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Exploiting the Properties of GaInAsP/GaInAs Based Multi-Junction Solar Cell

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ABSTRACT

Increasing the conversion efficiency of a multi-junction solar cell is a challenging task. There have been a number of different works that show different ways of improving conversion efficiency. For instance, incorporating GaInAsP,GaInAs and related materials have proven to successful. Despite the recent success, the GaInP/GaAs/InGaAs multi-junction solar cell's conversion efficiency still not up to the mark. In this context, we studied a GaInAsP based p-i-n solar cell where we used Indium phosphide (InP) as n-type layer with SCAPS-1D simulator. We added an absorption layer GaInAs after GaInAsP. We also added a buffer layer between the window InP and intrinsic type GaInAsP. So the new structure of the solar become n+-InP/n-GaInP/i-GaInAsP/p-GaInAs/p+-GaAs. The solar cell performance is simulated and analyzed carefully using Solar cell Capacitance Simulator (SCAPS-1D). By tuning different physical parameters of the absorber layer of the solar cell including absorber layer thickness, band gap of the quaternary material, the front and back contact of the solar cell. By varying these parameters the performance of the solar cell was analyzed sharply. From the above analysis of this solar cell, we find out the maximum efficiency of 34.70% with fill factor 84.88, Voc 1.0922V and Jsc 37.431929mA/cm2.

Index Terms – Hetero-Junction Solar Cell, GaInAsP, Multi-Junction Solar Cell, SCAPS-1D.

1. INTRODUCTION

Solar cell efficiency in a single layer or band gap is limited due to lack of ability of p-n junction for absorbing a wide range of photons from the solar spectrum. In blue spectrum, beneath the band gap, photons either go through the solar cell or are transformed into heat due to molecular demonstration. Again photons having the energy above the red spectrum are also lost because the energy which is necessary to generate electron hole pair is converted into heat [1]. On the other hand, Hetero-junction solar cells consist of two different types of materials. Hetero-junction is different from homo-junction semiconductor materials due to its unequal band gaps. In hetero-junction solar cells, we used two different types of semiconductor materials and those materials have unique band gap, because of that these type of solar cell can absorb two different energized photons [2]. As a result, more light energy will absorbed and it will give more efficiency.

In n-i-p hetero-junction solar cell there is a couple of hetero junction. They are p-i and i-p junction that make the generated electric field stronger. As a result more light energy will absorbed by the two junctions and give comparatively a greater efficiency of the solar cell.

Solar cell using III-V materials are called the fourth generation solar cell. According to many theoretical simulation and practical analysis, GaInAsP and GaInAs established as effective absorber among the III-V semiconductor materials. During 1990, the effects of an overlying GaAs filter, solar cells of n/p Ga0.25In0.75As0.54P0.46 are designed for single sun operation and found efficiencies of 5.8% under the AM0 spectrum and at 25°C and 22.2% at AM0 and at 25°C and 24.1% efficiencies at Global 25°C have been reached for InP/Ga0.47In0.53 as tandem cells [3]. An efficiency of 20.8 ± 1% under AM1.5D spectrum is obtained in an n-i-p solar cell where GaInAsP having 1.7eV band gap is used as intrinsic absorber layer [4]. Again, we found that under the AM1.5 G173 global spectrum photovoltaic conversion efficiencies of 32.6%±1.4% was achieved using GaInAsP (1.7eV) and GaInAs both as absorber layer in a multi-junction solar cell [5].

Mechanically stacked or monolithically integrated is the two principal ways for Multiple-junction cells of which it can be realized. For monolithic single-sun GaInP/GaAs tandem cell, highest reported efficiency is 30.3% at AM1.5 [6] and 26.9% at AM0 [8]. Again, in case of two-terminal InP/InGaAs tandem cell efficiency has been reached at 22.2% at AM0 [8]. For monolithical GaInP/GaAs/Ge triple cells, efficiency attained of 25.8% at AM0 [11]. However, for triple cell consisting of a monolithical tandem GaInP/GaAs cell stacked on an InGaAs cell grown on InP, the efficiency was obtained in the range of 33%–34% at AM1.5 [7].

