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Hybrid indium tin oxide/Ag nanowire electrodes for improving the light output power of near ultraviolet AlGaN-based light-emitting diode

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ABSTRACT

Ag nanowires (Ag NWs) were combined with a thin indium tin oxide (ITO) film as the *p*-type electrode in near ultraviolet (NUV) AlGaN-based light-emitting diodes (LEDs) to improve the light output power. The Ag NWs (30 ± 5 nm in diameter and 25 ± 5 μm long) were dispersed in ethanol (0.3 wt%). The transmittances of 10 nm-thick ITO, ITO/Ag NWs coated at 1000 rpm, and ITO/Ag NWs coated at 3000 rpm were 98%, 90%, and 97% at 385 nm, respectively. LEDs (chip size: 300 × 800 μm^2) fabricated with the ITO/Ag NW electrode exhibited higher forward-bias voltages than the LEDs with the ITO-only electrode. However, LEDs with ITO/Ag NWs films coated at 1000 and 3000 rpm yielded 7.9 and 14.0% higher light output power, respectively, at 100 mA than the LED with ITO-only electrode. The improved output power with the ITO/Ag NWs films is attributed to an optimal trade-off between optical transmittance and current spreading.

1. Introduction

AlGaN/InGaN-based near ultraviolet (NUV) light-emitting diodes (LEDs) have attracted considerable interest because of their use in various applications such as UV curing, water purification, and solid-state lighting [1–4]. In spite of their importance, their external quantum efficiency (EQE) is fairly low. This is in part because the *p*-type electrodes absorb most of the photons generated from the active region. Thus, to enhance the EQE, the light extraction efficiency (LEE) should be further improved. For conventional top-emission UV LEDs, films made from oxidized Ni/Au or transparent conducting oxides (TCOs) such as indium tin oxide (ITO) and ZnO-based oxides were extensively investigated to develop transparent *p*-type electrodes [5–11]. For example, Jo et al. [7] found that electron beam (e-beam) irradiation of ITO films deposited by radio frequency (RF) magnetron sputtering significantly reduced the films' electrical resistivity but increased their optical band gap, and the corresponding NUV-LEDs exhibited 58% higher optical power at 100 mA than untreated LEDs. Tun et al. [11] investigated the effects of Al-doped ZnO (AZO), Ni/AZO, and NiO_x/AZO current spreading layers on the performance of GaN-based UV LEDs, and reported that LEDs with Ni/AZO and NiO_x/AZO contacts exhibited 38.2% and 60.6% higher light output, respectively, at 350 mA than those with Ni/Au ohmic contacts. However, the transmittance of TCO-based *p*-type electrode in the NUV region is still far from satisfactory. This is because a desired low electrical resistance (sheet resistance < 80 Ω/sq) requires approximately 200 nm thickness in the TCO films. Recently, transparent conducting electrodes (TCEs) using graphene, carbon nanotubes (CNTs) and silver nanowires (Ag NWs) have been extensively investigated because of their high optical transmittance and low electrical resistance [12–21]. For instance, Cho et al. [14] showed that the NUV LEDs (415 nm) with thermally annealed Au-doped multilayer graphene (MLG) exhibited 34% more optical output power compared with LEDs with bare MLG. This improvement was attributed to the reduced sheet resistance and enhanced current injection efficiency. Seo et al. [15] reported that using graphene/Ag NWs film as a transparent, current spreading electrode led to

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improved output performance in NUV-LEDs. Kim et al. [17] observed that uniformly distributed Ag NWs-based electrodes exhibited higher UV transmittance than 200-nm-thick ITO electrodes, and both types of LED have comparable output powers. In this study, we investigated the effect of ITO/Ag NWs hybrid electrodes on the optical performance of NUV (385 nm) LEDs as a function of the density of Ag NWs by adjusting the spin-coating speed during fabrication. The commercially used 200-nm-thick ITO film has low resistivity (approximately 10^{-4} Ω cm) [22] but low NUV transmittance, and a much thinner (10 nm) ITO film combined with Ag NWs may exhibit both low resistance and high NUV transmittance. Emission images are taken to characterize the output performance of LEDs with different *p*-type electrodes.

