

# Dependence of InGaN solar cell performance on polarization-induced electric field and carrier lifetime\*

Yang Jing(杨静)<sup>a)</sup>, Zhao De-Gang(赵德刚)<sup>a)†</sup>, Jiang De-Sheng(江德生)<sup>a)</sup>, Liu Zong-Shun(刘宗顺)<sup>a)</sup>, Chen Ping(陈平)<sup>a)</sup>,  
Li Liang(李亮)<sup>a)</sup>, Wu Liang-Liang(吴亮亮)<sup>a)</sup>, Le Ling-Cong(乐伶俐)<sup>a)</sup>, Li Xiao-Jing(李晓静)<sup>a)</sup>,  
He Xiao-Guang(何晓光)<sup>a)</sup>, Wang Hui(王辉)<sup>b)</sup>, Zhu Jian-Jun(朱建军)<sup>b)</sup>, Zhang Shu-Ming(张书明)<sup>b)</sup>,  
Zhang Bao-Shun(张宝顺)<sup>b)</sup>, and Yang Hui(杨辉)<sup>a)b)</sup>

<sup>a)</sup>State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

<sup>b)</sup>Suzhou Institute of Nano-tech and Nano-bionics, Chinese Academy of Sciences, Suzhou 215123, China

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The effects of Mg-induced net acceptor doping concentration and carrier lifetime on the performance of a p-i-n InGaN solar cell are investigated. It is found that the electric field induced by spontaneous and piezoelectric polarization in the i-region could be totally shielded when the Mg-induced net acceptor doping concentration is sufficiently high. The polarization-induced potential barriers are reduced and the short circuit current density is remarkably increased from 0.21 mA/cm<sup>2</sup> to 0.95 mA/cm<sup>2</sup> by elevating the Mg doping concentration. The carrier lifetime determined by defect density of i-InGaN also plays an important role in determining the photovoltaic properties of solar cell. The short circuit current density severely degrades, and the performance of InGaN solar cell becomes more sensitive to the polarization when carrier lifetime is lower than the transit time. This study demonstrates that the crystal quality of InGaN absorption layer is one of the most important challenges in realizing high efficiency InGaN solar cells.

**Keywords:** nitride materials, solar cell, polarization

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## 1. Introduction

The material system of III-group nitrides has proven to be useful for making full spectrum light emitting devices<sup>[1]</sup> and electronic devices for power electronics and high frequency applications.<sup>[2]</sup> The excellent material properties which make III-N semiconductors appealing for light emitters and electronics are also advantageous for high performance solar cells. The properties including the wide range of band gap energies available (0.7 eV to 3.4 eV), high mobility of carriers, high resistance against irradiation damage, and high absorption coefficients ( $\sim 10^5 \text{ cm}^{-1}$ )<sup>[3,4]</sup> present a great potential for photovoltaic applications. However, the growth of both high indium content and high quality InGaN alloy, which is essential for high efficiency InGaN solar cells, poses great challenges.<sup>[5]</sup> An inherent threading dislocation density as high as  $10^9 \text{ cm}^{-2} \sim 10^{10} \text{ cm}^{-2}$  was reported in the literature.<sup>[6]</sup> The defect density in the absorption layer of a solar cell may have great influence on its performance. On the other hand, a strong polarization-induced electric field may also severely decrease the carrier collection efficiency and result in a serious degradation of the conversion efficiency of the solar cell.<sup>[7]</sup> Many methods have been sought to reduce the detrimental effect of polarization, such as using *N*-face templates<sup>[8]</sup> and compositional grading interlayers.<sup>[9]</sup> However, both of them add difficulties to the growth of high quality

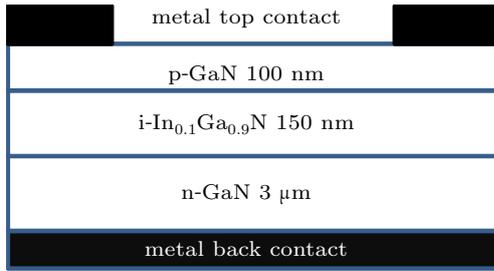
material. In this article, we provide a simple method to reduce the detrimental effect of polarization by elevating Mg-induced net acceptor doping concentration in the p-GaN region and study its effect on the performance of a solar cell in detail using the advanced physical models of semiconductor devices (APSYS) simulation program. In addition, we find that carrier lifetime is an important parameter affecting solar cell sensitivity to polarization. We investigate the effect of carrier lifetime on the performance of a solar cell, such as the short circuit current density, and establish their relation with carrier lifetime and transit time of i-InGaN absorption layer, which may provide a substantial theoretical base for the research of InGaN based high efficiency solar cells.

