Optimization of Individual Single-Junction Cells for the Development of High-Efficiency Ge-GaAs-InGaP Multi-Junction Solar Cells

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Abstract:

Solar energy- the most abundant source of energy in nature- has been considered a viable solution to solve the energy crisis in the society in long term. High efficiency concentrated multijunction solar cells have the capability to revolutionise the cost structure for photovoltaic power generation. This paper discusses the design and optimization of various single junction cells used in 3 junction solar cells which have recorded the highest efficiencies. The Modern Shockley Queisser limit places the theoretical limit for any single junction solar cell at 33%. The single junctions included in the design are Ge, GaAs and InGaP and the optimizations have been performed using the Silvaco ATLAS TCAD software. The optimizations are made based on the epitaxial layer thickness for base and emitter of each single junction for various values of base and emitter doping. Back surface field layer and window layer are also considered for the cells. Efficiencies of 30.06%, 21.93% and 11.54% have been achieved for the optimized structures of GaAs,InGaP and Ge cells respectively. The efficiencies are at par with the reported results worldwide . The designs have a fill factor >89% for GaAs and InGaP and >70% for Ge cells. The results are obtained for AM 1.5 spectrum under 1 sun illumination at a constant device temperature of 300K.

1. Introduction:

Solar cells find application in various space and terrestrial electric power applications, which would include power supplies for electronics and power satellites.[1] The first dual junction solar cell based on AlGaAs/GaAs was successfully fabricated in 1985[2]. .Since then III-V multijunction solar cells based on InGaP/(In)GaAs/Ge have been the subject of research and development due to very high efficiencies offered by the material system. As it belongs to a

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lattice matched material system, further loses are also seen to be minimum. The present state of art conversion efficiency for terrestrial concentrated cells has gone beyond 43% [3]. The optimization of solar cells with high number of epitaxial layers through experimental techniques is not feasible since it involves very high cost, high complexity and time consumption. Thus the better option for optimization and understanding of the physical concepts is to take aid of numerical modelling and simulations which would reduce cost and time for design.

2. Concept of Multijunction Solar Cells:

When a photon of energy hν greater than the bandgap of the material E_g is incident on a certain material, the excess energy is lost as heat within the material whereas it does not absorb the photon if the hν is less than E_g. Since the solar spectrum consists of photons with energies varying from 0 to about 4eV, the conversion efficiency obtainable by a single junction cell consisting of any particular material is inherently limited. Thus conceptually the solar spectrum has to be split into various regions and each region assigned to the material with the corresponding bandgap. Conventionally this is achieved by stacking the junctions one on top of the other in descending order of their bandgaps from top to bottom and connecting them in series. This configuration is illustrated in Fig 1.

In this paper, we report the optimization of each individual single junction cell, to be stacked in series to form high efficiency tandem InGaP/GaAs/Ge solar cells. Optimization is performed by varying the physical parameters like base and emitter thickness and doping for all the three single junctions using the Silvaco ATLAS TCAD tool. The conversion efficiency and fill factor for each sub-cell is investigated.

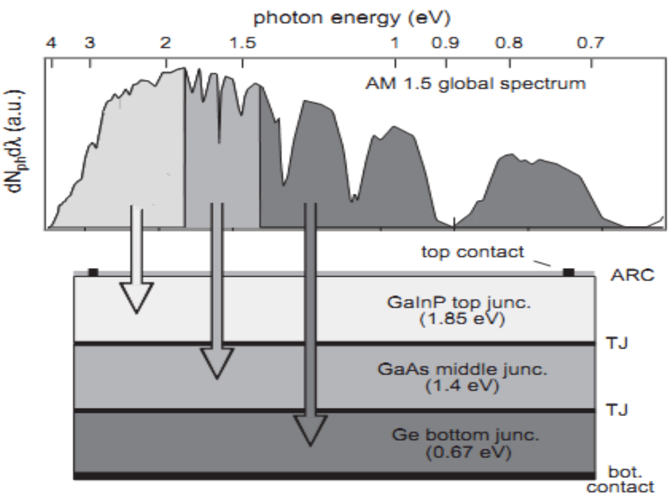

Fig 1. Schematic representation of distribution of photons from the solar spectrum into various junctions of a stacked, series connected triple junction solar cell. TJ is the tunnel junction and ARC is the anti-reflection coating [4]

