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Increasing the efficiency of triple-junction solar cells due to the metamorphic InGaAs subcell

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The efficiency of GaInP/GaAs/$In_xGa_{1-x}As$ triple-junction solar cells obtained by replacing (in the widely used „classical" GaInP / GaAs / Ge heterostructure) the lower germanium with $In_xGa_{1-x}As$ subcell formed using the metamorphic growth technology has been investigated. Based on an original approach, the optimal indium concentration in the narrow-gap subcell has been found. The main parameters of $In_xGa_{1-x}As$ subcells with an indium concentration from $x = 0.11$ to 0.36 were determined and were used to calculate the IV characteristics of GaInP/GaAs/$In_xGa_{1-x}As$ solar cells. It has been determined that at $x = 0.28$ the efficiency of the triple-junction solar cell increases by 3.4% (abs) in comparison with the „classical" solar cell, reaching a value of 40.3% (AM1.5D). Also it has been shown that the efficiency of such solar cells can be increased up to 41%.

Keywords: Multi-junction solar cells, photoconverters, metamorphic buffer.

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Semiconductor $In_xGa_{1-x}As$ $p-n$-junctions, formed on a substrate, mismatched along the lattice perimeter (e.g., GaAs), using metamorphic buffer layers (metamorphic buffer) are being actively used in various fields of photovoltaics. They were used in multi-junction (MJ) solar cells (SC) to obtain record-braking efficiency values for three- [1], four- [2], five- [3] and six-junction [4] SCs. They also provided record-braking efficiency values for photoconverters (PC) intended for conversion of powerful laser radiation [5,6]. Such wide application of $In_xGa_{1-x}As$ $p-n$-junctions is related to the possibility of control of the PC absorption edge due to metamorphic buffer layers. Several technological approaches to the use of $In_xGa_{1-x}As$ $p-n$-junctions in MJ SCs have been developed. Firstly, the $In_xGa_{1-x}As$ subcell is included in classical structures on the Ge substrate [3,7], secondly, a technology of inverted growth on the GaAs substrate has been developed [1,4,8–10], and MJ SCs with a mechanical coupling of $In_xGa_{1-x}As$ subcells and the technology of glued substrates have been created [11].

This paper presents the results aimed at improving the efficiency of the „classical" GaInP/GaAs/Ge SC [12] by replacing the germanium subcell with $In_xGa_{1-x}As$ [5]. The making of high-efficiency MJ GaInP/GaAs/$In_xGa_{1-x}As$ SCs is described in a number of papers that search for the optimal (from the viewpoint of current matching for subcells and overall efficiency of the MJ SC) percentage of indium in the lower subcell that sets its forbidden bandwidth E_g. Thus, one of the first papers [8] simulated the MJ SC characteristics and showed that the optimal subcell for ground-based application will be the $In_xGa_{1-x}As$ subcell with the forbidden bandwidth of 1.01 eV, which will yield the device efficiency of 41.5% during conversion of concentrated ground solar radiation (AM1.5D, 250 X). The optimal forbidden bandwidth in [9] is stated to be 1.0 eV, the forbidden bandwidths for two upper junctions (GaInP and GaAs) being equal to 1.85 end 1.42 eV respectively. Thereat, it is said that 1.0 eV is achieved at $x = 0.25$, while the experimentally obtained efficiency is 37.9% (10X). In [10], the forbidden bandwidth for the $In_xGa_{1-x}As$ subcell, equal to 1.0 eV, is also considered optimal, but it is achieved at $x = 0.3$, the forbidden bandwidth for the upper GaInP subcell being 1.8 eV. Efficiency of the obtained SC was 38.9% (AM1.5D, 81). [1] states the record-braking efficiency of 44.4% (AM1.5D, 302) for a sample having the following declared set of subcells' forbidden bandwidths: GaInP(1.88 eV)/GaAs(1.43 eV)/InGaAs(0.98 eV).

The revealed spread of forbidden bandwidth values for a narrow-gap $In_xGa_{1-x}As$ subcell and indium percentage in its layers is to a large extent caused by the fact that the optimal efficiency is achieved only in case of complete balance of photogenerated currents of all MJ SC subcells [13], and this is defined both by the balance of the currents of two upper subcells and by the dependence of photogenerated current of the lower $In_xGa_{1-x}As$ subcell on indium concentration. The first factor is mainly defined by the forbidden bandwidth of the GaInP subcell that varies depending on ordering of atoms in the chip [14–16]. The second factor is mainly affected by quality of the metamorphic $In_xGa_{1-x}As$ buffer that may vary with increase of indium content, as, for instance, in [9].