## 2. Parameters for simulation

The investigated structure of p-i-n InGaN solar cells is shown in Fig. 1. It consists of a 3- $\mu\text{m}$  Si-doped n-type GaN layer with  $n \sim 5 \times 10^{18} \text{ cm}^{-3}$ , a 150 nm intrinsic InGaN absorption layer with  $n \sim 1 \times 10^{17} \text{ cm}^{-3}$  (In content is 10%), and a 100-nm Mg-doped p-type GaN layer. In the simulation calculations, either Mg-induced net acceptor doping concentration in p-GaN layer or the carrier lifetime of i-InGaN layer is taken as variable.

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†Corresponding author. E-mail: dgzhao@red.semi.ac.cn



**Fig. 1.** (color online) Schematic diagram of the simulated p-i-n solar cell structure.

### 3. Results and discussion

#### 3.1. Effect of Mg-induced net acceptor doping concentration on the performance of a solar cell

The device performance of a solar cell is simulated by using the APSYS program. As is well known, the III-nitride semiconductor grown on *c*-plane sapphire features piezoelectric and spontaneous polarization. The strong polarization-induced heterointerface charges and the corresponding electric field may severely reduce the carrier collection efficiency. Actually, in an InGaN p-i-n solar cell, it has been reported that the effects of spontaneous and piezoelectric polarizations may seriously degrade the conversion efficiency.<sup>[10,11]</sup> In the present work, the degree of polarization is changed by modifying the parameter “screening factor (*P*)”. A factor of unity means 100 percent of the theoretical interface charge induced by both spontaneous and piezoelectric polarization is used in the simulation. When the value of *P* increases, the polarization increases proportionally. The screening factor (*P*) was conventionally assumed to be less than 0.5 for a GaN based LED,<sup>[10]</sup> but in order to obtain a better understanding of the effect of Mg doping concentration on screening the detrimental effect of polarization, the screening factor in this section is assumed to be 1 for p-GaN/i-InGaN/n-GaN solar cells. At first, it is assumed that no defect-induced recombination is considered in the active region and a fixed value of carrier lifetime of 100 ns is taken. The effect of lifetime on device performance is considered in Section 2. The Si doping concentration of the n-GaN layer remains constant when Mg-induced net acceptor doping concentration of the p-GaN layer varies from  $1 \times 10^{18} \text{ cm}^{-3}$  to  $1 \times 10^{20} \text{ cm}^{-3}$  as shown in Table 1. The activation energy values of Si donors and Mg acceptors are taken to be 20 meV and 180 meV in the stimulation, respectively.

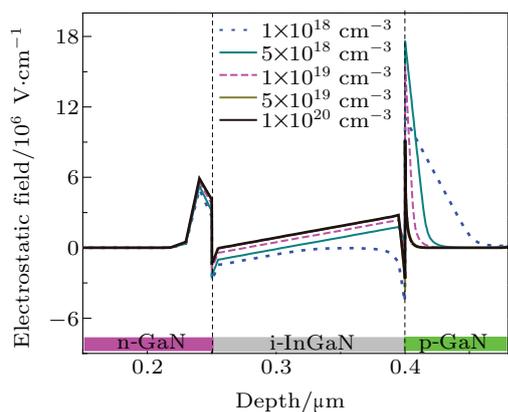
The *J*-*V* characterization results of solar cells are shown in Table 1, where the filling factor (FF) is defined as the ratio between the maximum output power and the product of short circuit current density ( $J_{SC}$ ) and open circuit voltage ( $V_{OC}$ ). It can be seen that in general the conversion efficiency ( $\eta$ ) of a solar cell increases with the increase of Mg-induced net acceptor doping concentration, which could be mainly attributed to the enhancement of the short circuit current density ( $J_{SC}$ ) when Mg-induced net acceptor doping concentration increases from

$1 \times 10^{18} \text{ cm}^{-3}$  to  $5 \times 10^{18} \text{ cm}^{-3}$  and also to the enhancement of filling factor (FF) when Mg-induced net acceptor doping concentration increases from  $5 \times 10^{18} \text{ cm}^{-3}$  to  $5 \times 10^{19} \text{ cm}^{-3}$ . It is found that in these processes the open circuit voltage ( $V_{OC}$ ) is only slightly reduced.