3. Modelling and Optimization

For the design of a multijunction solar cell, the junctions used to tap the solar spectrum are made of InGaP, GaAs and Ge from top to bottom respectively. In our work, each junction is considered separately as a single junction and optimized individually. The structure for all the junctions is kept as constant with a p-doped base and n-doped emitter. Back surface field (BSF) layer and window layer are also applied to all the cells. Window layers are used as potential barriers for minority carriers and BSF layer acts as a reflector for minority carriers towards the junction. Both these layers help in reducing the losses due to the surface recombination effects. The n-contact is placed on the top centre and p-contact is at the bottom. Fig 2 shows the structure used ,except for Ge subcell where the BSF layer can be excluded due to the presence of bottom contact (in the triple junction structure), which will enhance the reflection. Then, each single junction is considered separately and optimized to obtain the highest conversion efficiency. The individual junctions considered are of InGaP, GaAs and Ge. Ge junction is made on the substrate. Table 1 shows the materials used as window layer and BSF layer for each subjunction. The InGaP cell with a wide bandgap of ~1.9eV absorbs mostly the short wavelength part of the solar spectrum while the rest are passed on to the GaAs subcell of bandgap ~1.42eV. The wavelengths which are still left unabsorbed are passed to the Ge subcell which has a bandgap of ~0.66eV, thus absorbing the longer wavelengths. The Silvaco ATLAS TCAD tool is used to model the solar cell with physical parameters such as material properties, compositions, doping concentrations and layer thicknesses. We investigate the conversion efficiency and fill factor of all the three subcells taken individually.

Table 1 Materials for window and BSF layers for subcells

Single jn Material	Window Layer	BSF
InGaP	AlInP	InGaP
GaAs	AlGaAs	InGaP
Ge	AlGaAs	-

Each single junction structure is taken separately and is simulated for different values of emitter and base thickness at varying values of base and emitter doping. The best value is taken as the set of doping and thickness values which show the best conversion efficiencies and fill factor. The performance parameters for any solar cell are the short circuit current (J_{sc}), open circuit voltage (V_{oc}), fill factor and the conversion efficiency (η). The maximum doping concentration of $5x10^{19}$ cm^{-3} for InGaP and GaAs, and $3x10^{18}$ cm^{-3} for Ge are considered for all simulations mainly because of the limitations in materials' technology [5].

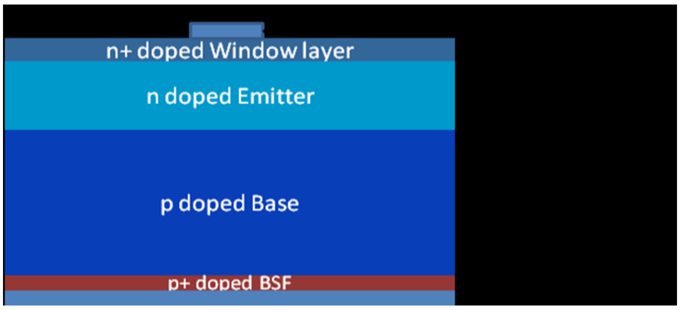

Fig 2: Common structure for single junction subcells.

4. Results and Discussions:

Figs 3(a) - 3(d) show the variation of conversion efficiency with the change in doping values of the base and emitter region for InGaP subcell. It is noted that the best efficiency values are obtained for a base doping of $3x10^{17}$ cm^{-3} and an emitter doping value of $1x10^{18}cm^{-3}$.