In order to calculate the cell performances of the proposed solar cells we used SCAPS software [9]. The SCAPS software gives the performance by solving two equation, 'electron and hole continuity equation and Poisson equation'.

The Poisson equation connecting the potential to the densities of the charge carriers is given by:

$$\frac{\delta^2\Psi}{\delta x^2}+\frac{q}{\varepsilon}[-n(x)+p(x)-N_A^-+N_D^++\rho(n,p) \qquad =0 \qquad 1.1$$

Where Ψ is the electronic potential at the point x, ε is the permittivity; ND + and NA- are ionized donors and acceptors densities; q is the electron charge.

At the steady state and under illumination, the continuity equations for electron and holes are given bellow:

$$\frac{1}{q}\frac{dj_n}{dx}=-G_{op}x+R(x) \qquad 1.2$$

$$\frac{1}{q}\frac{dj_p}{dx}=-G_{op}x-R(x) \qquad 1.3$$

Here current densities for the electrons are Jn and for holes are Jp, Gop is the generation rate of electron-holes and R is the rate of direct and indirect recombination. Then we have to solve the above mentioned three equations according to the boundary condition and finally found the values of the electrostatic potential and the quasi-Fermi level for holes and electrons at every point in the solar cell using SCAPS software. If we collect these values as a function of depth then we can solve the carrier concentration, electric fields and currents and device different parameters like the open circuit voltage (Voc), short circuit current density (Jsc), Fill Factor (FF), and efficiency (η).

2. MODELING AND SIMULATION

At the beginning, we developed an n-i-p hetero-junction solar cell where graded GaInAsP used as absorber layer. Then we added GaInP as buffer layer between the n-type InP and intrinsic GaInAsP. We also added an extra p-type GaInAs layer between intrinsic GaInAsP and p-type substrate GaAs which is also used as an absorber layer. Then we tuned the intrinsic GaInAsP layer and GaInAs absorber layer thickness except window layer and optimized the total cell thickness. The effect of different band gap of graded GaInAsP layer to the cell performance was optimized. Then we analyzed the effect of temperature and resistance to different cell parameters such as Fill Factor (FF), efficiency (η), Open circuit Voltage (Voc), and Short circuit current density (Jsc). Finally, we reduced total cell thickness as 2 µm.

In the whole structure of the solar cell, we used five semiconductor layer using III-Materials. So there creates four junctions which make solar cell with multi-junction. At the top of the structure, we used highly doped InP as window layer which is connected to front contact and the buffer layer. As it is window layer and sun light enter the absorber layer through this layer, so its thickness should low. We kept the thickness of window layer fixed at 50nm.

After the window layer, there is a buffer layer which is used to increase the generated build in potential between the p-n junctions. In the field of thin-film solar cells, buffer layers are usually used to optimize the cell design. Moreover, to maintain the overall solar cell performance the thickness of GaInP buffer layer should not be less than 40 nm and should not be greater than 60 nm. If we put the thickness is so narrow than 40 nm, light immediately passed to the thin intrinsic silicon layer and reached to the absorber layer. At that time, the absorber layer absorbed more sun light and created more electron-hole pair generation. As a result, more recombination is caused to reduce cell performance. For this reason, we optimize GaInP buffer layer as 50 nm thick for better performance.

There is added an additional tinny intrinsic GaInAsP layer. Its function as a surface passivation that acts also buffer layer which decreases reverse bias current of the cell by minimizing the recombination loss of the inspired mobile carriers. But it increases the open circuit voltage. Thus this layer increases the cell conversion efficiency.

