The effects of InGaN layer thickness on the performance of InGaN/GaN p–i–n solar cells*

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InGaN/GaN p–i–n solar cells, each with an undoped $In_{0.12}Ga_{0.88}N$ absorption layer, are grown on *c*-plane sapphire substrates by metal–organic chemical vapor deposition. The effects of the thickness and dislocation density of the absorption layer on the collection efficiency of InGaN-based solar cells are analyzed, and the experimental results demonstrate that the thickness of the InGaN layer and the dislocation density significantly affect the performance. An optimized InGaN-based solar cell with a peak external quantum efficiency of 57% at a wavelength of 371 nm is reported. The full width at half maximum of the rocking curve of the (0002) InGaN layer is 180 arcsec.

Keywords: nitride materials, crystal growth, solar cell, X-ray diffraction

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1. Introduction

InGaN-based solar cells have been extensively investigated for photovoltaic applications due to their unique properties, including a wide alloy band-gap that covers the solar spectrum, high absorption coefficients, and high mobility.[1–4] In particular, InGaN alloys present great potential applications in space concentrator solar cells due to their much higher resistance against irradiation damage in comparison with conventional GaAs and InGaP solar cell materials.[5,6] The tunable energy band-gap makes them the best potential candidate for application in fabricating multijunction solar cells with high efficiency (60%).[7,8] For a single-junction InGaN/GaN p–i–n solar cell, the thermodynamic limit of the energy conversion efficiency is 27.49% with an In content value of 0.74 ($E_g = 1.39$ eV) and a thickness of 4 μm of the i-InGaN layer.[9] However, the efficiency of the reported InGaN-based solar cell device is not higher than 3%. The main reason for this is that it is difficult to grow high-quality thick InGaN epitaxial layers with high In content by metal–organic chemical vapor deposition (MOCVD).[10] In addition, InGaN/GaN layers grown on sapphire usually contain high-density threading dislocations due to the large lattice mismatch between InN and GaN, which can seriously deteriorate device performance.[11] Recently, Sang *et al.*[12] improved the performance of InGaN solar cells by using a superthin AlN interlayer that could suppress the structural defects, and the reverse leakage current was reduced by more than two orders of magnitude. Therefore, dislocation density does have a significant influence on the performance of InGaN-based solar cells. In fact, the dislocation density may be closely related to the thickness of the InGaN absorption layer. Thus, it is meaningful to investigate the relationship between the thickness of the InGaN layer and the performance of an InGaN-based solar cell. In this letter, we report on the relation between the performance of an InGaN/GaN p–i–n solar cell and the thickness of the InGaN absorption layer. The structural properties of the InGaN/GaN solar cells are characterized by X-ray diffraction (XRD). The device fabrication and external quantum efficiency (EQE) testing are also presented and analyzed.

2. Experiments

InGaN-based solar cells were grown on *c*-plane sapphire substrates by MOCVD. Trimethylgallium, trimethylindium, and ammonia were used as the Ga, In, and N precursors, respectively. The material structure of the solar cell was composed of a 3-μm Si-doped n-type GaN layer ($n = 5 \times 10^{18}$ cm^{-3}), an unintentionally doped InGaN layer with different thickness values, and a 200-nm Mg-doped p-type GaN layer ($p = 3 \times 10^{17}$ cm^{-3}) as shown in Fig. 1(a). Three solar cell samples, denoted as A, B, and C, were grown for comparison. Samples A, B, and C contained InGaN layers with thickness values of 75 nm, 150 nm, and 300 nm, respectively. The A, B, and C samples were prepared under the same growth conditions, except for the thickness of the In-

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GaN layer. The electron concentration of the InGaN layer was 9.5×10^{16} cm^{-3}, as obtained by Hall measurement on an InGaN/GaN two-layer sample grown under the same conditions. The devices were processed into 1.2 mm×1.2 mm mesas by etching down to the n-type GaN by the ion beam etching technique, as schematically shown in Fig. 1(a). Ni/Au (5 nm/5 nm) semitransparent Ohmic contacts were deposited on the p-GaN layer by electron beam evaporation, followed by rapid thermal annealing at 500 °C in a forming gas of N_2:O_2(2:1) for 5 min. Finally, a Ti/Al/Ti/Au (15 nm/250 nm/50 nm/250 nm) layer was deposited on both the n-type GaN and Ni/Au semitransparent film to form electrodes.

