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Influence of the ITO current spreading layer on efficiencies of InGaN-based solar cells

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ABSTRACT

A systematic investigation of the utilization of indium-tin-oxide (ITO) as a current spreading layer (CSL) with and without a textured surface has been performed on InGaN-based solar cells, demonstrating a difference in the influence on the performance of the devices. It is found that employing an ITO CSL improves the conversion efficiency for devices with planar surfaces; whereas it reduces the efficiency for the surface textured devices. Consequently, best performance is achieved for the surface-textured solar cell without employing an ITO CSL, with an enhancement of 75% in the conversion efficiency compared to the planar cell without ITO. Our reflectance measurements show that the ITO CSL can effectively suppress surface reflection for the planar devices, while it becomes less effective for the surface-textured devices. Furthermore, a transmission measurement is carried out to estimate the absorption of the ITO CSL. The influence of the ITO CSL is discussed in terms of surface reflection and light loss due to the ITO shading effect as well as power loss associated with the absence of the ITO CSL.

1. Introduction

Indium gallium nitride (InGaN) alloys are increasingly attractive as prospective material for solar cells due to their tunable bandgaps covering the majority of the solar spectrum and the superior photovoltaic characteristics including high absorption coefficients and high carrier mobility [1–6]. Moreover, high thermal stability, superior radiation resistance and excellent chemical stability allow InGaN-based devices to be operated in harsh environments. Since the first demonstrations of InGaN-based solar cells grown on sapphire substrates [7], significant effort and progress have been made towards state of the art InGaN solar cells while both great opportunities and grand challenges exist. In addition to the relatively high defect density in nitride alloys due to lack of available defect-free native substrates, another important challenge for high-efficiency III-nitride solar cells is to grow high-quality $In_xGa_{1-x}N$ materials with high indium content. This is ascribed to the difficulty in indium incorporation in the InGaN alloy and large lattice mismatch between InN and GaN. The material quality becomes even worse with increasing the thickness of InGaN absorption layers and achieving the indium composition required to maximize the conversion efficiency of solar cells [8]. So far, multi-quantum-well (MQW) or superlattice (SL) structures appear as an efficient approach instead of a single InGaN absorption layer, to minimize the undesired trade-off between solar response and crystalline quality [1,3,9]. Although various efforts have been made to realize the goal of high-efficiency InGaN cells from the material viewpoint, the power conversion efficiencies of InGaN cells still remain at a very low level on the order of a few percent under 1 sun air-mass 1.5 global spectrum illumination (AM 1.5G), even on free-standing GaN substrates [7].

In parallel to devoting considerable effort to improving the crystal quality, it is also essential to enhance sunlight transmission into the device through device fabrication steps, such as utilization of anti-reflection coatings generally used in silicon cells. Surface-texturing has been proven to greatly enhance the efficiency of InGaN-based solar cells [2,9] and optimize transparency of top electrodes [4,10]. Unlike silicon solar cells, due to the high resistivity of p-type GaN, it is a well-accepted technology for InGaN-based solar cells to apply a current spreading layer (CSL) on the top of the p-type GaN layer in addition to metal pads. It is noted that the CSL on the top layer introduces extra light loss by shading effects. Semi-transparent thin Ni/Au layers, used conventionally as the p-type CSL in GaN-based optical devices, demonstrate a transmittance of less than 60% in 350–400 nm wavelength regions [11], producing a large amount of light loss. Currently, conductive indium-tin-oxide (ITO) material, with high transparency in the visible spectral region, serves as a CSL for GaN-based solar cells. The steady price increase of indium has prompted searches for alternative materials. Recently, graphene films have started to be employed in organic photovoltaic cells [12], silicon solar cells [13]

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and GaN-based light-emitting diodes [14,15] as CSLs due to high transparency and mechanical and chemical stability. Compared to ITO, graphene has a higher transmittance especially in the short wavelength range and can be used on flexible substrates. However, its high sheet resistance and low work function cause a high turn-on voltage with insufficient current spreading in high-resistance p-GaN of GaN-based optical devices [14].

This paper will investigate the influence of the ITO CSL on the performance of InGaN-based solar cells, so far not studied systematically in terms of resistive loss, light loss and surface reflection, especially when surface-texturing device fabrication techniques are applied. In this work, InGaN multi-quantum-well (MQW) solar cells operating at a wavelength of 520 nm have been fabricated with and without an ITO CSL. Moreover, the formation of a periodic nanostructure on the top of the p-GaN layer is also employed in the solar cell fabrication, which has recently demonstrated significant improvements in the performance of solar cells [16]. In combination with reflectance and transmission measurements, the solar cell characteristics are compared among the four cases and discussed to explore the influence of the different techniques.

2. Experiment

The InGaN MQW based solar cell structures were grown by metal-organic chemical vapor deposition (MOCVD) on (0001) sapphire substrates. They consist of a 1.4 µm un-doped GaN buffer, a 2 µm Si-doped n-type GaN layer, a 100 nm InGaN pre-layer with a low indium content for strain relaxation, 10 periods InGaN/GaN MQWs, and finally a 200 nm Mg-doped p-type GaN layer. A schematic of the device structure is shown in Fig. 1(a), which is very similar to a standard light emitting diode (LED) structure.