The bottom absorber layer GaAs based thin-film solar cell which can confirm upper sunlight into electricity conversion process along with thermal stability by small absorber material. Back contact layer is added to the absorber layer, which need to carry out the electric current to the outer load and an aback into the cell. The separation of charge carriers is occurred by a p-n junction which creates cell parameters as a current and voltage. By this process it fulfills an electrical circuit. Figure 1 below demonstrates the structure of the proposed solar cell.

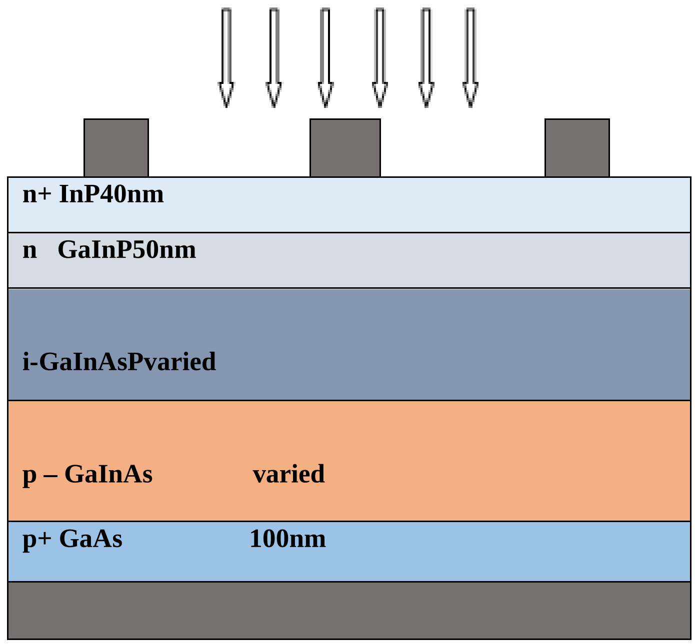

Figure 1 Structure of the Proposed Solar Cell

3. RESULTS AND DISCUSSIONS

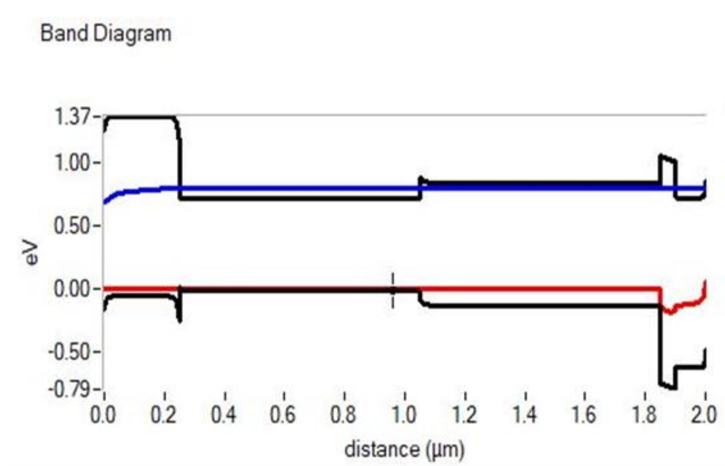

Figure 2 Energy Band Diagram

For doing the simulation of the I-V characteristics of graded p-i-n $Ga_xIn_{1-x}As_yP_{1-y}$ solar cell SCAPS-1D was used. Now we entered different parameters of all the layers in n+-InP/n-GaInP/i-GaInAsP/p-GaInAs/p+-GaAs device into the SCAPS-1D, as well as the front and back contact.

The material properties of the layers and contacts were taken from www.matprop.org [10] and in some cases we estimated different value of interface state density, defect density, bulk resistance, surface recombination velocity, effective state densities and metal work function, and also adjusted to get the curve fit to the experimental I-V curve at 300K.

After starting the simulation, we have found the energy band diagram which is shown in Figure 2.

And corresponding J-V curve has also been shown in Figure 3.

