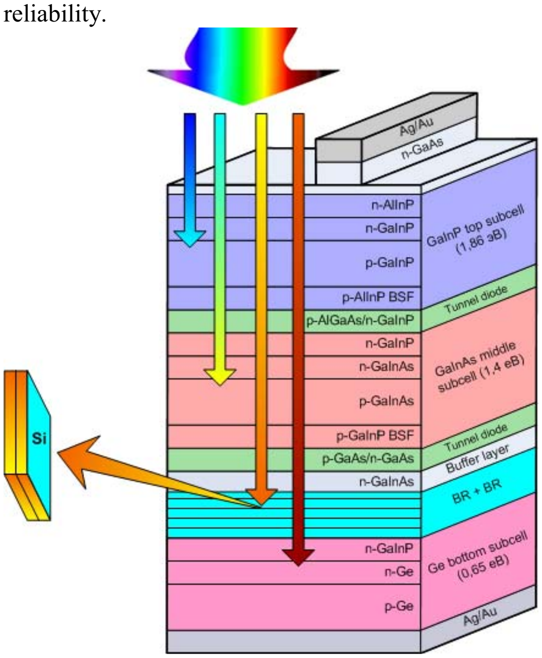

FIGURE 1. Triple-junction GaInP/Ga(In)As/Ge SC with a built-in doubled IR Bragg reflector.

MATHEMATICAL CONSIDERATION

The SC design with a doubled Bragg reflector (2BR) was elaborated by the method of mathematical simulation. Simulation of spectral characteristics and photocurrents was based on calculation of the electro-magnetic field of the light wave in the structure by the Abeles matrices method, which allows accounting for the interferential phenomena, and solwing the diffusion-drift problem for individual subcells [8].

For the simulating basis, a lattice-matched GaInP/Ga(In)As/Ge SC with the 36.2% (400 X, AM1.5D LAOD) efficiency was taken [9]. The contact grid configuration ensured shadowing of the cell surface by not more than 4%. In the model, the values of the refraction index and absorption coefficient have been used from [10, 11], and the diffusion length corresponded to the data of [7, 12]. The GaInP and Ga(In)As subcells' photocurrent densities were of about 13.7 mA/cm^2. The Ge subcell current density was more than by 1.5 times greater – 21.3 mA/cm^2.

An IR mirror based on two BRs with 15 pairs of alternating GaAs/AlAs layers each has been designed for the use in the TJ SC. The first BR ensured the effective reflection of radiation in the spectral range of 900-970 nm (reflection is centered for $\lambda = 940$ nm). The second reflector layer thicknesses were selected in such a way that after reflecting the IR radiation from the doubled BR, the Ge photocurrent density value would be somewhat greater than photocurrent densities for two top GaInP and Ga(In)As subcells. The simulation has shown that (Fig. 2) the optimum centering wavelength for the second reflector is 985 nm. At such a wavelength, the excess of the Ge photocurrent density is ensured at the level of 0.5-2.5 mA/cm^2 depending on the light incidence angle. The Si cell photocurrent density appears to be at the level of 6.5-7.0 mA/cm^2. Fig. 3 presents the results of simulation of spectral characteristics of a TJ SC with a 2BR at two light incidence angles.

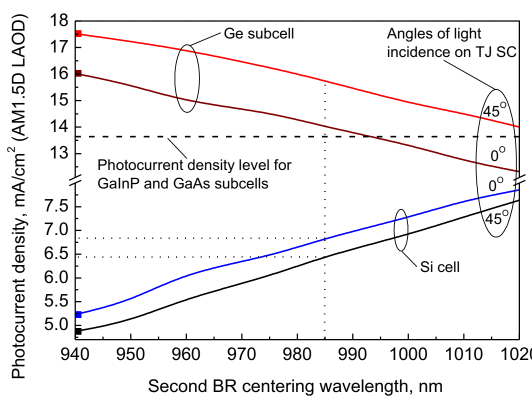

FIGURE 2. Dependencies of the photocurrent density for the Ge subcell of the GaInP/Ga(In)As/2BR/Ge TJ SC and Si cell operated in the reflected from 2BR light, on the centering wavelength of the second BR composing built-in 2BR for two light incidence angles. The colored squares at $\lambda = 940$ nm are indicating the photocurrent density values for a SC with single BR.

