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# A Study of Critical Built-in Electric Field in InGaN p-i-n Solar Cell

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## 1. Introduction

Recently InGaN alloys turn into new solar cell materials because that the band gap energy of InGaN alloys can be modulated from 0.7 eV for InN [1] to 3.4 eV for GaN, and cover almost the whole solar spectrum. This makes them become potential materials for photovoltaic applications. Manish Mathew et al. [2] have designed a GaN/InGaN p-i-n solar cell, there is an intrinsic layer inserted in the cell between p-type and n-type layers. As a consequence, both the light absorption and conversion efficiency has been enhanced. Owing to develop the photovoltaic devices with conversion efficiency of 40% or higher, the III-nitride materials have absolutely potential in the future. In this study, we employ GaN/InGaN p-i-n solar cell structure to analyze the built-in electric field in the InGaN layer by the APSYS simulation program [3]. From simulation results, we find the critical electric field (Fc) 100 kV/cm is the key to become a high efficiency GaN/InGaN p-i-n solar cell. Therefore, we expect to achieve the result by measuring its built-in electric field by electricmodulation spectroscopy, and further acquiring the quality of solar devices. The schematic structure of GaN/InGaN p-i-n solar cell used in this study is shown in Fig. 1 [4,5]. The top layer is a p-type gallium nitride (GaN) of thickness 0.15 μm with doping concentration of $8\times10^{17}$ $cm^{-3}$, and the bottom layer is a n-type GaN of thickness 3.0 μm with doping concentration of $5\times10^{18}$ $cm^{-3}$. The middle layer is an intrinsic $In_{0.1}Ga_{0.9}N$ layer with thickness of 0.15 μm. All of the simulated results of solar cells are performed under the condition of one-sun air mass (AM) 1.5 global spectrum at room temperature.

## 2. Results and discussion

The black line in Fig. 2 shows the simulated I-V curve of the solar cell and the red line is an experimental data published in the reference [5]. Owing to fit the simulated curve to the experimental data, the simulation parameters used in subsequent simulation are listed in table I [3]. From Fig. 2, we obtain that the short circuit current ($I_{sc}$) is 0.33 $mA/cm^2$, the open-circuit voltage ($V_{oc}$) is 2.21 V and the transfer efficiency is 0.65% without anti-reflection coatings. The p-type layer thickness and doping concentration are important parameters for the electrical behavior of a solar cell. Fig. 3, therefore, shows the effect of p-layer thickness on the efficiency of the cell. From simulation results, it has been found that the optimum thickness of p-type layer locates between 0.1 and 0.2 μm. Omkar Jania et al. [4] have proposed that the top p-region is limited to 100 nm. This value is consistent with our simulation results, from which it has a maximized absorption in the i-region to provide charges and transfer them into electric power.

Fig. 4 shows the I-V curves for different doping concentrations of the p-type layer. It is worth to note that the doping concentration should be larger than $4\times10^{16}$ $cm^{-3}$ at least for getting a good performance cell, which has a large short circuit current and a high fill factor.

Energy band diagram of the GaN/InGaN p-i-n solar cell under illumination and electric field distribution plot of the different doping concentration on the p-type layer are summarized in Fig. 5(a) and (b). From Fig. 5(a), we can find the discontinuity steps in bandgap energy of these two materials at the interfaces and understand that electrons and holes are accumulated on the n and p terminals, respectively.

The dependence of solar cell efficiency on the electric field strength has been summarized in Fig. 6(a). It is worth to note that there exists a critical value of Fc located near 100 kV/cm for different lifetimes. Only as the electric field strength larger than Fc, the transfer efficiency becomes a stable value. Furthermore, transfer efficiency increases with increasing SRH lifetime but the Fc is kept at the same value of 100 kV/cm. We compare the efficiency vs. electric field strength in the InGaN layer with different layer thicknesses. Due to the InGaN layer is the main optical absorption layer to generate photoexcited current, we increase the thickness of InGaN layer, consequently, the photocurrent and efficiency are increased as well. Conversely, the increase of InGaN layer thickness results in the decrease of the electric field strength in InGaN layer. So, it is necessary to increase the doping concentration of p-layer to keep the electric field strength in InGaN layer above the Fc value.

In Fig. 7(a), it can be observed that an obvious SRH recombination peak occurs near the top interface for low p-type doping concentration. Fig. 7(b) illustrates the SRH recombination rate, electron and hole concentrations vs. position in p-type layer which has doping concentration of $3\times10^{16}$ $cm^{-3}$. Because the electric field strength in the depletion region does not strong enough to separate the electrons and holes before they get recombine, the SRH recombination rate reaches its peak at the position near 0.12 μm, where the amount of electrons and holes are close. This result tells us that a high SRH recombination rate resulting from a low electric field will destroy the performance of solar cells.