This paper suggests a solution of the given miltifactorial problem that can be used to determine the optimal lower $In_xGa_{1-x}As$ subcell for a specific MJ SC. This solution

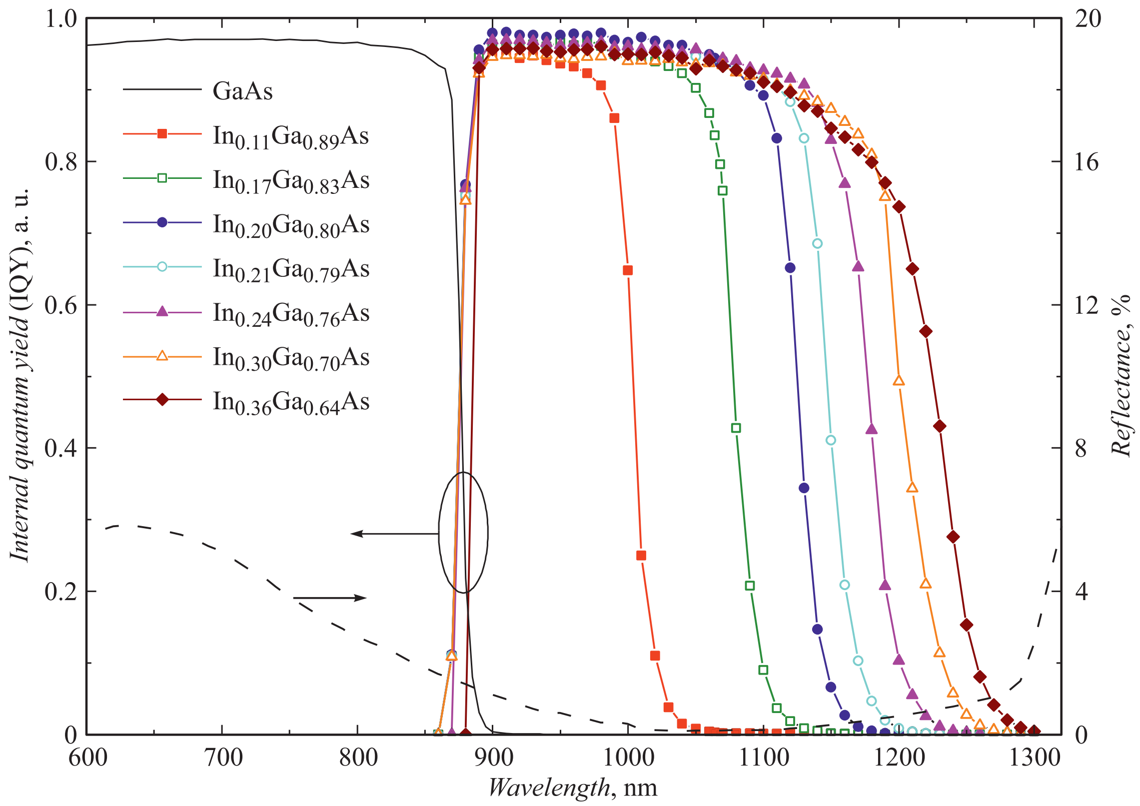

Figure 1. Experimental dependences of internal quantum yield of the photo-response for PCs based on GaAs (dark solid line) and for studied subcells $In_xGa_{1-x}As$ of a triple-junction SC GaInP/GaAs/$In_xGa_{1-x}As$ (lines with symbols).

differs from the previous ones [8,17,18] in that it is based on the experimental dependences obtained for the $In_xGa_{1-x}As$ [5] subcells, on a two-diode model of MJ SC [13], as well as on experimentally recorded spectral characteristics of optimized MJ SC and single-junction PCs based on $In_xGa_{1-x}As$. The method is applicable for any technologies of MJ SC making, where the metamorphic $In_xGa_{1-x}As$ subcell is created separately from the pseudomorphic tandem of GaInP/GaAs subcells, e.g. by inverting the growth on the GaAs substrate, growth on the GaAs back side or separate epitaxial growth of $In_xGa_{1-x}As$ and its subsequent mechanical coupling [1,4,8–11,19].

