Improved Conversion Efficiency of Textured InGaN Solar Cells With Interdigitated Imbedded Electrodes

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Abstract—Textured n-GaN/i-InGaN/p-GaN solar cells with interdigitated imbedded electrodes (IIEs) eliminating the electrode-shading loss have been investigated. In the absence of the electrode-shading effect, the optimized textured solar cell exhibits a conversion efficiency of 1.03%, which is 78% and 47% higher than those of the conventional structure and the structure with mirror coated on silicon substrate with electrode shading, respectively. The short-circuit current density of this textured IIE device is about 0.65 mA/cm², which is 71% and 44% higher than those of the two compared structures, respectively.

Index Terms—Electrode shading, interdigitated imbedded electrodes (IIEs), n-GaN/i-InGaN/p-GaN solar cell, textured.

I. INTRODUCTION

UNABLE In₃Ga₁₋ₓN energy bandgap ranging from 0.7 eV (x = 1) to 3.4 eV (x = 0) and nearly covering the full solar radiation spectrum makes ternary InGaN alloy one of the potential candidates for the application of achieving high-efficiency (50%) multijunction solar cells [1], [2]. However, recent research on InGaN solar cells shows a quite-low conversion efficiency of less than 2% [3], [4], which mainly results from the difficulty in obtaining indium-rich InGaN alloy and the insufficiency of photon absorption in the InGaN layer. A variety of approaches for improving the conversion efficiency via epilayer growth and optical management have been proposed. The techniques of facet-initiated epitaxial lateral overgrowth, pendeo epitaxy, and patterned sapphire substrates [5]–[8] are all milestones making a significant contribution for improving the epilayer quality. We also optimized the InGaN thickness and the indium proportion in InGaN showing no phase separation and relaxation [9]. However, the nearly optimized InGaN layers, which have no observable defect such as V-shaped pits and dislocations, are typically too thin to absorb sufficient photons in the solar spectrum to maximize the device performance. The back-mirror reflector on silicon substrate [10] is one of the techniques for optical confinement, which is achieved with an increment of 57.6% in short-circuit current density (Jsc). However, there still exists the electrode-shading problem. In this letter, n-side-up devices with interdigitated imbedded electrodes (IIEs) for overcoming the electrode-shading problem are provided and fabricated. The effect of the thickness and roughness of the top n-GaN layer on solar cell performance is also studied.

II. EXPERIMENT

The p-GaN : Mg/i-In₀.₁Ga₀.₉N/n-GaN : Si epitaxial layers of the conventional structure of high quality [9] are grown on undoped-GaN (u-GaN)/c-plane (0001) sapphire substrates by metalorganic chemical vapor deposition. The sandwich p-i-n structure consists of a 150-nm Mg-doped top p-type GaN layer, a 150-nm intrinsic absorption InGaN layer, and a 3-μm Si-doped bottom n-type GaN layer. The indium composition of InGaN was confirmed by X-ray rocking curve and PL measurements. The emission wavelength (measured by PL) of In₀.₁Ga₀.₉N is about 393 nm. Each chip with an area of 1 × 1 mm² is fabricated. The electrode contact pads are patterned with C/Al (25 nm/200 nm) by thermal evaporation. The schematic cross section of the conventional p-i-n structure is shown in Fig. 1(a). Undoped GaN and indium tin oxide act as an epitaxial buffer layer and a transparent conducting layer for current spreading, respectively. The process flow of the GaN/InGaN solar cells with the IIE structure is schematically shown in Fig. 1(b)–(e). First, the top side (p side) of the conventional device is upside down bonded onto a thin-film-coated silicon substrate, which consists of SiO₂ (900 nm) and Ti/Al (15 nm/250 nm), using epoxy glue bonding, as shown in Fig. 1(b). The laser lift-off process shown in Fig. 1(c) is then employed for sapphire removal. Subsequently, the pattern of the electrode contact pads is defined by photolithography, which is followed by a highly anisotropic etching process, as shown in Fig. 1(d), using an inductively coupled plasma reactive-ion etching to expose the p- and n-contact pads. The IIE device is consequently finished with the wet processing of H₃PO₄ and NaOH solution for reducing the thickness and roughening the
(0–6 min) of the window layer, are shown in Fig. 3. The curve of $V_{oc}$ keeps nearly constant, which is comprehensible since the optical management is supposed to be independent of the electrical potential. The whole curve of $J_{sc}$ for D3 with various n-GaN etching times is greater than 0.59 mA/cm², and the optimal value occurs at an etching time of 3 min, which is denoted as “D3-3” in the $x$-axis. The FFs of D3, which are merely 3%–4% higher than those of D1 and D2, seem to be dramatically unaffected by the etching time. The $\eta$ in the figure has a quite similar tendency to $J_{sc}$. The optimal $\eta$ of 1.03% for D3 also occurring at an etching time of 3 min is 78% and 47% higher than those for D1 and D2. Thus, the improvement of the efficiency for D3 is apparently attributed to the increment of the photocurrent from employing effective light-absorbing treatments, including the back-mirror reflector, the surface texture, and the IIE structure.

It is well known that the doped window layer is typically highly defective and light absorbent [11]. Thus, the too-thick window layer will prohibit the incoming photons from effectively entering the absorbing layer, leading to insufficient absorption for the photovoltaic effect. The reduction and optimization of the thickness of the window layer but most likely the integrity of the surface texture of the electrical potential. The whole curve of $J_{sc}$ for D3 with various n-GaN etching times is greater than 0.59 mA/cm², and the optimal value occurs at an etching time of 3 min, which is denoted as “D3-3” in the $x$-axis. The FFs of D3, which are merely 3%–4% higher than those of D1 and D2, seem to be dramatically unaffected by the etching time. The $\eta$ in the figure has a quite similar tendency to $J_{sc}$. The optimal $\eta$ of 1.03% for D3 also occurring at an etching time of 3 min is 78% and 47% higher than those for D1 and D2. Thus, the improvement of the efficiency for D3 is apparently attributed to the increment of the photocurrent from employing effective light-absorbing treatments, including the back-mirror reflector, the surface texture, and the IIE structure.

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IV. Conclusion

In summary, GaN/InGaN double-heterojunction solar cells, in the absence of electrode-shading loss, have been demonstrated with an improved conversion efficiency of 1.03%, which is 78% and 47% higher than those of the conventional structure and the structure with mirror coated on silicon substrate, respectively. The tendency of the conversion efficiency of the proposed structure is in well agreement with the short-circuit current density. It reveals that the improvement of conversion efficiency is attributed to the increased photocurrent from enhancing light absorption, including the surface texture, the back-mirror reflector, and the IIE structure. To verify the optimized thickness of the window layer, the consistent textured surfaces for different etching conditions need to be used for future work.

REFERENCES