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InGaN/GaN solar cells grown on wet-etched patterned sapphire substrates

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1. Introduction

III-nitrides are ideally suited to the fabrication of optoelectronics devices such as lasers and light-emitting diodes , due to their high efficiency and wide applicability. The properties of III-nitrides include large carrier mobility, high drift velocity, strong optical absorption, and resistance to radiation, making them ideal for the development of photovoltaics [1]. In particular, InGaN-based solar cells with a direct energy bandgap covering nearly the entire solar spectrum (0.7—3.4eV) have been of particular interest to researchers. Despite the tremendous advantages and potential applications provided by InGaN-based solar cells, growing an InGaN layer (>100 nm) with high crystal quality remains a challenge, and has severely limited the number of studies on p-GaN/i-InGaN/n-GaN heterojunction solar cells [2]. In general, a large lattice mismatch between InN and GaN and the low temperature growth of InGaN detracts from the crystalline quality in epitaxial layers and induces defects due to threading dislocation (TD), thereby generating nonradiative recombination centers (NRCs) in the light absorbing layer [3]. Furthermore, these defect centers trap and interact with photogenerated carriers, thereby reducing the carrier lifetime and short-circuit current carrier of the solar cells [4]. In this letter we report on our progress in enhancing the conversion efficiency of InGaN multiple quantum well (MQW) solar cells grown on a patterned sapphire substrate (PSS).

2. Experiments and Discussion

Figure 1(a) is a schematic representation of InGaN MQW solar cells grown on PSS. The details of the processes involved in fabricating PSS can be found where. Individual holes were approximately 3 μm in diameter with a 7 μm pitch in the array. Grown wafers with mesa size of 800×800 μm^2 were patterned using a standard photolithographic process, and partially dry-etched down to the n-type GaN [Insert of Fig. 1(a)]. For comparison, we also fabricated a conventional solar cell on a planar sapphire substrate. Figure 1(b) shows the X-ray diffraction (XRD) spectra of the (0002) solar cells grown on planar and patterned sapphire substrates.The satellite-peaks occurring in the same location over a wide measurement range for both samples suggest that the composition of the indium in the MQW is unrelated to the PSS beneath. The insert of Fig. 1(b) (left-hand) shows a cross-sectional SEM image of a solar cell grown on PSS.An enlarged cross-sectional TEM image focusing on the GaN/sapphire interface is shown in the insert of Fig.1(b) (right-hand), in which a large number of stacking faults (marked by arrows) appear in the trench region of the PSS. These stacking faults interact with the TD defects, preventing further penetration into the MQW.

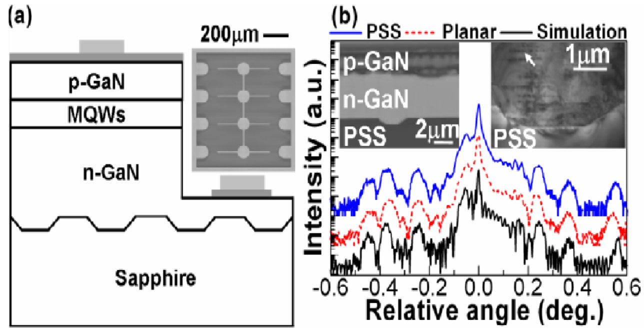

Fig. 1 (a) Schematic of the InGaN-based MQW solar cell grown on PSS. Insert: SEM image of the actual device; (b) XRD rocking curves of both solar cells; Inserts: Cross-sectional SEM image of the solar cell grown on PSS and an enlarged TEM image.