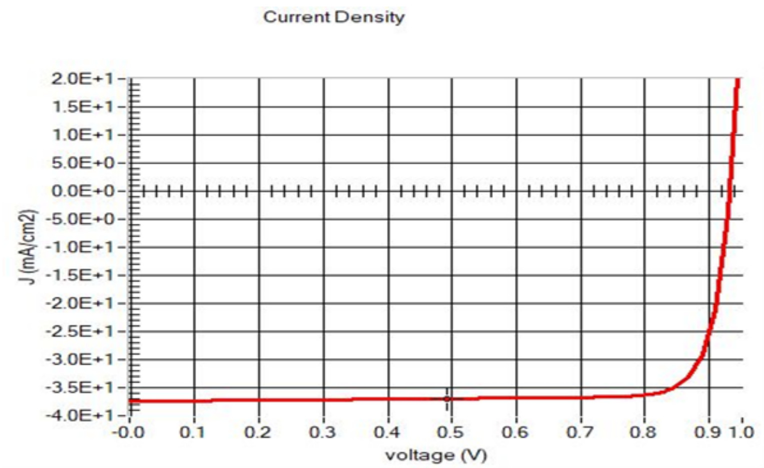

Figure 3 J-V Curve

Then short circuit current, open circuit voltage, fill factor and efficiency were observed at 300K temperature which is shown in Table 1 below.

Open circuit voltage, Voc (V)	1.0920
Short circuit current, Jsc(mA/cm2)	37.431939
Fill Factor, FF (%)	84.90
Efficiency (%)	34.70

Table 1 Efficiency of $^{+}$-InP/n-GaInP/i-GaInAsP/p-GaInAs/p^{+}-GaAs Solar Cell for Temperature 300K

3.1 Effect of i-GaInAsP Thickness

Here, we keep the thickness of other layer fixed and by changing the thickness of GaInAsP absorber layer thickness and investigated the effect of it on the solar cell performance. Table 2 below shows this effect.

GaInAsP layer thickness (nm)	Voc (V)	Jsc(mA/cm2)	FF (%)	Efficiency (%)
400	1.0924	37.494109	84.70	34.69
600	1.0924	37.443986	84.82	34.69
800	1.0924	37.431939	84.86	34.70
900	1.0924	37.427004	84.88	34.71
950	1.0924	37.426909	84.90	34.71

Table 2 GaInAsP Thickness Effect on Efficiency

3.2 Effect of GaInAsP Band Gap

Again the intrinsic layer is graded as $Ga_xIn_{1-x}As_yP_{1-y}$ here. The band gap of this layer can be changed by changing their composition. We have found some changes in efficiency which is shown in Table 3.

$Ga_xIn_{1-x}As_yP_{1-y}$ Band gap(eV)	Voc (V)	Jsc (mA/cm2)	FF (%)	Efficiency (%)
0.85	1.0927	37.4249	84.35	34.49
0.97	1.0922	37.4319	84.88	34.70
1.15	1.0877	37.4267	85.86	34.95
1.30	1.0820	37.4180	86.40	34.98
1.42	1.0805	37.4027	86.27	34.94
1.55	1.0820	37.3293	81.57	32.95

Table 3 Different Grading Effect

After that if we plot efficiency corresponding to band gap of GaInAsP, then we found a curve which is shown Figure 4 below.

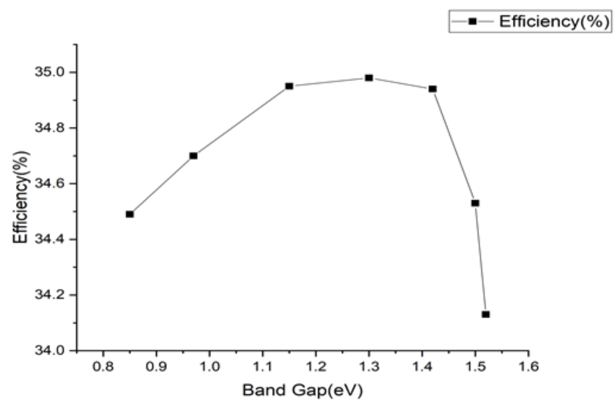

Figure 4 Efficiency vs Band Gap of GaInAsP Curve

Here we varied the band gap of GaInAsP from 0.85eV to 1.55eV by changing the quaternary metal compositions. From 0.85eV to 1.30eV efficiency increases and after that efficiency start to decreases.

