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THE EFFICIENCY OF THE SINGLE JUNCTION AND MULTIJUNCTION $In_xGa_{1-x}N$ SOLAR CELL USING AMPS-1D SIMULATOR

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ABSTRACT

Transparency loss and excess excitation loss are responsible for relatively lower conversion efficiency of single junction solar cell. One way to reduce these two losses is to use multijunction solar cell. In this research $In_xGa_{1-x}N$ based single, double and triple junction solar cells were simulated employing AMPS-1D simulator. The band gap of each layer depends on the composition percentage of InN and GaN within $In_xGa_{1-x}N$. In this simulation the authors found 24.51, 33.89, and 42.12% efficiencies for single, double and triple junctions, respectively.

Key words: Solar cell, High efficiency, Multijunction, $In_xGa_{1-x}N$, AMPS-1D

INTRODUCTION

As the global energy reserves such as fossil fuels, nuclear and geo-thermal dwindle and the global energy expenditure exponentially increases at unprecedented rates, it is increasingly apparent that renewable energy solutions must be utilized. Because of its sheer abundance, solar can play a dominant role in renewable energy armament if a solution can be found to reduce costs and to increase efficiency. The two major losses that are responsible for relatively lower conversion efficiency of solar cell are "transparency loss" and "excess excitation loss" (Yamamoto *et al.* 2010). The former is due to that photons with energies less than band gap E_g of the solar cell pass through the cell without interaction and thus cannot be utilized. The latter is due to the excess excitation of electrons from the top of the valence band to the conduction band by photons with enerties lager than E_g. The excited electron loses its energy thermally and comes down to the bottom of the conduction band. The excess energy, $(h\upsilon - E_g)$, thermally dispersed in a cell, cannot be utilized.

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The most effective way to reduce both the losses largely and simultaneously, that is, to realize high conversion efficiency, is to fabricate a multijunction tandem solar cell, where sub-cells composed of a different band gap material that are stacked perpendicularly and are electrically connected. For a multijunction tandem solar cell, semiconductor materials with band-gap energy from 0.6 to 2.5 eV are needed (Yamamoto *et al*. 2010).

A number of research groups have established that the fundamental direct band gap range of the III-nitride alloy system is the widest of any compound semiconductor, extending from InN (0.7 eV (Davydov *et al*. 2002, Wu *et al*. 2003 and Matsuoka *et al*. 2002), near-IR), to GaN (3.4, mid-UV), and finally to AlN (6.2 eV, deep-UV) (Wu *et al*. 2003, Wu *et al*. 2002, Wu *et al*. 2002, Kim *et al*. 1997, Shan *et al*. 1999 and Pereira *et al*. 2001).

The band gap of $In_xGa_{1-x}N$ varies with the value of x and follows the following equation (Wu *et al*. 2002),

$$E_g(\mathrm{ln}_x\mathrm{Ga}_{1-x}\mathrm{N}) = 0.7x + 3.4\,(1 - x) - 1.43x\,(1 - x)$$

Thus $In_xGa_{1-x}N$ can have a band gap ranging from 0.7 to 3.4 eV, since GaN has a band-gap of 3.4 eV. This interesting criterion of $In_xGa_{1-x}N$ makes it useful to design and implement multijunction solar cells.

MODELLING OF THE CELL

Fig. 1. shows the construction of a single junction, double junction and a triple junction solar cell.