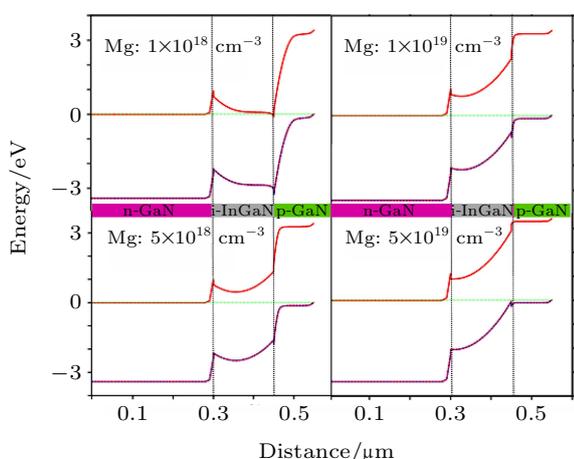
**Table 1.** Solar cell parameters evaluated from *J*-*V* curve.

Si doping concentration/cm <sup>-3</sup>	$5 \times 10^{18}$				
Mg doping concentration/cm <sup>-3</sup>	$1 \times 10^{18}$	$5 \times 10^{18}$	$1 \times 10^{19}$	$5 \times 10^{19}$	$5 \times 10^{20}$
$V_{OC}/V$	2.71	2.69	2.57	2.49	2.49
$J_{SC}/\text{mA}\cdot\text{cm}^{-2}$	0.21	0.95	0.95	0.95	0.95
FF/%	74	29	62	69	69
$\eta/\%$	0.4	0.74	1.5	1.65	1.65

The effect of a Mg-induced net acceptor doping concentration on device performance can be well understood by a further analysis of the relation with the electric field and band diagram as shown in Figs. 2 and 3, respectively. As is well known, the total electric field in an i-InGaN layer is the vector sum between the built-in electric field and the polarization-induced electric field. It is noted that the polarization-induced electric field is a constant when the In composition of InGaN layer is fixed. In addition, it has a direction opposite to the built-in electric field, resulting in a down-shifted or even a reversed electric field in the i-InGaN region. It is found that the InGaN absorption layer possesses a built-in field always higher than polarization-induced electric field when Mg-induced net acceptor doping concentration is high enough, and therefore results in a positive electric field as shown in Fig. 2. In this case, a larger total electric field is responsible for a better capability of drifting the photo-generated carriers, thereby making them collected by electrodes. On the other hand, such an increase of  $J_{SC}$  with Mg-induced net acceptor doping concentration can also be explained from the band diagrams of p-GaN/i-InGaN/n-GaN solar cell at equilibrium state as shown in Fig. 3. It is noteworthy that in the structure with Mg doping concentration lower than  $5 \times 10^{18} \text{ cm}^{-3}$  there are obvious potential barriers near the n-GaN/i-InGaN interface in the conduction band (for electrons) and the i-InGaN/p-GaN interface in the valance band (for holes). They may prevent the photo-generated holes (electrons) in the InGaN region from reaching p-GaN (n-GaN) layer, resulting in the reduction of photocurrent. The upward tilting of the energy band of InGaN absorption layer is enhanced with the increase of Mg-induced net acceptor doping concentration, so the collection efficiency of photo-generated carriers increases. From the above results, we are aware that the high Mg-induced net acceptor doping concentration can effectively screen the effect of polarization-induced electric field in the i-InGaN region and affect the performance of a solar cell.



**Fig. 2.** (color online) Electric fields for p-GaN/i-InGaN/n-GaN solar cells with different Mg-induced net acceptor doping concentrations.



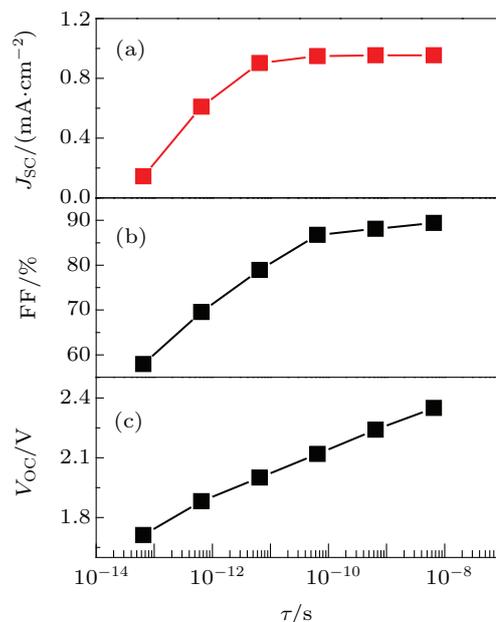
**Fig. 3.** (color online) Band diagrams for p-GaN/i-InGaN/n-GaN solar cells with different Mg-induced net acceptor doping concentrations in an equilibrium state.