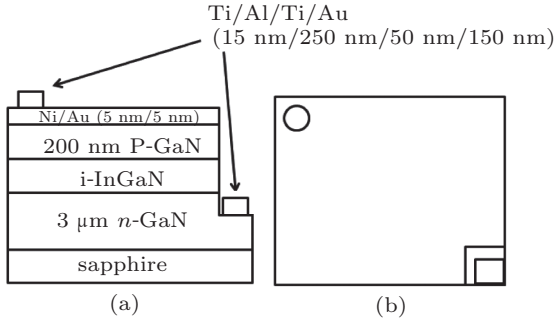


Fig. 1. (a) Schematic diagram of the InGaN/GaN solar cell device structure, and (b) the top view of a solar cell (b).

3. Results and discussion

Figure 2(a) shows the high-resolution (0002) ω–2θ X-ray diffraction (XRD) curve of an InGaN/GaN solar cell sample. The peak at $2\theta = 34.10°$ comes from InGaN. The In composition of the InGaN layer is calculated to be 12% by the Vegard law, which corresponds to a band-gap of 3.08 eV ($\lambda = 403$ nm). The phenomenon of indium phase separation is not obviously observed in this sample. In order to further characterize the influence of layer thickness on the quality of InGaN, the rocking curves through (0002) reflection are measured for InGaN layers of samples A, B, and C with different thickness values. Figure 2(b) shows the full width at half maximum (FWHM) values of the (0002) XRD rocking curves for the three samples. The FWHM values are 522, 900, and 1216 arcsec for samples A, B, and C, corresponding to the thickness values of 75, 150, and 300 nm, respectively. It is known that the FWHM value of the (0002) XRD rocking curve can indirectly represent the density of screw-type threading dislocation (TD), which is an important component of the defect.[13] Based on the well-known relation between dislocation density and XRD FWHM,[14] the screw-dislocation density can be calculated, and the results are shown in Fig. 2(b). The results show that the density of threading dislocations in InGaN increases rapidly with increasing InGaN layer thickness.

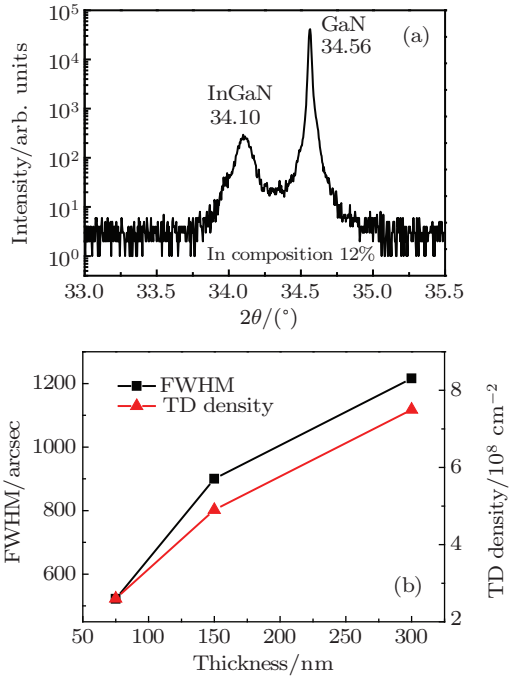


Fig. 2. (color online) (a) The (0002) ω–2θ XRD patterns of an InGaN/GaN solar cell sample, and (b) the FWHM values of the (0002) rocking curve and TD density as a function of InGaN layer thickness measured for three series samples.

The EQE of the solar cell is defined as the ratio of the number of electrons collected by the electrodes to the number of incident photons absorbed. The devices are illuminated with an Xe lamp in the EQE (λ) measurement. The incident light power is calibrated with a silicon photodetector. Figure 3 shows the measured EQE spectral responses of three InGaN/GaN p–i–n solar cells. It is shown that the major absorption peaks for two devices with 75-nm and 150-nm thick InGaN absorption layers occur in the 360 nm–415 nm wavelength range, corresponding to the bandgap energy around $\sim$ 3.08 eV of the $In_{0.12}Ga_{0.88}N$ layer. The highest external quantum efficiency is 15% at $\lambda = 371$ nm for the former device, and 17.4% at $\lambda = 369$ nm for the latter one, respectively. However, it is noted that the peak EQE decreases sharply to 4.5% at $\lambda = 365$ nm when the absorption layer increases to 300 nm.