Lowering the Ge subcell photocurrent implies the decrease of TJ SC efficiency owing to some reduction of the I-V characteristic FF and the cell open circuit voltage. To estimate the value of the efficiency reduction, a simulation of the TJ SC I-V characteristic was carried out with allowance for the ratio of the Ge subcell photocurrent density to that of the GaInP and Ga(In)As subcells.

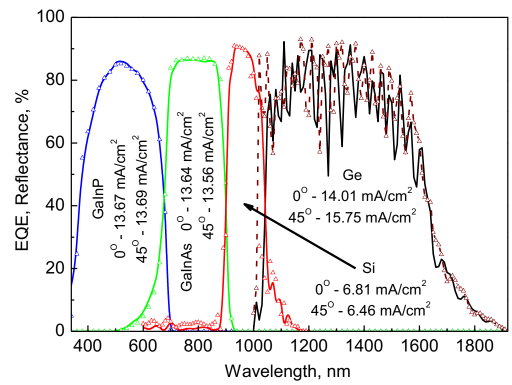

FIGURE 3. Simulated spectral dependencies of the external quantum efficiency for GaInP/Ga(In)As/2BR/Ge TJ SC and Si SC (the latter being operated under the radiation reflected by a 2BR) for two light incidence angles on TJ SC: 0° - solid lines, 45° –dots.

In simulating, the distributed three-dimensional equivalent circuit described in [13] has been used. Fig. 4 presents the results of the simulation compared to the experimental data. Also the tendency for variation of the efficiency for lattice-matched TJ SCs having the highest sunlight conversion efficiency achieved up to now [14] is shown in this figure. Transferring the TJ SC to the regime of the complete photocurrent matching between subcells at the decrease of the Ge subcell photocurrent results in the reduction of the TJ SC efficiency by not more than 1.5%. At the same time, the Si SC will allow adding extra 4-5 % to the system efficiency at conversion of the IR radiation reflected from TJ SC with 2BR (Si SC photocurrent density at 1 Sun illumination is about 6.6 mA/cm²).

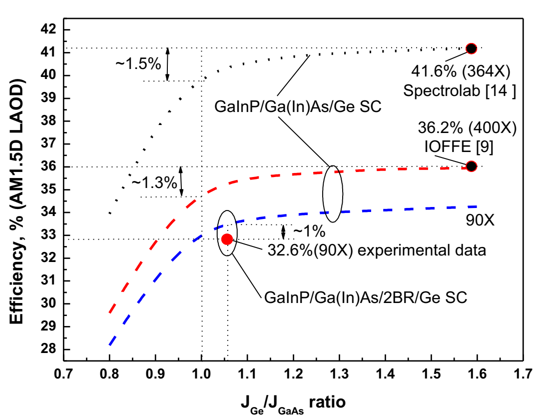

FIGURE 4. Simulated dependencies and experimental values of the efficiency for GaInP/Ga(In)As/Ge TJ SCs on the photocurrent mismatch between the top two subcells and the Ge subcell. Experimentally measured data for GaInP/Ga(In)As/2BR/Ge SC is indicating by a red dot.

Thus, the proposed system design with spectral splitting of the light flux ensures the sunlight conversion efficiency increase by 2.5-3.5% compared to the conventional high-effective GaInP/Ga(In)As/Ge TJ SCs.

EXPERIMENTAL RESULTS

The structures of GaInP/Ga(In)As/2BR/Ge TJ SC were grown by the MOVPE technique on a R&D installation with a horizontal reactor at low pressure. The installation is equipped with an in-situ monitoring system, which was used for the analysis of the structures and for the control of a number of important epitaxial parameters during the growth by means of measuring single-wavelength time dependences of normalized reflection and reflectance anisotropy signal. This approach was described elsewhere [15, 16]. SCs with 3.4x3.0 mm² DIA were fabricated on the grown structures.

The fabricated specimens of SCs have demonstrated rather high values of photocurrents with their matching at the level of 13.3 мA/cм² (AM1.5D LAOD) for the top subcells and insignificant exceeding by the photocurrent for the Ge subcell (14.1 мA/cм²) (Fig. 5). The IR radiation coming out of the structure has allowed obtaining the 6.6 мA/cм² photocurrent density for the Si SC.