3.3 Temperature Dependency

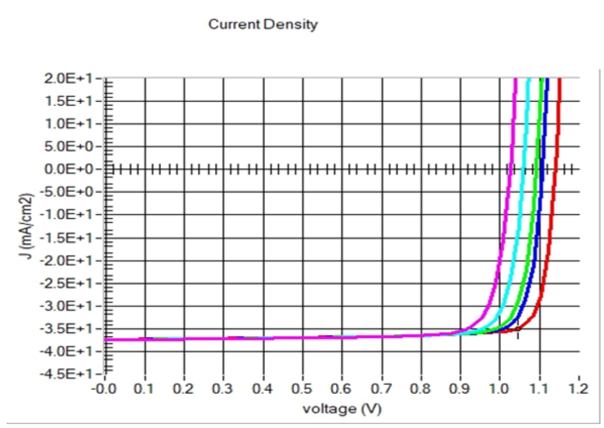

Figure 5 Effect of Temperature from 270k to 340k

Now J-V measurements were obtained at light for the temperatures 270K, 290K, 300K, 320K, 340K and corresponding J-V curve is found in Figure 5 and Table 4 summarizes this effect.

Temperature (K)	Voc (V)	Jsc (mA/cm2)	FF (%)	Efficiency (%)
270	1.14	37.400535	85.69	36.53
290	1.1083	37.419458	85.16	35.32
300	1.0924	37.431939	84.88	34.70
320	1.0595	37.460898	84.26	33.44
340	1.0262	37.498292	83.54	32.15

Table 4 Different Temperature Effect

If we plot efficiency with respect to temperature then we have found a straight line which is revealed in Figure 6.

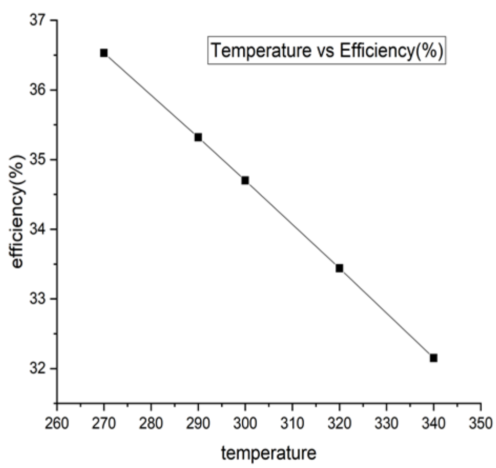

Figure 6 Effect of Temperature from 270k to 340k

From the table 4, we can say that the efficiency of the solar cell influenced by the atmospheric temperature. When the temperature of the environment increases, efficiency goes low, that means efficiency increases with the decreasing temperature.

4. EFFECT OF BACK CONTACT METALWORK FUNCTION

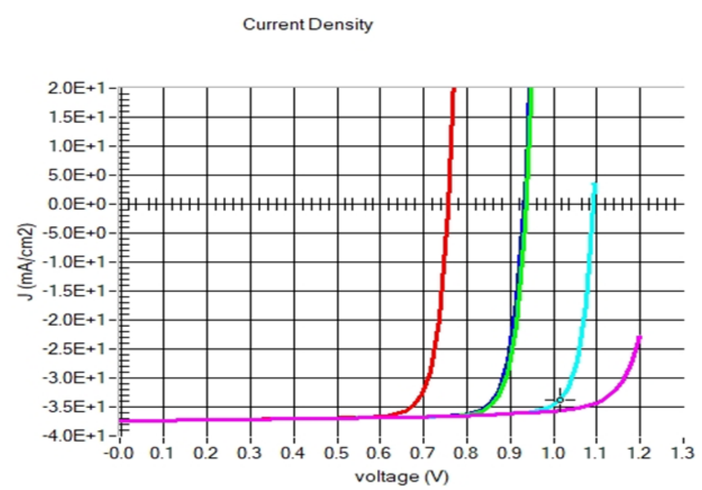

Figure 7 Effect of Back Contact Metal Work Function on J-V Characteristics for Fe (Red), Pd (blue), Ir (green), and Pt (violet)