Figure 2(a) displays the dark current vs. voltage (*I-V*) curves on a semi-log scale of both solar cells. In the reverse-bias region (V<0), the reverse current of the solar cell grown on PSS was approximately one order of magnitude lower than that of conventional solar cells. This is entirely due to a reduction in leakage path associated with TD fects in MQW. The inset in Fig. 2(a) presents the electrical circuit of a solar cell, where I_{SC} denotes the short circuit current, and R_S and R_P represent the series and shunt resistance values of the solar cells, respectively. By considering resistive losses due to series and shunt resistance, the *I-V* equation of the solar cell can be expressed as

$$I(V)=I_{SC}-I_o\left(\exp\left(\frac{e(V-IR_S)}{nkT}\right)-1\right)-\frac{(V-IR_S)}{R_P} \qquad (1)$$

where the multiplier I_O is the saturation current, and n in the denominator of the exponent is the ideality factor. According to Eq. (1), the *I(V)* current measured by the external circuit increases with an increase in R_P, which can be achieved through the adoption of a PSS scheme. Figure 2(b) shows the spectra of electrical luminescence (*EL*) for both solar cells at I =20mA. In this case, the solar cell grown on PSS demonstrated approximately a 30% enhancement in *EL* intensity, which can be attributed to the scattering of guided light by PSS to meet the escape cone, enhancing the light-extraction efficiency of the device [6].

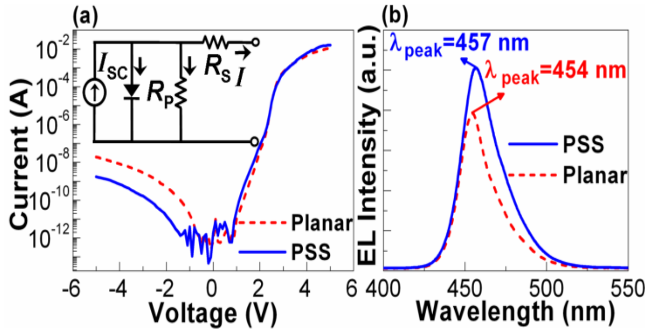

Fig. 2 (a) Dark *I-V* curves of both solar cells. Insert: Effective electrical circuit of a solar cell; (b) Typical *EL* spectra of both solar cells.

Figure 3(a) plots the current density vs. voltage (*J-V*) characteristics of both solar cells under AM 1.5 illumination (insert of Fig. 3(a), power density=100 mW·cm^{-2}). The adoption of PSS increased J_{SC} appreciably from 0.68 to 1.09 mA·cm^{-2} (a 60 % enhancement), and slightly decreased the fill factor (*FF*) from 56 % to 51 %, compared to conventional solar cells. It should be noted here that although the TD defects of the sample grown on PSS is significantly reduced, the radiative recombination of photogenerated carriers is barely affected [5]. Figure 3(b) plots power-density vs. voltage curves for both solar cells. Accordingly, the maximum power-density (P_{max}) of the solar cells grown on planar and patterned sapphire substrates were approximately 0.79 and 1.14 mW·cm^{-2}, corresponding to an enhancement of approximately 44 % in the overall conversion efficiency.

3. Conclusions

In conclusion, this study fabricated InGaN-based MQW solar cells grown on PSS to evaluate the effect of TD fects on the overall performances of the device. Improved crystalline quality in MQW was obtained through the tion of PSS, slightly reducing the fill factor but enhancing the short-circuit current density by 60 %. The proposed device achieved a fill factor of 51 %, a short-circuit current density of 1.09 mA·cm^{-2}, and an open circuit voltage of 2.05V, under 1 sun AM 1.5 illumination.

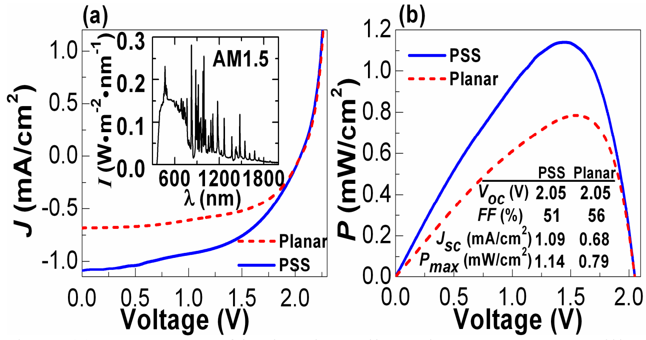

Fig. 3 (a) *J-V* curves of both solar cells under 1 sun AM 1.5 illumination. (b) Power-density vs. voltage curves of both solar cells.

Acknowledgements

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