In general, the EQE of the InGaN-based solar cell device is related to the reflections at the surfaces, the absorptions in the p-GaN layer and InGaN layer, and the carrier collection efficiency, which depends on the defect-induced recombination of the photo-generated carriers. In the ideal case, the absorption increases with the increase in the thickness of the i-layer without any defects. With the increase in the thickness of the i-InGaN layer, more photons can be absorbed, especially in an energy range of E_g (InGaN) $\leq E \leq E_g$ (GaN). However, it should be noted that when the thickness of the InGaN layer increases from 75 nm to 150 nm, the magnitude of the EQE of the InGaN solar cell slightly increases. When the thickness of the InGaN layer reaches 300 nm, the EQE sharply decreases.

Actually, the existence of defects is inevitable during the epitaxial growth of InGaN/GaN by MOCVD. Such defects can induce carrier recombination. The defect-induced recombination centers may lead to a low collection efficiency and reduction of the EQE. As shown in Fig. 2(b), the XRD FWHM value, or the TD density, increases with the increasing thickness of the InGaN layer, which indicates the increase in the density of the recombination centers. Therefore, it is understandable that for an InGaN solar cell with a relatively thick InGaN layer of 300 nm, the increased defect-induced recombination and reduced collection efficiency results in a lower EQE than for the two devices with thinner InGaN layer thickness of 75 nm and 150 nm.

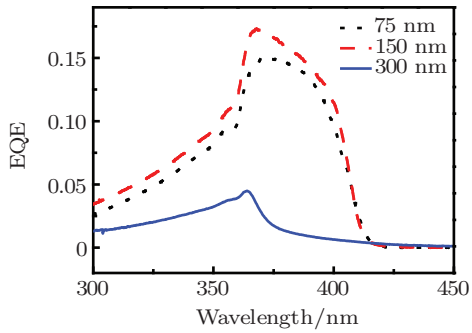


Fig. 3. (color online) Curves of EQE versus wavelength for InGaN/GaN p–i–n solar cells with different InGaN layer thickness values.

From the above discussion, we know that defect-induced recombination plays a key role in determining the performance of InGaN solar cells. In general, the minority carrier (hole) lifetime is closely related to the defect density in the InGaN layer, so the defects existing in the absorption layer significantly affect the collection efficiency. The collection efficiency in the solar cell is defined as the ratio of the number of collected carriers contributing to the photovoltaic current and the total number of photo-generated carriers. Collection efficiency, χ, one of the key parameters for InGaN/GaN p–i–n solar cells, can be written as[15,16]

$$\chi = \frac{1}{L}\frac{l_n l_p}{l_n \exp\left(\frac{L}{L_c}\right) - l_p \exp\left(-\frac{L}{L_c}\right)} \times \left[\exp\left(\frac{L}{L_c}\right) - \exp\left(-\frac{L}{L_c}\right)\right],$$

where L is the thickness of the i-InGaN layer, and $L_c = 2l_n l_p/(l_n - l_p)$, l_n and l_p are the drift lengths of the free electrons and holes, respectively. The drift length is dependent on carrier lifetime. Given different minority carrier (hole) lifetimes, the values of collection efficiency χ can be calculated each as a function of InGaN layer thickness, as shown in Fig. 4.

As can be seen from the simulation results in Fig. 4, the collection efficiency decreases with the increasing thickness of the i-InGaN layer. With long minority carrier lifetime, the collection efficiency is insensitive to the thickness of the absorption layer, while the collection efficiency decreases sharply with the increase in the thickness of the absorption layer for the case of the short minority carrier lifetime. In general, the minority carrier (hole) lifetime can be a function of the defect density in the InGaN layer based on the Shockley–Read–Hall theory model.[14,17] Therefore, the defect density-dependent carrier lifetime should be responsible for the calculated results as shown in Fig. 4. The carrier lifetime at low defect density is longer than that at high defect density. The higher carrier lifetime usually results in a longer diffusion length and larger collection efficiency.