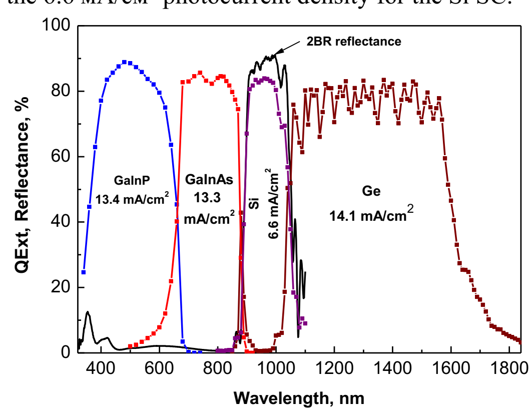

FIGURE 5. Spectral dependences of the external quantum efficiency for GaInP/Ga(In)As/2BR/Ge TJ SC and Si cell (the latter being operated under the radiation reflected by a 2BR). Reflection coefficient of a TJ cell with a 2BR is also presented.

In investigating the I-V characteristics of SCs, the efficiencies at the level of 32.6% have been obtained for a TJ SC with a 2BR, which agrees quite well with the model estimations of the SC efficiency change in transferring to the regime of practically complete photocurrent matching of subcells and with the experimental results for conventional TJ SCs (see Fig. 5).

Thus, at extra 4% from the Si SC, the total efficiency of 36.6% (90X, AM1.5D LAOD) for the pair “TJ SC with a 2BR + Si cell” was recorded.

Correction of the technological regimes for creating TJ SCs and substituting the GaInAs(P) SC (E_g ~0.98 eV) [17] for the Si cell should allow close approaching the record efficiency values for such systems.

CONCENTRATOR OPTICS WITH SPECTRUM SPLITTING

The proposed optical system with the spectral splitting of the light flux appears to be extremely simple, does not require complicated additional elements and can be easily adapted to the elaborated "all-glass" concept of a PV modules with Fresnel lenses [18, 19]. A sketch of an optical system based on Fresnel lens concentrators and "GaInP/Ga(In)As/2BR/Ge TJ - Si SJ" SCs arranged in spectrum splitting concept is presented in Fig. 6.

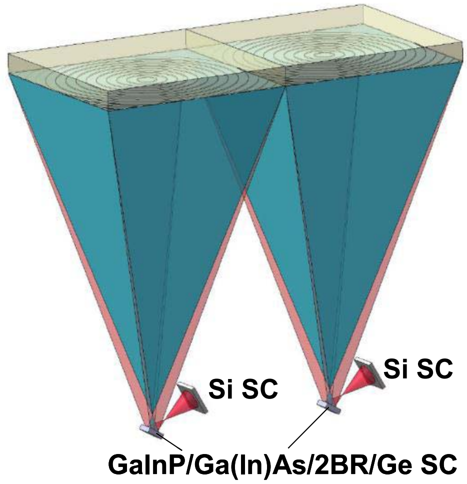

FIGURE 6. Spectrum splitting concept of an optical system with Fresnel lens concentrators and "GaInP/Ga(In)As/2BR/Ge TJ - Si SJ" SCs.

CONCLUSION

Thus, in the work, an absolutely new direction in development of photovoltaic systems with spectral and spatial splitting of the sunlight fluxes has been proposed. The main idea of the proposed approach lies in realization of additional feasibilities of multijunction semiconductor structures assigning to the multijunction cell a part of not only photovoltaic converter, but also of a selective optical mirror. Fabricating a complicated structure of such a SC in one and the same technological MOVPE process we simplify it significantly and make the optical part of the system cheaper and at the same time more effective. At first practical realization of the "GaInP/Ga(In)As/2BR/Ge TJ + Si SJ" SC the efficiency of 36.6% (90X, AM1.5D LAOD) have been achieved.

Apparent are the merits of the proposed approach also in creating systems for space application. Absence of the absorption bands in Ge subcell spectral sensitivity range in the out-atmosphere solar spectrum makes the excess of this subcell photocurrent even more significant compared to the case of power conversion of the terrestrial sunlight. Hence, relatively more essential part of radiation can come from a specimen for the following conversion, which will ensure even more significant addition to the efficiency of such a system.

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