The Effect of Indium Composition on Open-Circuit Voltage of InGaN Thin-Film Solar Cell: An Analytical and Computer Simulation Study

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Abstract. In this work we have evaluated the open-circuit voltage developed across a metal/n-InGaN Schottky junction solar cells through both analytical and computer simulation as a function of varying indium composition. Our study includes four different systems such as Au/n-InGaN/Al, Pd/n-InGaN/Al, Ni/n-InGaN/Al and Pt/n-InGaN/Al with a variation of Indium composition. It is reported that there exists a certain value of Indium composition which decides the InGaN as a Schottky junction solar cell. This cut-off value of Indium is calculated for all the systems by analytical and simulated approach and a comparison is also made between them. The difference of 19.4% for Au, 18.91% for Pd, 20.50% for Ni and 15.15% for Pt between analytical and simulation is reported.

Keywords: solar cell, Schottky diode, work function, open circuit voltage
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INTRODUCTION

Indium Gallium Nitride ($In_xGa_{1-x}N$ or generally "InGaN") is a III-V group compound semiconductor. Its band gap can be tuned by varying the indium composition from 0 (GaN, E_g = 3.4 eV) to 1 (InN, E_g = 0.7 eV) and spans ninety percent of Sun's spectrum, which motivate the study of InGaN for photovoltaic applications. After the revision of the band gap of indium nitride (InN), Wu J. *et al.* calculated the high-efficiency potential of InGaN solar cells [1], while Jani *et al.* demonstrated high open-circuit voltages (V_{OC}) of 2.4 V [2].

In a Schottky junction solar cell (SJSC), a semiconductor is sandwiched between two metals which makes a Schottky contact (rectifying current-voltage characteristics) on one side and an Ohmic contact (linear current-voltage characteristics) on the other side. A Schottky contact (SC) formed by a metal/n-type semiconductor, refers to the contact of a metal of higher work function with the semiconductor of lower work function [3,4] and has long been considered as the simplest photovoltaic devices of all. The doping concentration of semiconductor in case of SJSC is low, i.e., less than the density of states in the conduction or valence band [5].

In this work, we have studied the effect of indium composition on V_{oc} of InGaN SJSC evaluated by the analytical and computer simulation and a comparison is drawn between them. Our study involves four systems (Au/n-InGaN, Pd/n-InGaN, Ni/n-InGaN and Pt/n-InGaN). We have used our previous work on analytical modeling of open circuit voltage [6,7] and TCAD SILVACO, Version: Atlas 5.16.3.R for simulation.

FORMULATION

Analytical Study of Metal/n-InGaN:

In analytical study we have taken metal/n type semiconductor under illumination of monochromatic light at the Schottky interface. The boundary condition is that the total current (J_T) i.e. the combination of drift and diffusion currents of electrons and holes flowing in the cell, must be zero [6,7,8,9]:

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$$J_T = J_n(W) + J_p(W) \quad (1)$$

$$J_T = qn\mu_n E + qD_n \frac{dn}{dx} + qp\mu_p E - qD_p \frac{dp}{dx}$$

Since $J_T = 0$ (2)

So $qn\mu_n E + qp\mu_p E + qD_n \frac{dn}{dx} - qD_p \frac{dp}{dx} = 0$ (3)

Where, n and p are the electron and hole concentrations, respectively. μ_n, D_n and μ_p, D_p are the mobility and diffusion coefficient of electrons and holes, respectively and E is the electric field.

The open circuit voltage calculated by Behura *et al.* [6], across M/n-InGaN is given by Eq. (4):

$$V_{OC} = -\Phi_S + \frac{D_n\left(\frac{S_n}{\tau_p}\right) - D_p}{\mu_n\left(\frac{S_n}{\tau_p}\right) + \mu_p}\left[\log\left\{\frac{\left(C_3 \exp\left(\frac{L}{L_p}\right) + C_4 \exp\left(\frac{-L}{L_p}\right) - Q_2 \exp(-\alpha L)\right)}{(C_1 + C_2 - Q_1)}\right\}\right] \quad (4)$$

Where C_1, C_2, C_3 and C_4 are the constants of integration and Q_1 and Q_2 are the coefficients.

Simulation Study of Metal/n-InGaN:

We have simulated metal/n-InGaN/metal Schottky junction solar cell under illumination of polychromatic light (200 nm to 400 nm) at the Schottky contact of metal and n-type semiconductor. We have considered four systems [Ni (5 nm)/n-InGaN (987 nm)/Al (10 nm)], [Au (5 nm)/n-InGaN (987 nm)/Al (10 nm)], [Pd (5 nm)/n-InGaN (987nm)/Al (10nm)] and [Pt (5nm)/n-InGaN (987nm)/Al (10nm)]. Figure 1 describes the basic structure for system simulation.

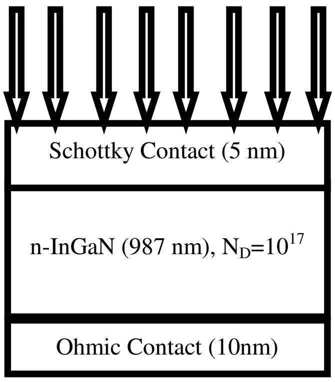

FIGURE 1. M/n-InGaN Schottky Junction Solar Cell.