The starting point for optimization was a triple-junction GaInP/GaAs/Ge SC the characteristics of which are presented in [13]. Structures of single-junction PCs based on $In_xGa_{1-x}As$ with indium content from $x = 0.11$ to 0.36, as well as PCs based on GaAs were made by metalorganic vapor-phase epitaxy [5]. The structures comprised a GaAs substrate, a metamorphic buffer consisting of a number of $In_xGa_{1-x}As$ layers with a stepped indium concentration and providing the achievement of the required active region composition, a rear potential barrier $In_xAl_{1-x}As$, $In_xGa_{1-x}As$ *p–n*-junction itself, as well as a broad-zone gap $In_xAl_{0.5}Ga_{(0.5)(1-x)}As$. An antireflection coating was not used, which allowed for an increased accuracy of composition assessments when choosing $In_xGa_{1-x}As$ subcells required for the making of current-balanced MJ GaInP/GaAs/$In_xGa_{1-x}As$ CS. Possible variations (determined, among other things, by the process) in the parameters of antireflection coatings deposited on top of the $In_xGa_{1-x}As$ layers of a different composition, can introduce a considerable error into the recorded spectral dependences of external quantum yield (EQY) of PC photo-response. Therefore, the experiment included measurements of spectral dependences of external quantum yield of PC photo-response without antireflection layers and surface reflection coefficients, followed by obtaining of data for the internal quantum yield (IQY) of photo-response.

The final spectral characteristics of internal quantum yield directly for the $In_xGa_{1-x}As$ subcell were generated taking into account the filtration of the long-wavelength part of the spectrum by GaInP/GaAs subcells (Fig. 1).

The estimated dependences of internal quantum yield of photo-response were used to obtain the corresponding photogenerated currents of $In_xGa_{1-x}As$ subcells in the structure of MJ GaInP/GaAs/$In_xGa_{1-x}As$ SC, taking into account the parameters of a typical antireflection coating for the lower $In_xGa_{1-x}As$ subcell (Fig. 1). The values of the obtained photogenerated currents are given in the table. Evidently, the photon-induced currents $J_{g,\mathrm{IQY}}$, obtained on the basis of the data on internal quantum yield of photo-response, are the limit attainable ones. In their turn, the values of $J_{g,\mathrm{EQY}}$, characterized by the spectra of external

The $In_xGa_{1-x}As$ subcell parameters, used in the calculation of GaInP/GaAs/$In_xGa_{1-x}As$ efficiency (x is indium content in the $In_xGa_{1-x}As$ subcell)

x	E_g, eV	$J_{g,\mathrm{IQY}}$, mA/cm^2	$J_{g,\mathrm{EQY}}$, mA/cm^2	J_{01}, A/cm^2	J_{02}, A/cm^2
0.11	1.26	6.03	5.68	$3.47\cdot10^{-17}$	$1.67\cdot10^{-9}$
0.17	1.202	10.20	9.69	$1.03\cdot10^{-15}$	$9.07\cdot10^{-9}$
0.20	1.209	12.02	11.46	$5.32\cdot10^{-15}$	$2.06\cdot10^{-8}$
0.21	1.213	12.29	11.73	$9.13\cdot10^{-15}$	$2.70\cdot10^{-8}$
0.24	1.203	13.22	12.65	$4.51\cdot10^{-14}$	$6.01\cdot10^{-8}$
0.30	1.201	14.11	13.64	$9.92\cdot10^{-13}$	$2.52\cdot10^{-7}$
0.36	1.198	14.45	13.91	$1.90\cdot10^{-11}$	$1.23\cdot10^{-6}$

