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Modeling For High Efficiency GaN/InGaN Solar Cell

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Abstract: *GaN/InGaN heterostructure contains a unique property of piezoelectric polarization charges at the interface due to different thermal expansion coefficients. In this paper, we report a simple mathematical model for Ga-face GaN/InGaN heterostructure solar cell. The results obtained from the given model indicates that the piezoelectric polarization charges at the interface of Ga-face GaN/InGaN heterostructure improves the efficiency of a single GaN/InGaN heterostructure photovoltaic solar cell in comparison to the non-polar solar cells by 45% for AM 1.5. This structure can also provide a fundamental solar cell unit for developing very high efficiency MQW solar cell and a MJ solar cell using Ga-face GaN/InGaN structure.*

Keywords: *GaN/InGaN hetero-structure, Multi-Quantum-Well, Multi-Junction solar cell, Piezoelectric polarization*

I. Introduction

The III-nitrides offer a great potential to develop high efficiency solar cells due to their wide band gap ranging from 0.65 eV (InN) to 6.2 eV (AlN) [1] and superior photovoltaic characteristics (direct band gap in the entire alloy range, high carrier mobility, drift velocity, radiation resistance and high optical absorption of ~ 10^5/cm near the band edge). A unique property of III-nitrides is the strong polarization, which is due to their non-centrosymmetry structure in nature. These polarizations (spontaneous and piezoelectric) influence their optical and electrical properties of the system and play a significant role in designing of the high efficiency solar cells. This polarization induces an electrical field of the order ~ 1-2 MV/cm [2]. The effect of polarization may be used to reduce ohmic contact resistance, to enhance carrier collection and band bending. In this paper, we investigate theoretically the effect of polarization for Ga- face GaN/InGaN heterostructure solar cell grown on sapphire substrate. In Ga-face GaN/InGaN heterostructure both spontaneous and piezoelectric polarizations are oriented in opposite directions. These polarization charges may be utilize at interface of the heterostructure to increase the short circuit current of the solar cell, which ultimately improve the performance of solar cell in terms of efficiency.

II. Model

In our structure, we have taken a 200 nm thick p-GaN layer above n-InGaN of 500nm thickness as shown in fig 1. The above structures are on Sapphire substrate. We assume that light enters from p-GaN.

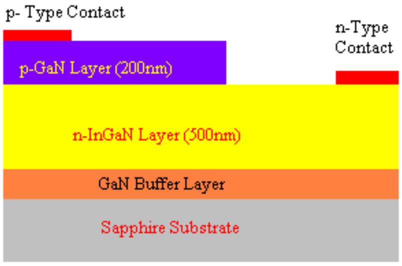

Fig.1. Schematic structure for p-GaN/n-InGaN solar cell

The effect of polarization in semiconductor materials is expressed by

$$D = \varepsilon_0 \varepsilon_r E + P \qquad (1)$$

In equation (1), D is the displacement vector in dielectric, E is the electric field (V/m), P is the net polarization in the solar cell structure (C/m^2), ε_0 is the vacuum permittivity and ε_r is relative permittivity of the GaN material.

The spontaneous polarization of InGaN layer in terms of Indium composition (x_1) is [3]

$P_{sp}^{InGaN} = -0.003 \times x_1 - 0.029$ (2)

The piezoelectric polarization InGaN layer in terms of Indium composition (x_1) is [4]

$P_{pz}^{InGaN} = 0.176 \times x_1$ (3)

The spontaneous polarization of GaN layer will be fixed and its value is [5]

$P_{sp}^{GaN} = -0.034 C/m^2$ (4)

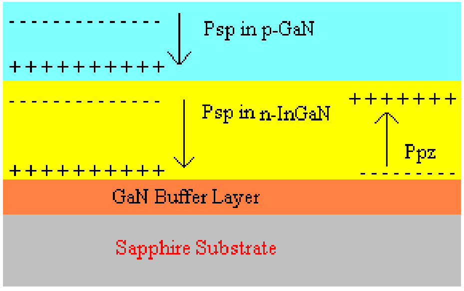

Fig.2. Orientation of polarizations in Ga-face p-GaN/n-InGaN heterostructure.