For the surface-textured samples, a periodic nanorod array structure has been fabricated on the p-GaN layer by means of a modified silica nanosphere lithography technique which we developed very recently [16]. The detailed procedure: a SiO_2 layer of 100 nm thickness is initially deposited on the device sample by plasma-enhanced chemical vapor deposition, and then treated under O_2 plasma in a reactive ion etching (RIE) to generate a hydrophilic surface, which facilitates an excellent uniformity of the subsequent deposition of a silica nanosphere monolayer. Silica nanospheres with a diameter of 300 nm in *de-ionized* water are spin-coated, and then form a monolayer of hexagonally close-packed silica nanospheres on the surface of the sample. The monolayer of silica nanospheres then undergoes a selective etching process by an RIE technique to tune both the diameter and sidewall separation of the silica nanospheres, which will be employed as the first mask to etch to the GaN surface. Finally, a Cl_2 based inductively-coupled plasma (ICP) dry etching process is used to etch p-GaN into a hexagonal nanorod array structure with a height of 150 nm. Fig. 1(b) shows a typical scanning electron microscope (SEM) image of our textured p-GaN layer, showing a

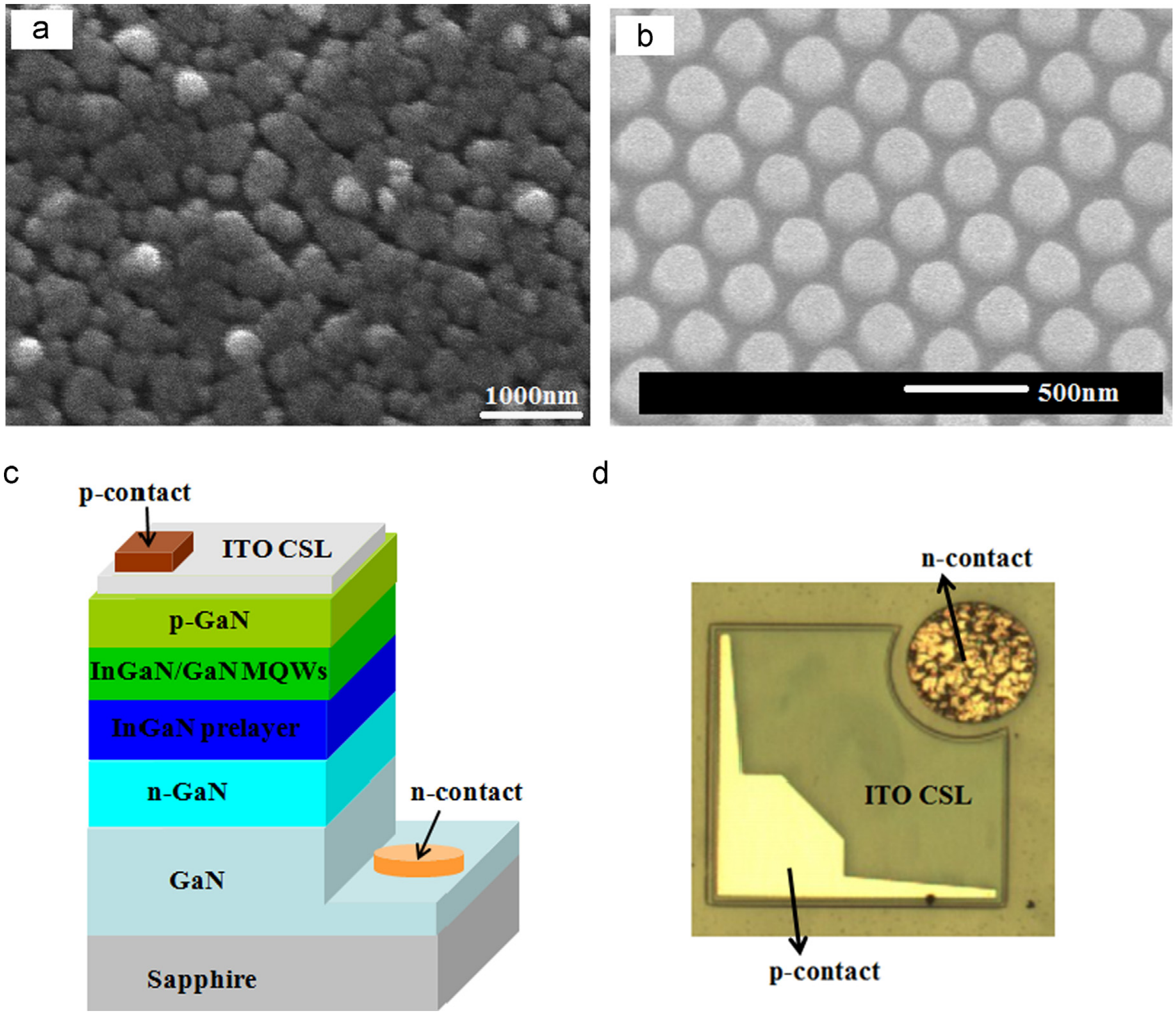

Fig. 1. (a) SEM image of annealed ITO CSL on the p-GaN layer; (b) SEM image of nanorods form on the top p-GaN layer; (c) Schematic of InGaN MQW solar cell; (d) Optical photo of a solar cell device.