We have done simulations using silver (Ag), iron (Fe), Irridium (Ir), nickel (Ni) and platinum (Pt) as back contact metal. As their work function is different so the J-V curve was found with different efficiency which is shown in Figure 7. Table 5 shows the work functions and corresponding efficiency values.

Back contact material	Ag	Fe	Ir	Ni	Pt
Φm	4.81	5.22	5.40	5.50	5.93
Voc	0.7572	0.9318	0.9383	1.0922	1.2967
Jsc	37.421	37.432	37.432	37.431939	37.432
Fill Factor	83.20	84.98	84.98	84.88	77.79
Efficiency	23.57	28.97	29.85	34.70	37.74

Table 5 Effect of Back Contact Metal Work Function

When we plotted efficiency with respect to work function of back contact metal, we have found the result like Figure 8. So, from the figure and analysis the efficiency increases with the increase of metal work function of back contact.

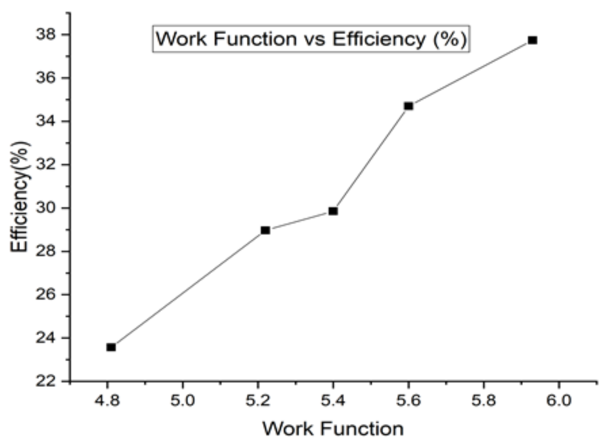

Figure 8 Back Contact Metal Work Function vs Efficiency Curve

5. EFFECT OF FRONT CONTACT METAL WORK FUNCTION

Similarly, we have done simulations using cadmium (Cd), aluminium (Al), mercury (Hg), chromium (Cr) and iron (Fe) as front contact metal and we observed different efficiency for different front contact metal which is shown in the Table 6 below.

Back contact material	Cd	Al	Hg	Cr	Fe
Φm	4.08	4.20	4.44	4.5	4.67
Voc	1.0929	1.0920	1.0922	1.0922	1.0922
Jsc	47.261	37.738	37.432	37.432	37.432
Fill Factor	74.52	84.32	84.88	84.88	84.88
Efficiency	38.49	34.75	34.70	34.70	34.70

Table 6 Effect of Front Contact Metal Work Function

After plotted these value we have found Figure 9.

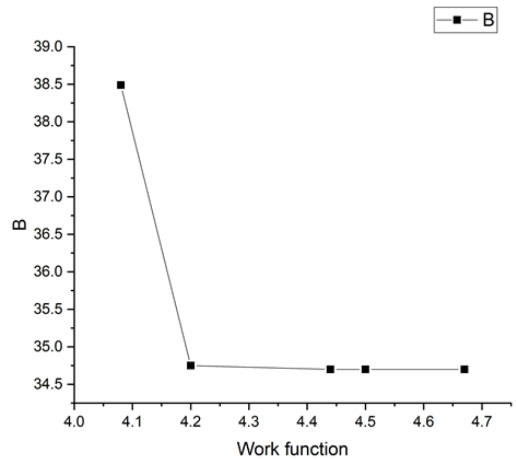

Figure 9 Front Contact Metal Work Function vs Efficiency Curve

Here we see that cell efficiency decrease with front contact metal work function increases.