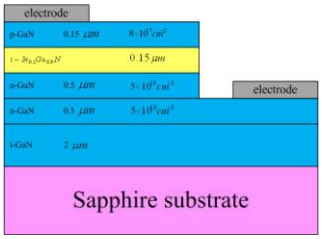


Fig. 1 Schematic structure of GaN/ InGaN p-i-n solar cell.

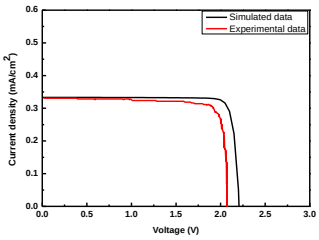


Fig. 2 I-V curves of GaN/ InGaN p-i-n solar cell.

Table I. Simulation parameters

| Parameters | Values |
|---|---|
| Solar spectrum | AM1.5G @ 1 sun |
| SRH recombination lifetime of $In_{0.1}Ga_{0.9}N$ | 0.3 ns |
| SRH recombination lifetime of GaN | 0.3 ns |
| Bandgap energy of $In_{0.1}Ga_{0.9}N$ | 2.9 eV |
| Bandgap energy of GaN | 3.4 eV |

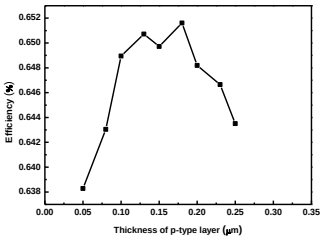


Fig. 3 Transfer efficiency of the GaN/InGaN p-i-n solar cell with different p-type layer thickness.

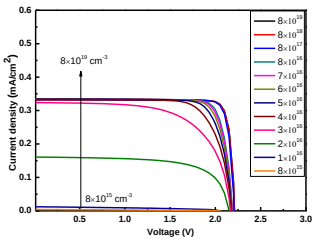


Fig. 4 I-V curves of the GaN/InGaN p-i-n solar cell.

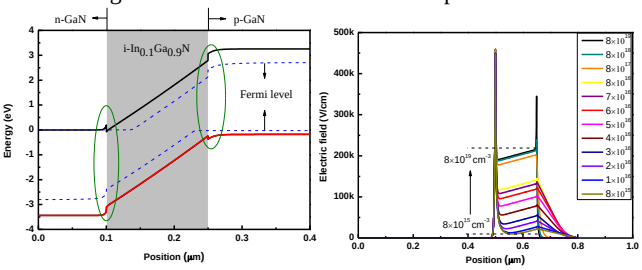


Fig. 5 (a) Energy band diagram of the GaN/InGaN p-i-n solar cell under illumination. (b) Eletric field distribution plot of the different doping concentration on the p-type layer.

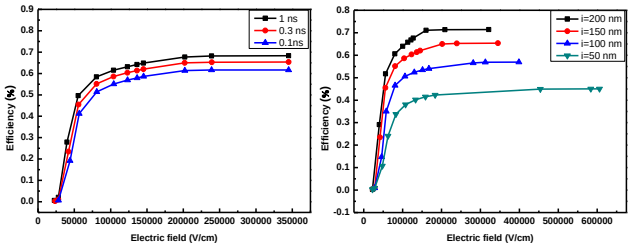


Fig. 6 Transfer efficiency vs. electric field of GaN/InGaN p-i-n solar cell ： (a) different Shockley-Read-Hall (SRH) lifetime, (b) different intrinsic layer thickness.

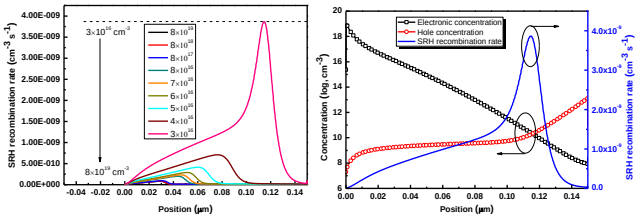


Fig. 7 (a) SRH recombination rate of the different doping concentration on the p-type layer. (b) Concentrations and SRH recombination rate under the p-type layer doping concentration of $3\times10^{16}$ cm$^{-3}$.

## 3. Conclusions

In this study, we employ the APSYS simulation program to analyze the electric field effect on the performance of InGaN p-i-n solar cell. From analyzing the simulation results, we find that the doping concentration of p-type layer should be larger than $4\times10^{16}$ cm$^{-3}$ and the suitable thickness of p-type layer is between 0.1 to 0.2 μm. We also find that the critical electric field strength Fc (100 kV/cm) plays an important role for getting a good performance and can be used as a guide to design a solar cell with high transfer efficiency and low SRH recombination rate.


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