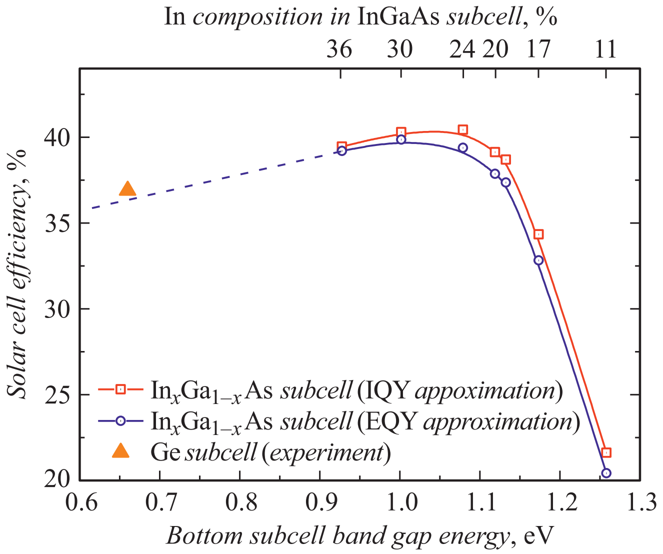

Figure 2. Estimated dependences of GaInP/GaAs/$In_xGa_{1-x}As$ SC efficiency on forbidden bandwidth and indium concentration for the $In_xGa_{1-x}As$ subcell in two cases: a solid line with squares is the ultimate case (photogenerated current of the $In_xGa_{1-x}As$ subcell was obtained from the experimental spectra of the internal quantum yield of photo-response, Fig. 1), a solid line with circles is the realistic case (photogenerated current was obtained on the basis of the data on external quantum yield of photo-response). The dashed line shows a possible trend into the region of a smaller forbidden bandwidth. The triangle corresponds to the efficiency value for the initial „classical" triple-junction SC with Ge-subcell.

quantum yield of photo-response, can be implemented in practice in a MJ SC.

The electric parameters of $In_xGa_{1-x}As$ $p-n$-junctions were determined using the experimental dependence of saturation currents on the prohibited bandwidth of $In_xGa_{1-x}As$ $p-n$-junctions [5]. As a result, diffusion (J_{01}) and recombination (J_{02}) saturation currents were obtained for all the $p-n$-junctions under consideration (see the table).

Search for the optimal parameters of the $In_xGa_{1-x}As$ subcells was performed using the model described in [13] to calculate the volt-ampere characteristics and efficiency of the triple-junction GaInP/GaAs/$In_xGa_{1-x}As$ SC. The calculations used the parameters of the GaInP and GaAs subcells and series resistance given in [13], while the parameters of the $In_xGa_{1-x}As$ subcells were taken from the table. Equality of photogenerated currents of the GaInP and GaAs subcells was assumed: 13.75 mA/cm^2 (AM1.5D) (established as the average value of the experimentally determines currents of both subcells). The calculation result is given in Fig. 2.

The limit photo-conversion efficiency for the case when the photogenerated currents were calculated from the spectra of internal quantum yield of photo-response is attained with the forbidden bandwidth of the $In_xGa_{1-x}As$ ($x = 0.26$) subcell equal to 1.052 eV. The maximum efficiency for the realistic case (photogenerated current of the subcell is calculated from external quantum yield of photo-response) is attained at 1.027 eV ($x = 0.28$) and is 40.3%, which is 3.4% (abs.) higher than the initial value for the GaInP/GaAs/Ge SC (36.9% — the triangle in Fig. 2).

Thus, the previously developed MJ SC model [13] was used to calculate the optimal indium content in the lower subcell of the MJ GaInP/GaAs/$In_xGa_{1-x}As$ SC. It has been shown that MJ SC photo-conversion efficiency upon replacement of narrow-gap germanium by wider-gap $In_{0.28}Ga_{0.72}As$ (the forbidden bandwidth of 1.027 eV) increases by 3.4% (abs.). Improved quality of the material of the $In_xGa_{1-x}As$ ($x = 0.24-0.26$) subcell with a corresponding approach of its photogenerated current to the limit attainable values for the given composition will allow for the creation of MJ SCs having an efficiency of about 41% (AM1.5D). Efficiency can be further enhanced by improving the pair of the upper subcells. Thereat, the required correction of the optimal indium content in the $In_xGa_{1-x}As$ subcell can be performed by the method suggested here.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] T. Takamoto, H. Washio, H. Juso, in *2014 IEEE 40th Photovoltaic Specialist Conf. (PVSC)* (IEEE, 2014), p. 1. DOI: 10.1109/PVSC.2014.6924936

[2] R.M. France, J.F. Geisz, I. Garcia, M.A. Steiner, W.E. McMahon, D.J. Friedman, T.E. Moriarty, C. Osterwald, J.S. Ward, A. Duda, M. Young, W.J. Olavarria, IEEE J. Photovolt., **6**, 578 (2016). DOI: 10.1109/JPHOTOV.2015.2505182

[3] R.H. van Leest, D. Fuhrmann, A. Frey, M. Meusel, G. Siefer, S.K. Reichmuth, AIP Conf. Proc., **2149**, 020007 (2019). DOI: 10.1063/1.5124177