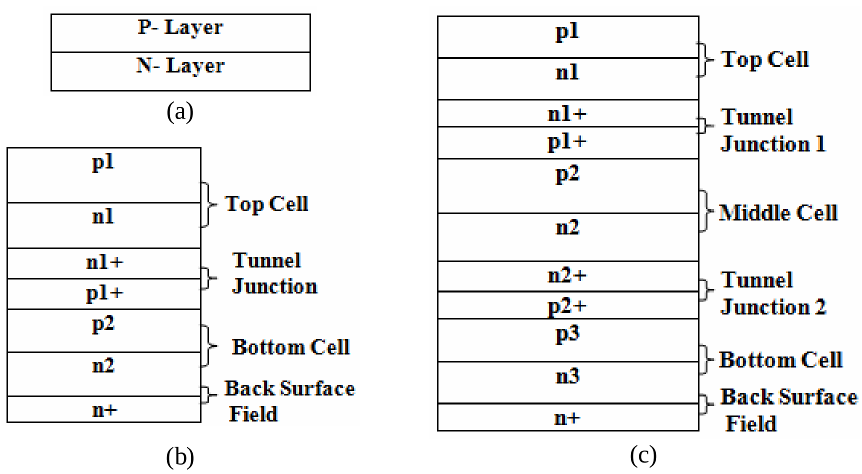

Fig.1. Construction of a (a) single junction, (b) double junction and (c) triple junction solar cell.

In case of single solar cell there exists no necessity of having any tunnel junction since in this case there exists no concern of tunneling of light through upper junction to bottom junction. But in case of multijunction (double junction and triple junction) there exists necessity of passing light through upper junction to the lower junction and thus require tunnel junction as shown in Fig. 1. Another important concern in multijunction is its current matching since the junctions are in series connection. Thus if current matching between different junctions are not maintained then the lowest current generated by any junction will be dominated.

MODEL CALCULATION

In modeling the solar cells it is considered that the physics of the device transport can be captured in three governing equations:

(a) Poisson's equation.

(b) The continuity equation for free holes.

(c) The continuity equation for free electrons.

In one-dimensional space, Poisson's equation (Donald 2002) is given by,

$$\frac{d}{dx}\left(-\varepsilon(x)\frac{d\Psi'}{dx}\right)=q\bullet[p(x)-n(x)+n_D^+(x)-N_A^-(x)+p\tau(x)-n\tau(x)]$$

where, the electrostatic potential Ψ' and the free electron n, free hole p, trapped electron n_t, and trapped hole p_t, ionized donor-like doping N_D^+ and ionized acceptor-like doping N_A^- concentrations are all functions of the position coordinate *x*. Here, ε is the permittivity and q is the magnitude of charge of an electron.

The generalized representation for continuity equation for hole is given by the following equation (Donald 2002),

$$\frac{\partial p}{\partial t}=-\frac{dF_p^+}{\partial x}+g_p-\frac{p}{\tau_{pt}}$$

where, p is the density of holes; F_p^+ is the hole-particle flux and has units of nmber of holes/cm^2-s, $\frac{\partial F_p^+}{\partial x}$ is the rate of increase of the number of holes per unit time due to hole flux, g_p is the increase in the number of holes per unit time due to the generation of holes, $\frac{p}{\tau_{pt}}$ is the decrease in the number of holes per unit time due to the recombination of hole and τ_{pt} defines the thermal equilibrium carrier lifetime and the excess carrier lifetime.

The generalized representation for continuity equation for electron is given by the following equation (Donald 2002),

$$\frac{\partial p}{\partial t} = -\frac{\partial F_p^-}{\partial x} + g_n - \frac{n}{\tau_{nt}}$$

where, n the density of electrons, F_n^- it is the electron-particle flux, and has units of number of electrons/cm^2-s, $\frac{\partial F_n^-}{\partial x}$ The rate of increase of the number of electrons per unit time due to electron flux, g_n the increase in the number of electrons per unit time due to the generation of holes, $\frac{n}{\tau_{nt}}$ the decrease in the number of electrons per unit time due to the recombination of electrons, here, τ_{nt} includes the thermal equilibrium carrier lifetime and the excess carrier lifetime.