The orientation of all these polarizations in Ga-face p-GaN/n-InGaN heterostructure is shown in fig. 2 and according to it the net polarization in n-InGaN layer at the interface is
$P = P_{pz}^{InGaN} + (P_{sp}^{InGaN} - P_{sp}^{GaN})$ (5)

The net polarization charges at the interface of p-GaN/n-InGaN heterostructure will be [1]

$\sigma_s = P/q$ (6)

Where, q is the electronic charge.
In this heterostructure solar cell, we assume that light enters the p-n diode from the wide band gap side as shown in fig. 3.

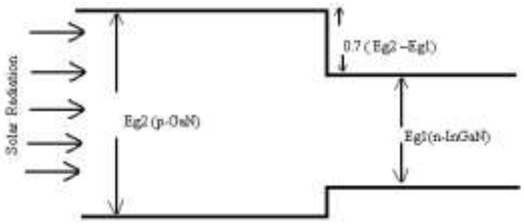

Fig. 3. Energy band diagram of p-GaN/n-InGaN heterostructure

Photons with energies greater than E_{g2} are absorbed by the top p-type layer and photons with energies between E_{g2} and E_{g1} are absorbed by the smaller band gap n-type layer. The resultant short circuit current and open circuit voltage for this structure is limited by the smaller band gap region. The piezoelectric polarization charges will also contribute into the photo-generated current. Thus, photocurrent (short circuit current) in this heterostructure solar cell is represented by

$$I_{SC} = q \times [1-\alpha(x)] \times [1-R] \times \int_{\lambda Eg2}^{\lambda Eg1} N(\lambda) \, (dnph/d\lambda + \sigma s) \, d\lambda \quad (7)$$

In the above equation (7), $\alpha(x)$ is the absorption of optical power with respect to distance. Studies indicate that in GaN about 99% optical power is absorbed at 500 nm distance [6]. R is the reflectance at air-GaN interface (about 18%) [7, 8], N (λ) is the collection efficiency representing the number of electron-hole pairs generated from the absorbed photons. $dn_{ph}/d\lambda$ is the number of incident photons per cm^2 per second at a particular wavelength of the solar spectrum and calculated using $2\pi\nu c^2/$ [exp (hν/KT)-1]. Integration limits λEg1 is the wavelength corresponding to the band gap of n-InGaN layer and λEg2 is the wavelength corresponding to the band gap of p-GaN layer. σ_s is the piezoelectric charges at the interface of p-GaN/n-InGaN heterostructure.

The open circuit voltage for p-GaN/n-InGaN hetero-structure solar cell is
$V_{OC} = (KT/q) \times \ln[(I_{sc}/I_0)+1]$ (8)

Where, K is the Boltzmann constant, T is the operating temperature, I_{sc} is the photo-generated current and I_0 is the reverse saturation current. The saturation current in p-GaN/n-InGaN hetero-structure is

$I_0 = qA \times [(D_n \times n_i^{P\text{-}GaN})/(L_n \times N_A^{P\text{-}GaN}) + (D_P \times n_i^{n\text{-}InGaN})/(L_p \times N_D^{n\text{-}InGaN})]$ (9)

Where, A is the front cross section area of the solar cell. D_n and D_P are the diffusion coefficient for electrons in p-GaN and for the holes in n-InGaN. These diffusion coefficients are calculated by $D_n = \frac{KT}{q}\mu_n$ and $D_P = \frac{KT}{q}\mu_P$.

Where, μ_n and μ_p are the mobility of electron and hole, L_n and L_p are the minority carrier electron and hole diffusion lengths calculated by $L_n = [D_n\ \tau_n]^{1/2}$ and $L_P = [D_P\ \tau_P]^{1/2}$. Where τ_n and τ_P are the average re-combination time for electrons and holes, $n_i^{P\text{-}GaN}$ and $n_i^{n\text{-}InGaN}$ are the intrinsic concentration in p-GaN and n-InGaN, $N_A^{P\text{-}GaN}$ and $N_D^{n\text{-}InGaN}$ are the external doping in p-GaN and n-InGaN. The fill factor is

$F.F. = V_m I_m / V_{OC} I_{SC}$ (10)

Where, V_m is the maximum voltage across the load resistance and I_m is the maximum current in the load Resistance. For GaN based good performance solar cell its value is greater than 70% [10]. The external quantum efficiency of p-GaN/n-InGaN heterostructure solar cell

$\eta_e = V_m I_m / P_{in}$ (11)

Where, P_{in} is total incident solar power absorb by solar cell.