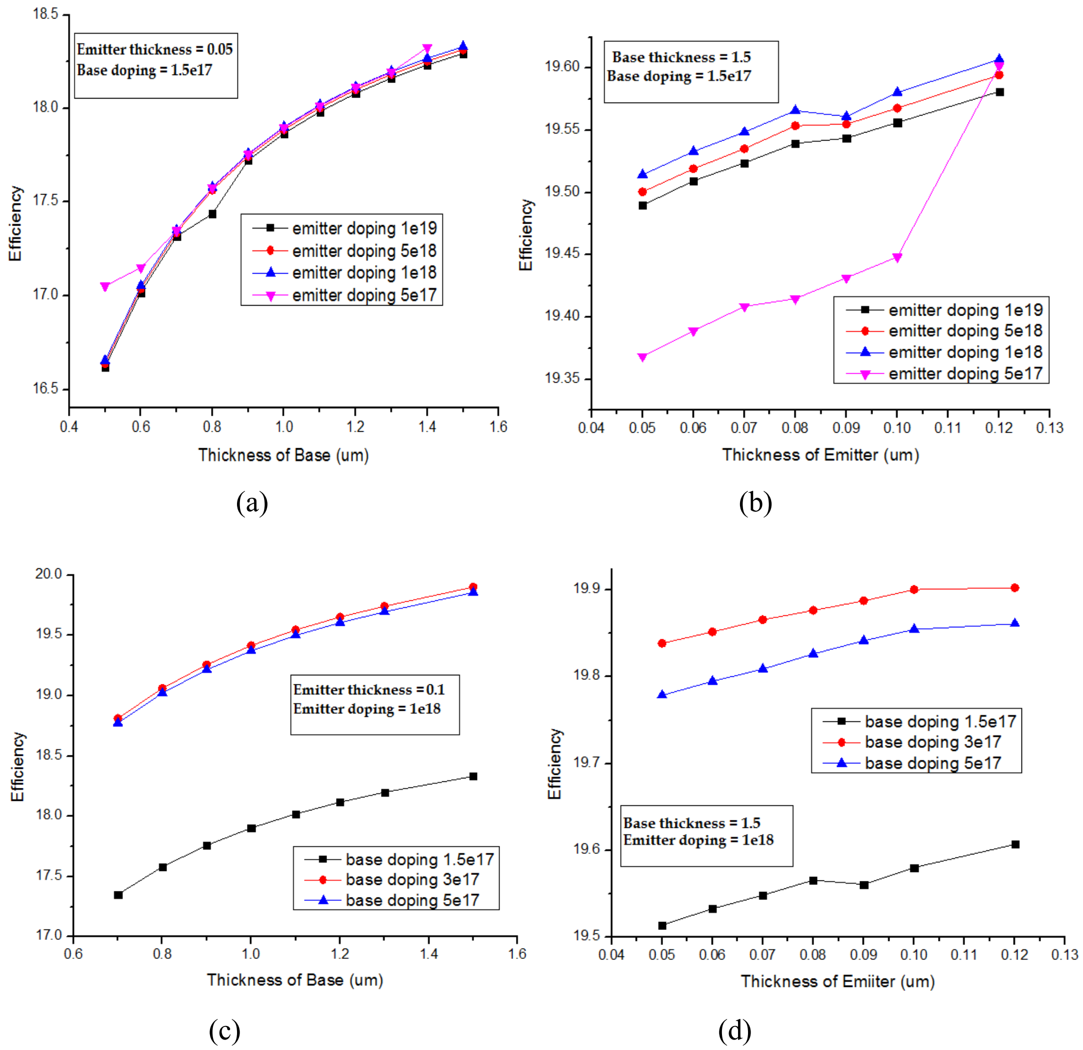

Fig 3. Conversion efficiency of InGaP subcell as a function of thickness of base [(a),(c)]and emitter[(b),(d)] for variation of emitter and base doping levels.

The GaAs subcell is observed to yield the best conversion efficiencies compared to the other two subcells studied. GaAs is also considered as an adequate material for the fabrication of single junction solar cells due to its high conversion efficiencies [6]; however, the disadvantage is the high cost of material. The efficiency change with the base thickness and emitter thickness can be seen from the Figs 4(a) - 4(d). The best doping is selected as the value where the efficiency is found maximum for both the graphs. The GaAs subcell showed the best efficiencies for comparatively lower doping values of ~1x10^{13} cm^{-3} , though for higher values till ~1x10^{16} cm^{-3} the overall variation is not more than 0.1% thus allowing for a wide range of base doping values. Similar trend is observed for emitter doping also.