[4] J.F. Geisz, R.M. France, K.L. Schulte, M.A. Steiner, A.G. Norman, H.L. Guthrey, M.R. Young, T. Song, T. Moriarty, Nature Energy, **5**, 326 (2020). DOI: 10.1038/s41560-020-0598-5

[5] N.A. Kalyuzhnyy, V.M. Emelyanov, V.V. Evstropov, S.A. Mintairov, M.A. Mintairov, M.V. Nahimovich, R.A. Salii, M.Z. Shvarts, Solar Energy Mater. Solar Cells, **217**, 110710 (2020). DOI: 10.1016/j.solmat.2020.110710

[6] N.A. Kalyuzhnyy, V.M. Emelyanov, S.A. Mintairov, M.V. Nahimovich, R.A. Salii, M.Z. Shvarts, AIP Conf. Proc., **2298**, 030001 (2020). DOI: 10.1063/5.0032903

[7] W. Guter, J. Schone, S.P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, A.W. Bett, F. Dimroth, Appl. Phys. Lett., **94**, 223504 (2009). DOI: 10.1063/1.3148341

[8] M.W. Wanlass, S.P. Ahrenkiel, R.K. Ahrenkiel, D.S. Albin, J.J. Carapella, A. Duda, J.F. Geisz, S. Kurtz, T. Moriarty, R.J. Wehrer, B. Wernsman, in *Conf. Record of the Thirty-first IEEE Photovoltaic Specialists Conf.* (IEEE, 2005), p. 530. DOI: 10.1109/PVSC.2005.1488186

[9] D.J. Friedman, J.F. Geisz, A.G. Norman, M.W. Wanlass, S.R. Kurtz, in *2006 IEEE 4th World Conf. on photovoltaic energy conversion* (IEEE, 2006), p. 598. DOI: 10.1109/WCPEC.2006.279527

[10] J.F. Geisz, S. Kurtz, M.W. Wanlass, J.S. Ward, A. Duda, D.J. Friedman, J.M. Olson, M.E. McMahon, T.E. Moriarty, J.T. Kiehl, Appl. Phys. Lett., **91**, 23502 (2007). DOI: 10.1063/1.2753729

[11] F. Dimroth, T. Tibbits, M. Niemeyer, F. Predan, P. Beutel, C. Karcher, E. Oliva, G. Siefer, D. Lackner, P. Fus-Kailuweit, A.W. Bett, R. Krause, C. Drazek, E. Guiot, J. Wasselin, A. Tauzin, T. Signamarcheix, IEEE J. Photovolt., **6**, 343 (2016). DOI: 10.1109/JPHOTOV.2015.2501729

[12] N.A. Pakhanov, V.M. Andreev, M.Z. Shvarts, O.P. Pchelyakov, Optoelectron. Instrum. Data Process., **54**, 187 (2018). DOI: 10.3103/S8756699018020115

[13] M.A. Mintairov, V.V. Evstropov, S.A. Mintairov, N.K. Timoshina, M.Z. Shvarts, N.A. Kalyuzhnyy, Semiconductors, **49** (5), 668 (2015). DOI: 10.1134/S1063782615050164.

[14] A. Zunger, S. Mahajan, in *Handbook on semiconductors* (Elsevier, Amsterdam, 1994), vol. 3, p. 1399.

[15] I. Pietzonka, T. Sass, R. Franzheld, G. Wagner, V. Gottschalch, J. Cryst. Growth, **195**, 21 (1998). DOI: 10.1016/S0022-0248(98)00594-6

[16] N.A. Kalyuzhnyy, S.A. Mintairov, M.A. Mintairov, V.M. Lantratov, in *Proc. of the 24th Eur. Photovoltaic Solar Energy Conf.* (WIP-Munich, 2009), p. 538. DOI: 10.4229/24thEUPVSEC2009-1CV.4.39

[17] S.R. Kurtz, D. Myers, J.M. Olson, in *Conf. Record of the Twenty Sixth IEEE Photovoltaic Specialists Conf.* (IEEE, 1997), p. 875. DOI: 10.1109/PVSC.1997.654226

[18] M.W. Wanlass, D.S. Albin, AIP Conf. Proc., **738**, 462 (2004). DOI: 10.1063/1.1841925

[19] H. Cotal, C. Fetzer, J. Boisvert, G. Kinsey, R. King, P. Hebert, H. Yoonand, N. Karam, Energy Environ. Sci., **2**, 174 (2009). DOI: 10.1039/b809257e