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Enhanced output power of (indium) gallium nitride light emitting diodes by a transparent current spreading-film composed of a disordered network of indium tin oxide nanorods

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ABSTRACT

A thin film consisting of a disordered nanorod network of indium tin oxide (ITO) and conventional ITO films are fabricated on gallium nitride (GaN) based-light emitting diodes (LEDs) by electron beam evaporation. The surface morphologies are observed by scanning electron microscopy (SEM). The disordered nanorod network of ITO is grown in vacuum without oxygen. It can be applied directly on the LED as the current spreading film unlike other nanorods which require growth on a conductive layer. The transmittance, current–voltage characteristic, and the dependence of light output power on current are measured for disordered nanorod network ITO LEDs and conventional ITO LEDs, respectively. The measurement results indicate that the nanorod network provides a significant improvement in the light output power of GaN-based LEDs. The influence of the structure of ITO films on the light output power of GaN-based LEDs is discussed.

1. Introduction

Recently, solid-state lighting based on gallium nitride (GaN) light emitting diodes (LEDs) has attracted much attention because of its high luminescence efficiency, low energy consumption and environmental advantages. GaN-based LEDs are the core of the semiconductor lighting device, which have been widely used in traffic signals, full color displays, solid-state lighting and backlighting of liquid crystal displays [1,2]. Blue light from GaN-based LEDs can be converted into white light through excitation of phosphor materials. However, the output power and efficiency of GaN-based LEDs should be further increased for solid-state lighting applications. As a result of significant worldwide research activity, progress has been made toward the development of white LEDs with enhanced luminosity [3]. Also, the increased market demand for GaN-based LEDs has prompted the development of lower cost devices [1,2,4].

To improve the light output power of GaN based LEDs, the surface texturing technique is often used to increase the critical angle of the light escaping from the device into air [5], such as roughening *p*-GaN [6] or *n*-GaN [7], using III-nitride photonic crystal [8], graded index films [9], micro-domes GaN structure [10,11] on light emitting diodes. In addition, surface roughening of the ITO [12–16] current spreading layer has been demonstrated as an alternative method for improving light extraction efficiency without degrading electrical characteristics. For

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example, nanoporous structures of ITO film [13], nanosphere ITO [14], micro-hole arrayed ITO [15], and ITO photonic crystal [16] have all been fabricated to enhance the light output power of GaN-based LEDs. In general, the above particular ITO structures are fabricated through the following procedures: wet or dry etching [13–15], lithography [16], and reactive magnetron sputtering [17]. However, there are many process difficulties in the fabrication of these particular ITO structures. Especially, the reproducibility of the roughing technique processing could not be assured because of the influence of leakage of the *p*-GaN layer thickness.

C.H. Chiu has successfully fabricated ITO nanorods by means of oblique electron beam evaporation in the nitrogen ambient in order to enhance light extraction efficiency from GaN/InGaN LEDs [18]. The nanorod ITO was grown on a normal ITO buffer layer as a current spreading film. However, the development of techniques that use the existing commercial ITO equipment to obtain a low cost nanorod ITO films is necessary for its integration in a mass-production line. In the present work, we try to fabricate a disordered nanorod net of ITO film on a GaN surface directly by electron beam evaporation under an anaerobic ambient without oblique evaporation technique. The ITO nanorod shows good crystal quality and orientates randomly. Compared with the oblique evaporation in the nitrogen ambient, our disordered nanorod network is fabricated using present commercial mass-production-scale equipment without any other process gas. It can be applied directly on the LED as a conductive film and does not require the growth of a normal ITO conductive layer underneath. This reduces the LED process cost and makes it a simple mass producible method to enhance LEDs' output efficiency.

Using the disordered nanorod ITO film as a current spreading layer on InGaN/GaN LEDs, the light exaction power increases 30% compared with that of another LED coated with a conventional ITO film. In addition, the electrical characteristic of the LED remains unchanged.