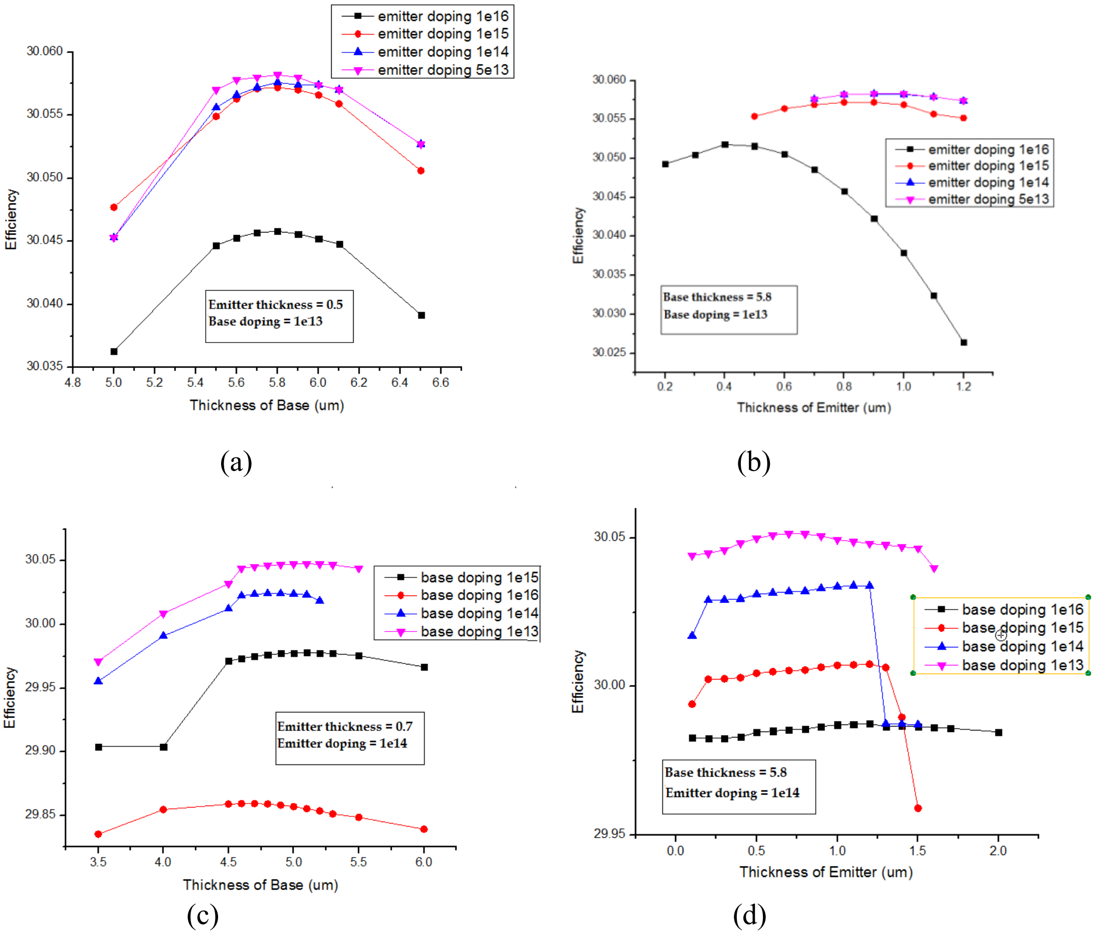

Fig 4. Conversion efficiency of GaAs subcell as a function of thickness of base [(a),(c)] and emitter[(b),(d)] for variation of emitter and base doping levels.

The Ge subcell is generally made from the Ge substrate itself and therefore, the area available is significantly more than the other two subcells. The Fig 5(a) and (c) show that as the base thickness increases the efficiency also increase but base thickness is limited by the thickness of the substrate due to which it is not kept more than ~300um. Due to limitation in material's technology, the maximum doping of Ge is considered upto a value of 3x10^{18} cm^{-3}.