In steady state, the time rate of change of the free carrier concentrations is equal to zero. As a result, the continuity equation for the free holes in the delocalized states of the valence band has the form,

$$\frac{1}{q}\left(\frac{dJ_p}{dx}\right) = G_{op}(x) - R(x)$$

and the continuity equation for the free electrons is the delocalized states of the conduction band has the form,

$$\frac{1}{q}\left(\frac{dJ_n}{dx}\right) = G_{op}(x) - R(x)$$

where, J_p the hole current density, J_n the electron current density, $R(x)$ the net recombination rate resulting from band-to-band (direct) recombination and S-R-H (indirect) recombination traffic through gap states, $G_{op}(x)$ the optical generation rate as a function of x due to externally imposed illumination.

These three coupled equations, along with the appropriate boundary conditions, are solved simultaneously to obtain a set of three unknown state variables at each point in the device : the electrostatic potential, the hole quasi-Fermi level and the electron quasi-Fermi level. From these three state variables, the carrier concentrations, fields, currents, etc. can then be computed.

RESULTS AND DISCUSSION

Electric field distribution curve shows gradual decrease in electric field from top cell to bottom cell. Noticeable change in electric field distribution in tunnel junctions are also revealed. This is because the thickness of tunnel is very small, only 10 nm. Sharp decrease in electric field in Back Surface Field (BSF) region is due to its very high doping with donor impurity and very small thickness, only 10 nm.

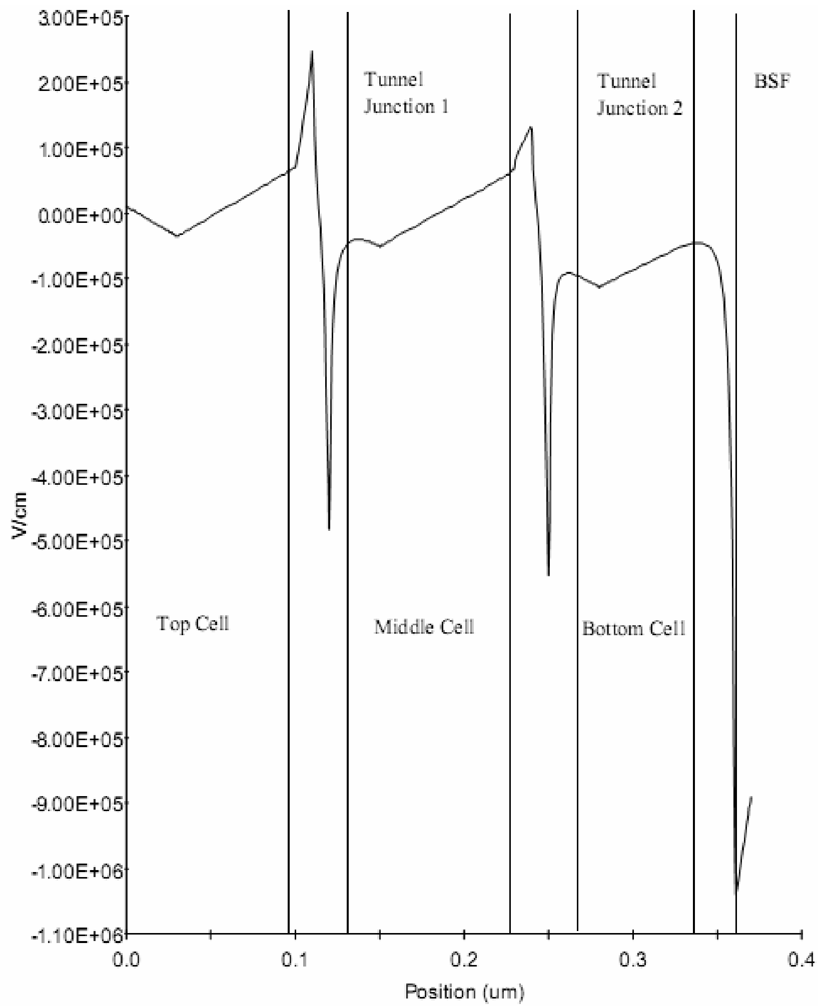

Fig. 2. Electric field distribution of $In_xGa_{1-x}N$ triple junction solar cell.