In our simulation, we have used the following models viz., AUGER for surface Auger recombination, SRH for Shockley Read Hall recombination, OPTR for optical recombination and KP model for effective masses and band edge energies for drift diffusion simulation. Newton's method is used as the solution method in simulation. All the above models are used from standard TCAD library.

RESULTS AND DISCUSSION

Analytical Study of Metal/n-InGaN:

Using the analytical model, we vary the Indium composition, and calculate the V_{oc} for four different SJSC systems as shown in Fig.2. Table 2 describes the constant parameters for these calculations.

TABLE 2. Constant Parameters for Calculation [10, 11, 12].

Sl. No.	Parameter	Value
1	Carrier life time (τ)	2 ns
2	Mobility for electron (μ_n)	8.11×10^{-2} cm^2/V. sec
3	Mobility for hole (μ_p)	1.53×10^{-2} cm^2/V. sec
4	Surface recombination velocity ($S_{p/n}$)	100 cm/sec.

The cut-off value of Indium composition calculated by analytical approach is 0.36, 0.37, 0.39 and 0.66 for Au, Pd, Ni and Pt, respectively.

Simulation Study of Metal/n-InGaN:

InGaN material background doping is $\sim 10^{16} cm^{-3}$ therefore, we simulated InGaN at $N_D = 10^{17} cm^{-3}$. SJSC is not doped greater than the density of states in the conduction band, as it would result into degeneracy of the semiconductor and form an Ohmic contact with the metal. From the literature, it is found that, the density of states in the conduction band is $\sim 10^{18} cm^{-3}$ for InGaN [5]. In simulation result as shown in Fig.3, we found that the In composition cut-off value is 0.29, 0.30, 0.31 and 0.56 for Au, Pd, Ni and Pt, respectively.

We compared the analytical and simulated data for four systems and found that the difference in In cut-off value i.e. 19.4% for Au, 18.91% for Pd, 20.50% for Ni and 15.15% for Pt. Among four metals studied we conclude that Pt is the best for making Schottky contact till 56% of In composition.

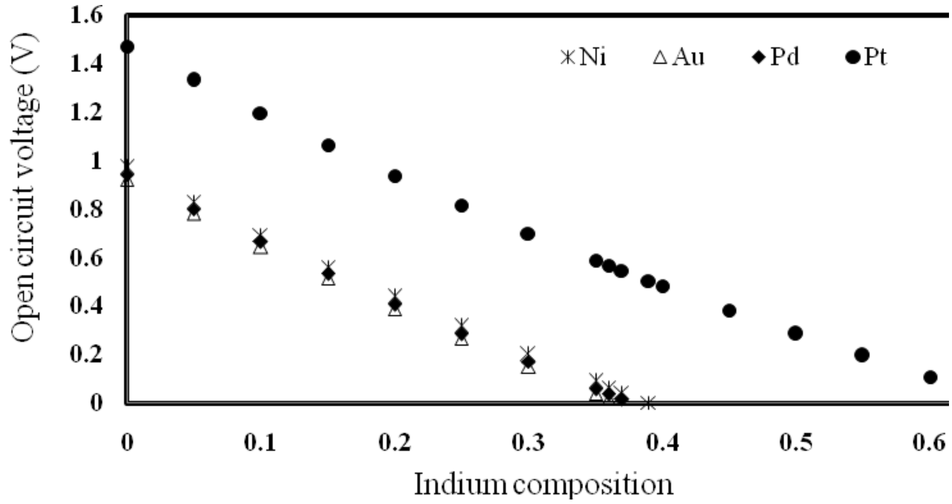

FIGURE 2. Variation of V_{oc} vs. Indium composition for four systems evaluated by analytical calculation.

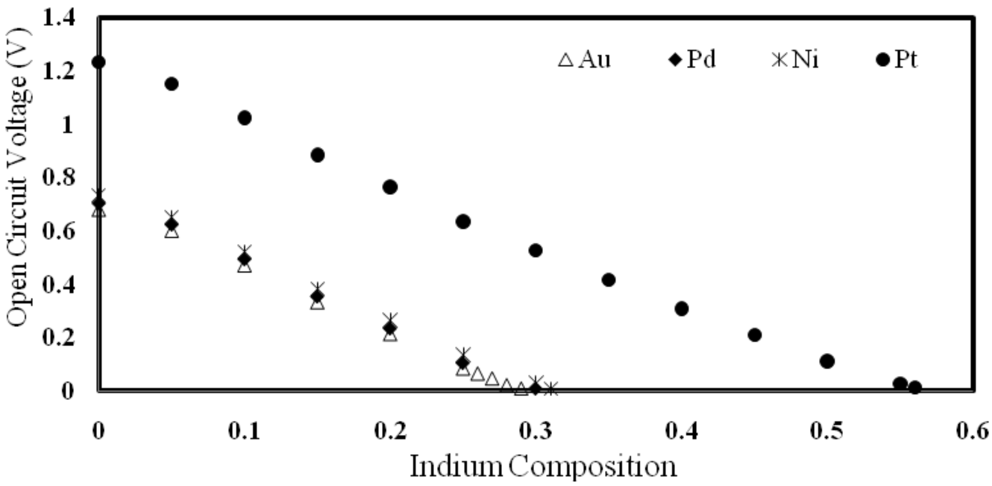

FIGURE 3. Variation of V_{oc} vs. Indium composition for four systems evaluated by simulation.

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