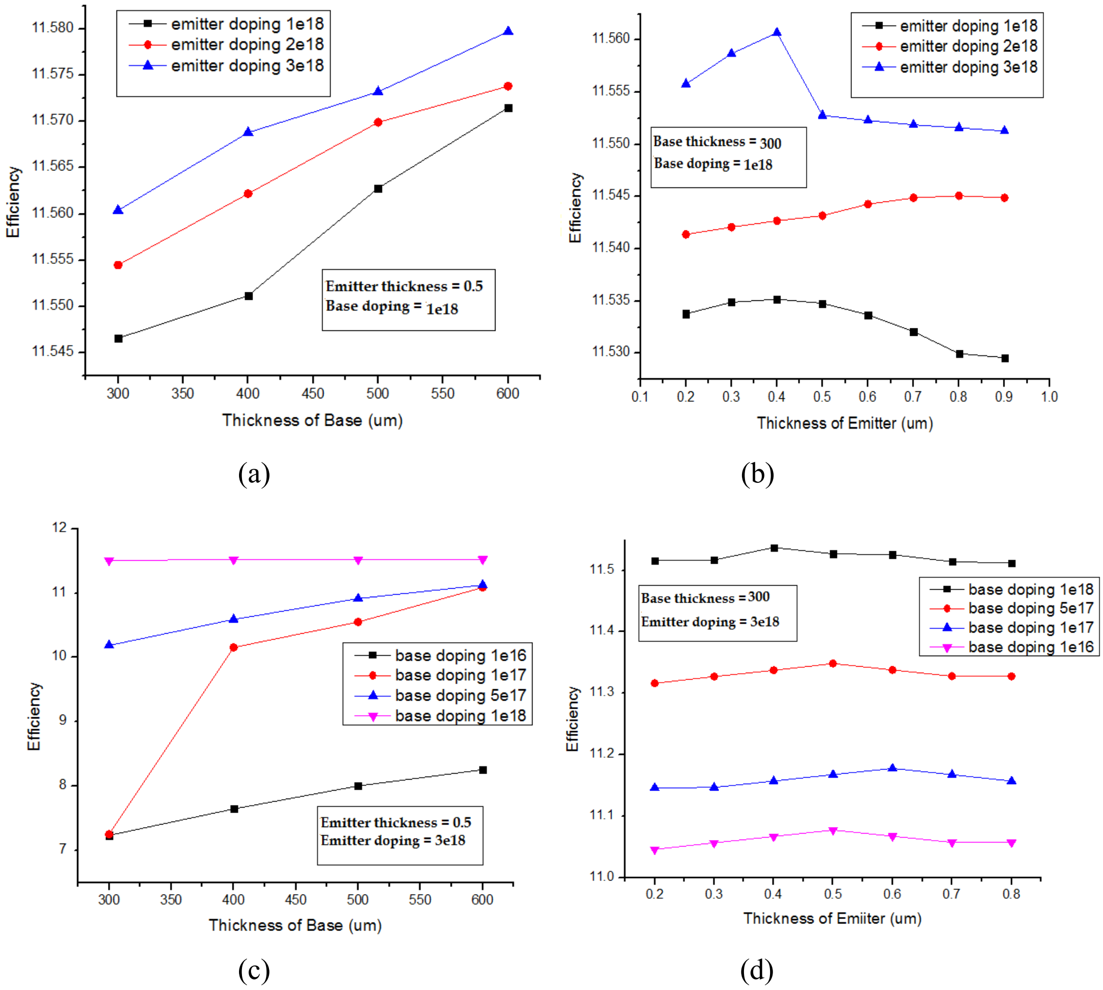

Fig 5. Conversion efficiency of Ge subcell as a function of thickness of base [(a),(c)] and emitter [(b),(d)] for variation of emitter and base doping levels.

Table 2 Optimized values for the individual subcells

	InGaP	GaAs	Ge
Emitter thickness(µm)	0.1	0.9	0.4
Emitter doping(cm^{-3})	1e18	1e14	3e18
Base thickness(µm)	1.5	5.8	300
Base doping (cm^{-3})	3e17	1e13	1e18
Window thickness (µm)	0.03	0.02	0.02
Window doping (cm^{-3})	5e19	1e18	1e18
BSF thickness (µm)	0.03	0.02	-
BSF doping (cm^{-3})	5e19	5e19	-

The optimized values for the subcells are given in Table 2. The optimizations have been done to find a practically realizable epitaxial layer thickness for the base and emitter regions based on the dopings of these layers. It is observed that the top InGaP layer gives its maximum intensity at a much lower layer thickness than the other two layers of which Ge needs the highest layer thickness. The emitter thickness for all the three layers are kept low, typically below 1μm since the best results can be achieved when the emitter thickness is typically less than the thickness corresponding to the minority carrier lifetime so that the chances of recombination before reaching the junction can be reduced. As the layer thickness increases the value of short circuit current density (J_{sc}) increases and that of open circuit voltage (V_{oc}) decreases. This is because the increase in thickness increases the carrier generation while the same reason leads to more chances of recombination before reaching the semiconductor junction. The figures of merit for the three individual junctions are given in Table 3.

Table 3 Parameters of Optimized single junction subcells under AM 1.5 spectrum

	Jsc(in mA/cm^2)	Voc (in V)	FF (in %)	Efficiency (in %)
InGaP SJ	16.40	1.34	90.89	19.90
GaAs SJ	32.46	1.04	89.31	30.06
Ge SJ	56.11	56.11	71.47	11.54

5. Conclusion

Design and optimization of each individual single junction cell, namely, Ge, GaAs and InGaP, that are required to develop triple junction solar cell, are carried out. The optimization of each single junction individually provides necessary insight into the behaviour of the subcells with changes in emitter and base doping and thickness and its impact. The various cell parameters are studied which is essential in developing the best cell efficiency of multijunction solar cell when stacked together. High subcell efficiencies obtained through simulation in the design optimization (~11.5% for Ge, ~30.1% for GaAs and ~19.9% for InGaP)are at par with the present state of the art results.

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