6. CONCLUSION

In this work, the performance analysis of n^+-InP/n-GaInP/i-GaInAsP/p-GaInAs/p^+-GaAs solar cell for temperature, different band gap of $Ga_xIn_{1-x}As_yP_{1-y}$, metal work function for front and back contact is done using the SCAPS-1D simulation software. The characteristics of the solar cell are found by varying different properties. From the above analysis, we find out the maximum efficiency of 34.70% with fill factor 84.88, V_{oc} 1.0922V and J_{sc} 37.431929mA/cm^2.

REFERENCES

[1] John R. Wilson & Griffin Burge, "Energizing Our Future: Rational Choices for the 21st Century" John Wiley & Sons, inc, Hoboken, New Jersy, 2008, p.257.
[2] Antonio Luque and Steven Hegedu, "Handbook of Photovolatic Science and Engineering", John Wiley and Sons Ltd, England, 2005, p.426.
[3] Nikhil Jain, Kevin L. Schulte, John F. Geisz, Daniel J. Friedman, Ryan M. France, Emmett E. Perl, Andrew G. Norman, Harvey L. Guthrey, Myles A. Steiner, M. A., "High-efficiency Inverted Metamorphic 1.7/1.1 eV GaInAsP/GaInAs Dual-junction Solar Cells", *Applied Physics Letters*, 112(5), 053905 (2018). doi:10.1063/1.5008517.
[4] Jain, N., Geisz, J. F., France, R. M., Norman, A. G., & Steiner, M. A., "Enhanced Current Collection in 1.7 eV GaInAsP Solar Cells Grown on GaAs by Metalorganic Vapor Phase Epitaxy", *IEEE Journal of Photovoltaics*, 7(3), 927–933 (2017). doi:10.1109/jphotov.2017.2655035
[5] M. W. Wanlass, J.S.Ward, T.A.Gessert, K.A.Emery, G.S.Horner and T.J. Coutts, "Development of High-Performance GaInAsP Solar Cells for Tandem Solar Cell Applications", *Solar Energy Research Institute (SERI), Golden, CO 80401* and G.F.Virshup and M.L.Ristow ,Varian Associates, Palo Alto, CA 94303.
[6] T. Takamoto, E. Ikeda, H. Kurita, M. Ohmori: Appl. Phys. Lett. 70, 381 (1997).https://aip.scitation.org/doi/10.1063/1.118419
[7] T. Takamoto, M. Yamaguchi, S.J. Taylor, E. Ikeka, T. Agui, H. Kurita: In Proc. 26th IEEE Photovoltaic Specialists Conference (IEEE, New York 1997) p. 1451.
[8] W.M. Wanlass, J.S. Ward, K. Emery, A. Duda, T.J. Coutts: In Proc. 1st World Conference on Photovoltaic Energy Conversion, (IEEE, New York 1994) p. 1717.
[9] M. A. Khan, and T. Suemasu, "Donor and acceptor levels in impurity-doped semiconducting $BaSi_2$ thin films for solar-cell application", *Phys. Status Solidi A*, No. 1700019, 2017, DOI: 10.1002/pssa.201700019.
[10] www.matprop.org
[11] Dario Di Carlo Rasi, Koen H. Hendriks, Gaël H. L. Heintges, Giulio Simone, Gerwin H. Gelinck, Veronique S. Gevaerts, Ronn Andriessen, Geert Pirotte, Wouter Maes, Weiwei Li, Martijn M. Wienk, René A. J. Janssen, "A Universal Route to Fabricate n-i-p Multi-Junction Polymer Solar Cells via Solution Processing", Solar RRL, 2(5):1800018. Wiley-VCH Verlag, 2018. doi: 10.1002/solr.201800018.

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