III. Results And Discussion

For above model we calculate the values of short circuit current (I_{SC}), open circuit voltage (V_{OC}) and external quantum efficiency (η_e) using parameter values listed in table-1.

S.No.	Parameters	Parameter Value
1	Indium composition (x)	0.2
2	External doping in p-GaN	5.1×0^{17} cm^{-3}
3	External doping in n-InGaN	5×10^{18} cm^{-3}
4	Intrinsic concentration in p-GaN	2.35×10^{-10} cm^{-3}
5	Intrinsic concentration in n-InGaN	7.21×10^{-4} cm^{-3}
6	Recombination time for electron [9]	2×10^{-9} Sec
7	Recombination time for hole [9]	2×10^{-9} Sec
8	Reflectance at air-GaN interface [7, 8]	0.18
9	Collection efficiency	0.7
10	Temperature equivalent voltage	0.026 (at 300 K)
11	Mobility of electron [9]	440 cm^2/V.sec
12	Mobility of hole [9]	10 cm^2/V.sec

Table-1

Table-2 shows the calculated values of short circuit current (I_{SC}), open circuit voltage (V_{OC}) for both without polarization effect and with polarization effect using the above model.

Type	I_{SC} (mA/cm^2)	V_{OC} (Volt)
Without polarization effect	1.88	1.96
With polarization effect	3.40	1.98

Table-2

Fig. 4 shows the curve between the short circuit current and open circuit voltage with polarization and without polarization effect.

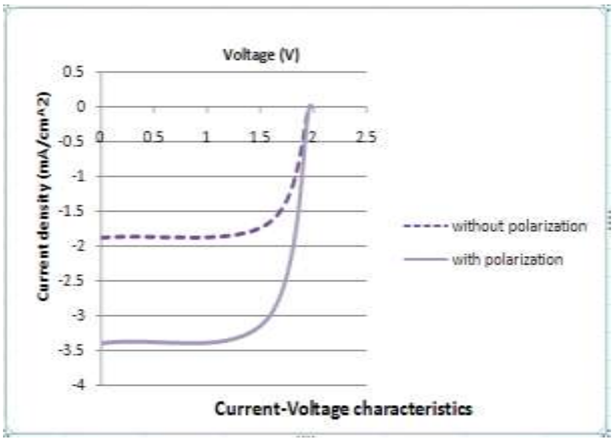

Fig. 4. Current-voltage characteristics

The values of I_{SC} and V_{OC} in table 2 indicate that the open circuit voltage and short circuit current of the solar cell increases due to piezoelectric polarization induced charges at the interface of p-GaN/n-InGaN heterostructure. The value of short circuit current increases from 1.88 mA /cm^2 to 3.40 mA /cm^2 and open circuit voltage increases from 1.96 Volt to 1.98 Volt. These results clearly indicate that the increase in efficiency of Ga-face p-GaN/n-InGaN heterostructure solar cell is mostly due to increase in short circuit current (from 1.88 mA /cm^2 to 3.40 mA /cm^2) of the solar cell.

IV. Conclusions

From above discussion we conclude that by using Ga-face p-GaN/n-InGaN heterostructure for the solar cell design the value of short circuit current increases by 44% and the open circuit voltage increases by 1%. Thus net improvement in external quantum efficiency of the solar cell is about 45% for AM 1.5. This is a large improvement in the performance of a single heterojunction photovoltaic solar cell, thus encourages us to use the Ga-face p-GaN/n-InGaN heterostructure solar cell structure in multi-quantum-well solar cell and multi-junction solar cell to design very high efficiency photovoltaic solar cell.

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