### 3.2. Effect of carrier lifetime on solar cell performance

The Mg-induced net acceptor doping concentration of the cell is an important design parameter which needs a balance between the requirements from maximum carrier collection and the high crystalline quality of p-GaN growth. According to our simulation results, the optimized parameters of Mg and Si doping concentrations are chosen to be  $1 \times 10^{19} \text{ cm}^{-3}$  and  $5 \times 10^{18} \text{ cm}^{-3}$ , respectively. The effect of polarization on the device performance is investigated based on these doping concentrations. From  $J$ - $V$  curves of p-GaN/i-InGaN/n-GaN solar cells with different values of the screening factor  $P$  (not shown here), the device parameters of solar cell can be calculated. It is found that the conversion efficiency remains nearly constant until  $P > 0.6$ , as can be seen from Fig. 6, which means that the polarization does not affect the performance of solar cell when the screening factor is smaller than 0.6 while according to the previously reported result in Ref. [7], the effects of spontaneous and piezoelectric polarization may seriously degrade the conversion efficiency of solar cell. We think that such a discrepancy may be caused by neglecting the significant effect of defects in the simulations. As is well known,

the defects, especially the threading dislocations which exist in the nitride material system often in a high density up to  $10^8 \text{ cm}^{-3}$ – $10^{10} \text{ cm}^{-3}$ , act as non-radiative recombination centres<sup>[12,13]</sup> and charged scattering centres, resulting in the reduction of carrier lifetime and mobility.<sup>[14]</sup> Thus, difference in defect density between epilayers may ultimately seriously influence the performance of solar cell. In this section, we simulate the effect of carrier lifetime (and polarization) on the performance of a solar cell. In order to achieve good agreement with experiments, the screening factor  $P$  is assumed to be 0.4 in the simulation.

The three important device parameters of p-GaN/i-InGaN/n-GaN solar cells, FF,  $J_{SC}$ , and  $V_{OC}$ , each as a function of carrier lifetime ( $\tau$ ) in the i-InGaN layer are shown in Fig. 4. The short circuit current density ( $J_{SC}$ ) is found to be not sensitive to carrier lifetime when  $\tau$  is larger than  $6.5 \times 10^{-12}$  s, but it vastly degrades with carrier lifetime when  $\tau$  is lower than  $6.5 \times 10^{-12}$  s. On the other hand,  $V_{OC}$ , and FF decrease gradually with carrier lifetime decreasing.



**Fig. 4.** (color online) Three important device parameters of p-GaN/i-InGaN/n-GaN solar cells,  $J_{SC}$ , FF, and  $V_{OC}$ , each as a function of carrier lifetime ( $\tau$ ) in the i-InGaN layer.

The variation of  $V_{OC}$  may be caused by increasing reverse saturation current density  $J_0$ . The  $V_{OC}$  can be expressed as

$$V_{oc} = \frac{k_B}{q} \ln \left( \frac{J_{SC}}{J_0} + 1 \right), \quad (1)$$

where

$$J_0 = qn_i^2 \left( \frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right), \quad (2)$$

$$L = \sqrt{D\tau}, \quad (3)$$

with  $L$  being the minority diffusion length, and  $D$  the carrier diffusivity. The decrease of carrier lifetime results in the increase of reverse saturation current  $J_0$ , and thus  $V_{OC}$  is reduced.

The variation of  $J_{SC}$  can be examined in relation with transit time in the following way. Transit-time ( $\tau_{tr}$ ) is defined as the time that carriers pass through InGaN absorption layer under electric field drift, which can be estimated roughly by using the thickness of InGaN region and the average electric field. It is assumed that when the carrier lifetime is longer than transit time, carriers will transport across the i-InGaN layer without recombination, i.e., the total photo-generated carriers in the InGaN region can be collected, resulting in a high short circuit current density. But when the carrier lifetime is lower than transit-time, short circuit current density will quickly degrade due to the reduced collection efficiency because photo-generated carriers lose a lot by recombination. As shown in Fig. 5, the Shockley-Read-Hall (SRH) recombination rate increases rapidly in the InGaN absorption region, especially near the i-InGaN/p-GaN interface, when the carrier lifetime is lower than  $6.5 \times 10^{-12}$  s. These SRH results can well support the viewpoint that the defect density may seriously affect the performance of InGaN solar cells.