2. Experimental

In this experiment, GaN-based LEDs were grown on sapphire substrates by metal organic chemical vapor deposition (MOCVD). Initially, the GaN nucleation layer was deposited on a sapphire substrate at a temperature of 560 °C. Then an undoped GaN epilayer with a thickness of 2 μm and a Si doped *n*-GaN epilayer with a thickness of 2.3 μm were deposited at 1100 °C and 1120 °C respectively. After the growth of the *n*-GaN template, a seven-period multi-quantum well composed of GaN/InGaN pairs was grown at 810 °C, and was found to emit at approximately 460 nm. Finally, a 600 nm-thick *p*-GaN layer and a 10 nm-thick highly doped *p*-GaN layer were grown at 1050 °C.

After the growth process, the LED wafers were cleaned by acetone, alcohol, hydrofluoric acid solution and deionized water. Then a 280 nm-thick ITO layer was evaporated onto the *p*-GaN surface to form a transparent ohmic contact layer by an electron beam evaporator. LED chips with dimensions of $254 \times 580\ \mu m^2$ were fabricated by mesa etching to expose *n*-GaN using the inductively coupled plasma (ICP) process. After ten minutes annealing at 550 °C in a nitrogen/oxygen ambient, the *p*-type and *n*-type contact pads were deposited using the metal stack CrAu. After grinding, laser scribing and splitting, LED chips were sorted and their electrical and optical characteristics were measured.

For the comparison study, we used electron beam evaporation equipment (FU-20TEB-ITO) to deposit disordered nanorod network of ITO and conventional ITO films on the *p*-GaN surface, respectively. The ITO source is a 90 wt% In_2O_3 and 10 wt% SnO_2 homogeneously mixed ingot with a diameter of 25 mm and a length of 10 mm. The evaporation was performed at a wafer temperature of 300 °C. The disordered nanorod network of ITO was evaporated at a vacuum of 4×10^{-5} Torr without any process gas. In contrast, the conventional ITO film was evaporated with an oxygen flow of 20 sccm. The obtained film thickness was nearly 280 nm with an evaporation rate of 1.0 A/s.

3. Results and discussion

Figs 1 and 2 are the scanning electron micrograph images for the disordered nanorod ITO and conventional ITO films, respectively. Fig. 1 shows that the deposited ITO film is composed by nanorods and the nanorods take a disordered arrangement. Their diameters and lengths are in a range of 30–40 nm and 200–400 nm, respectively. The nanorod has a good crystal quality and orientates randomly. Such surface morphology of the nanorod ITO film is more like a nanorod network, which would cause light scattering and spreading out of GaN LEDs. At the growth beginning, the evaporated ITO could be decomposed into metal In and Sn on the surface of GaN LED wafer at a temperature of 300 °C in an ambient without oxygen. As time progressed, there would be the liquid metal droplets formed as nanosized nuclei on the wafer surface. The liquid nuclei absorbed In_2O_3 and Sn_2O_3 source vapor, which diffused into the droplets. When the vapor became supersaturated through the liquid interface, the solid ITO began to grow through the vapor–liquid–solid (VLS) mechanism [19]. When the nano crystal grew to a certain height, nanorod ITO began to bend as the nanorod could not support the whole weight. As a result, many nanorods bent and interlaced, forming a conductive network. Among the bent nanorods the VLS crystal growth pattern

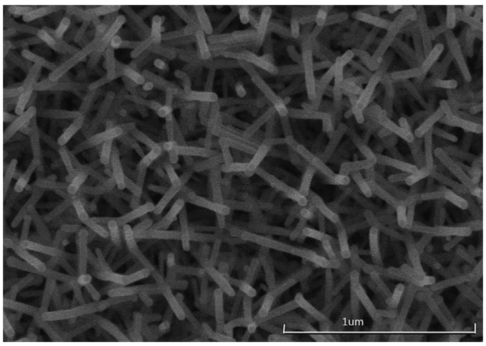

Fig. 1. Scanning electron micrograph image of disordered nanorod network of ITO film.