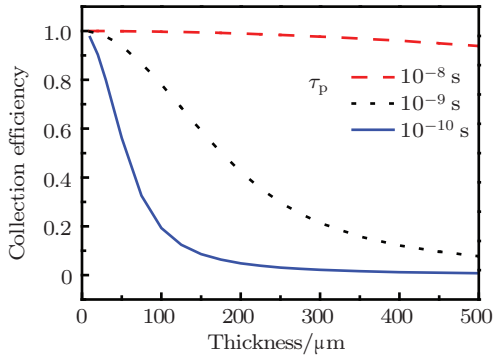


Fig. 4. (color online) Variations in collection efficiency with InGaN layer thickness for $In_{0.12}Ga_{0.88}N$/GaN p–i–n solar cells with various minority carrier lifetimes.

It is known that when the thickness of the InGaN layer is too thin, photons will not be able to be absorbed efficiently, while if the layer thickness is too thick, then the quality of the InGaN layer and the collection efficiency will quickly decrease with the increase in layer thickness, resulting in lower EQE, especially if the dislocation density in the InGaN layer is relatively high. Therefore, the thickness of the i-InGaN layer is a key parameter for improving the performance of InGaN solar cells. In addition, the TD density should be reduced as much as possible during InGaN layer epitaxial growth by MOCVD. In fact, by changing the growth conditions, especially the temperature and the growth rate, we can improve the structural quality of the InGaN/GaN p–i–n solar cell (denoted as sample D), which has an i-InGaN layer of 150 nm and a reduced screw-type TD density. Figure 5 shows the EQE of this InGaN/GaN p–i–n solar cell varying with wavelength. The XRD rocking curve of the i-InGaN layer is presented in the inset, which shows an FWHM as small as 180 arcsec. Compared with the peak EQE of 17% of the previously-mentioned solar cell with the same thickness of the i-InGaN layer, the EQE for this optimized device is increased up to 57%. In addition, it is noted that the spectral profiles of the two devices are quite different below 360 nm. The EQE of sample D is much higher than that of sample B at $\lambda < 360$ nm. In fact, the EQE below 360 nm is mainly related to the structural quality of the

p-GaN layer. The extension of dislocations from InGaN to p-GaN may increase the recombination of the photo-generated carriers in the p-GaN layer and lead to a reduced EQE below 360 nm of sample B, as observed in the measurements. The solar cell has a fill factor of 64.6% and an open circuit voltage of 1.60 V. The short circuit current density is 0.45 mA/cm^2 under concentrated AM0 illumination. Shown here is an example where the performance of the solar cell will be improved further if we can better reduce the TD density in the InGaN/GaN layer.

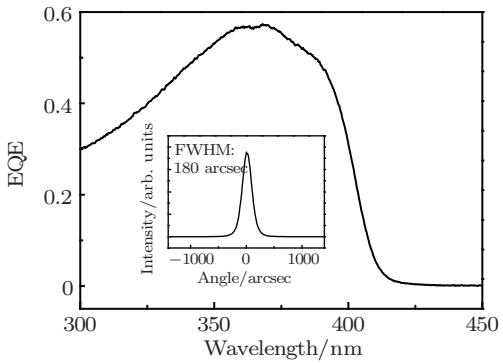


Fig. 5. EQE spectrum of the low dislocation density InGaN/GaN p–i–n solar cell, with the inset showing the (0002) rocking curve of the i-InGaN layer.

4. Conclusion

In this paper, InGaN/GaN p–i–n solar cells with different thickness values of the InGaN layer are fabricated and investigated. The dislocation density increases dramatically as the thickness of InGaN increases. The thickness and the dislocation density of the InGaN layer both determine the performance of the InGaN/GaN p–i–n solar cell. An optimized InGaN/GaN p–i–n solar cell with an EQE of 57% is obtained. The FWHM of the rocking curve of the InGaN layer is 180 arcsec. For the device, the fill factor is 64.6%, the open circuit voltage is 1.60 V, and the short circuit current density is 0.45 mA/cm^2, under concentrated AM0 illumination.

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