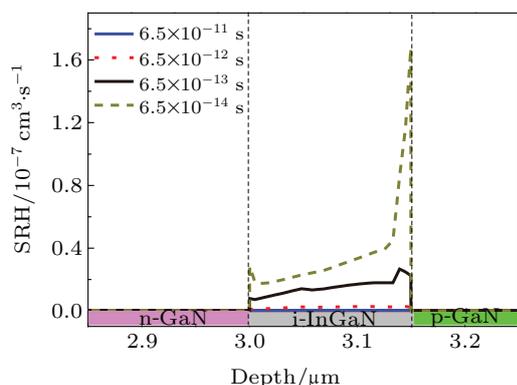


Fig. 5. (color online) SRH recombination rate of p-GaN/i-InGaN/n-GaN solar cells with different values of carrier lifetime.

When the effect of defects is considered in the simulation, the obvious difference in the effects of screening factor  $P$  on conversion efficiency can be clearly observed from Fig. 6. With a low carrier lifetime of 0.65 ps, the conversion efficiency starts to drop off when the screening factor is larger than 0.2, but when the carrier lifetime taken to be 100 ns, the conversion efficiency remains constant until the screening factor is larger than 0.6. The conversion efficiency of a solar cell with a lower carrier lifetime drops off faster than the one with a higher carrier lifetime when the screening factor increases. This simulation results are in agreement with results reported in Ref. [7], are reasonable, and explain why the result will deviated from experimental ones if the effect of defects in the InGaN layer is not taken into consideration.

Theoretically, a solar cell with a higher indium content i-InGaN absorption layer could possess higher conversion efficiency due to the extension of the absorption edge to a longer wavelength. However, according to the reported experimental results,<sup>[15]</sup> a reduction in the EQE is often ob-

served due to the higher defect density and a stronger polarization effect. Thus the crystal quality of absorption layer is really a very important factor for InGaN solar cell. The conversion efficiency of a p-GaN/i-InGaN/n-GaN solar cell with high In content will be greatly increased only when the crystal quality is good enough so that the carrier lifetime of InGaN layer is kept to be longer than the transmit time.

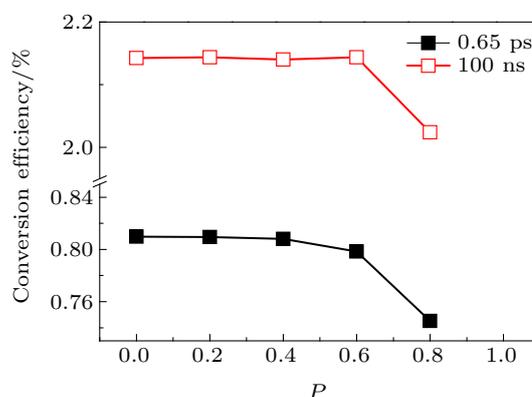


Fig. 6. (color online) Plots of efficiency versus screening factor with different values of carrier lifetime.

#### 4. Conclusion

The influences of Mg-doping concentration and carrier lifetime on the characteristics of a p-GaN/i-InGaN/n-GaN solar cell are investigated. It is found that the Mg-induced net acceptor doping concentration and carrier lifetime can seriously affect the performance of the solar cell. The short circuit current density increases with the increase of Mg-induced net acceptor doping concentration, resulting from an enhancement of carrier collecting efficiency. With a high Mg-induced net acceptor doping concentration, the built-in electric field in the i-InGaN layer is strong enough to result in a positive electric field in this active region. In addition, the performance of a solar cell with a high Mg-induced net acceptor doping concentration is not sensitive to the degree of polarization when the effect of defects is neglected. However, it will be deteriorated when the effect of defects is considered and consequently the carrier lifetime is shorter than the transit time of the InGaN region. A fast reduction of the short circuit current density will appear. In order to achieve a super-high efficiency InGaN based solar cell, the crystal quality of the InGaN layer is a critical issue which must be improved in the metal-organic chemical vapor deposition (MOCVD).

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