Gradual decrease in energy gap from top cell to bottom cell is clearly depicted in Fig. 3. This allows lower energy photons to reach to the next lower energy gap cell. In very thin tunnel junction, energy gap is very high which allows photons to pass through easily without any absorption. In BSF, energy gap is also relatively high and act as transparent medium to the lower energy photons.

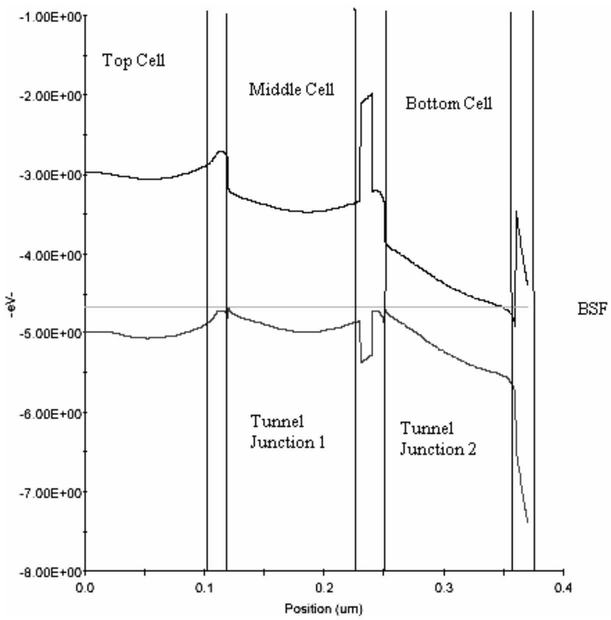

Fig. 3. Energy Band diagram of triple junction $In_xGa_{1-x}N$ solar cell.

In multijunction solar cell, since junctions are connected in series, thus open-circuit voltage of a tandem solar cell will be the sum of open-circuit voltages for all the cells whereas the short-circuit current will be dominated by the cell which has lowest value of short-circuit current. Thus, with increasing the number of junctions in multijunction solar cell, the value of open-circuit voltage will be increased but the value of short-circuit current will be decreased.

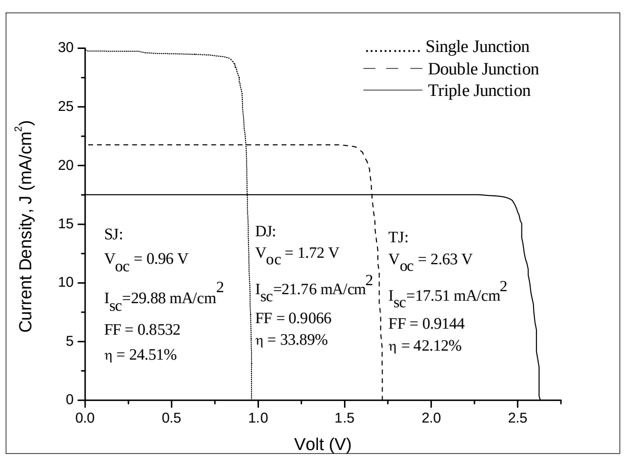

Fig. 4. Comparison of the efficiency curves for single, double and triple junction solar cell.

Again the investigated results show that, with increasing number of cell, the value of short-circuit current decreases and the value of open-circuit voltage increases. The overall efficiency also increases. But one important point is that, there is relatively less increase in efficiency from double to triple junction compared to the increase in efficiency from single to double junction. This result makes it clear that with the increase in number of cell, the efficiency of multijunction solar cannot be increased indefinitely. There must exist a trade-off in efficiency and number of cell used in multijunction solar cell.

CONCLUSION

The authors calculated the key properties of $In_xGa_{1-x}N$ tandem solar cells. The efficiencies of $In_xGa_{1-x}N$ solar cells were found 24.51, 33.89 and 42.12%, for the cases of single, double and triple junctions, respectively. This clearly reveals the increase in efficiency with increase in number of cells in a tandem solar cell.

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