2. Experimental procedure

Near UV (385 nm) AlGaN/InGaN multiple quantum wells (MQWs) LED structures were grown on (0001) sapphire substrates by metalorganic chemical vapor deposition (MOCVD). The epitaxial structure consisted of 5 layers: a 2.0-μm-thick undoped GaN layer, a 4.0-μm-thick *n*-type GaN:Si ($n_d = 9.0 \times 10^{18}$ cm^{-3}) layer, a 50-nm-thick AlGaN/InGaN MQWs active layer, a 2.0-μm-thick AlGaN electron blocking layer, and a 50-nm-thick *p*-type GaN:Mg ($n_a = 3.0 \times 10^{19}$ cm^{-3}) layer. Ag NWs (diameter 30 ± 5 nm, length 25 ± 5 μm) dispersed in ethanol at 0.3 wt% were purchased from NANOPYXIS Inc. Prior to metal deposition, all the samples were treated with a buffered oxide etch (BOE) solution for 1 min and rinsed in deionized water. To fabricate the LEDs (chip size 300 × 800 μm^2), standard photo-lithography and inductively coupled plasma reactive-ion etching (ICP-RIE) processes were performed. A transparent *p*-type ohmic contact was formed by depositing a 10-nm-thick ITO layer on top of *p*-type GaN by electron beam evaporation, followed by annealing at 650 °C for 1 min in a N_2 stream. After that, the ethanol Ag NW solution was spin-coated over the ITO layer at three different coating speeds of 500, 1000, and 3000 rpm for 30 s each. The resulting surface morphologies were observed by scanning electron microscope (SEM) and are shown in Fig. 1(a)–(c), respectively. The Cr/Ni/Au (20 nm/25 nm/50 nm) layer was deposited as both *p*-pad and *n*-pad. For comparison, LEDs using only 10-nm-thick ITO film were also fabricated. The schematic structures of LEDs without and with Ag NWs are shown in Fig. 1(d) and (e), respectively. The current–voltage (*I*–*V*) curves and light output power measurements were carried out by a Keithley 238 and a Newport dual channel powermeter, respectively. Transmittances of the ITO and ITO/Ag NWs films on sapphire substrates were measured using a UV/Visible spectrophotometer.

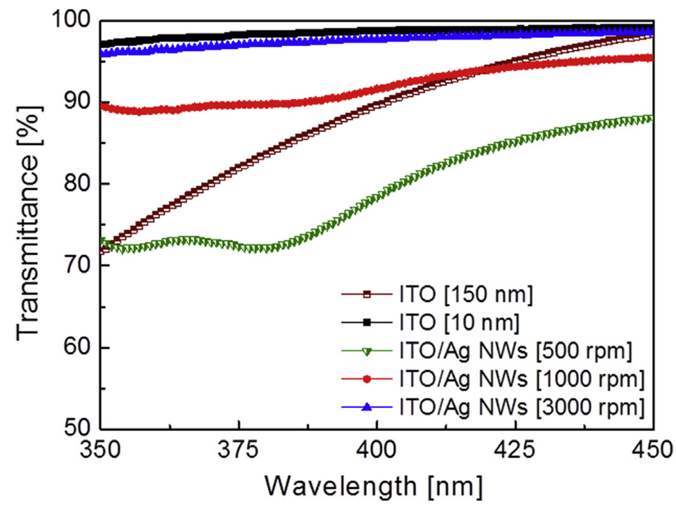

Fig. 2. The optical transmittance of 150 nm-thick ITO, 10 nm-thick ITO and ITO (10 nm)/Ag NWs films deposited at different coating speeds.

3. Results and discussion

Fig. 2 shows the optical transmittance of 10-nm-thick ITO and

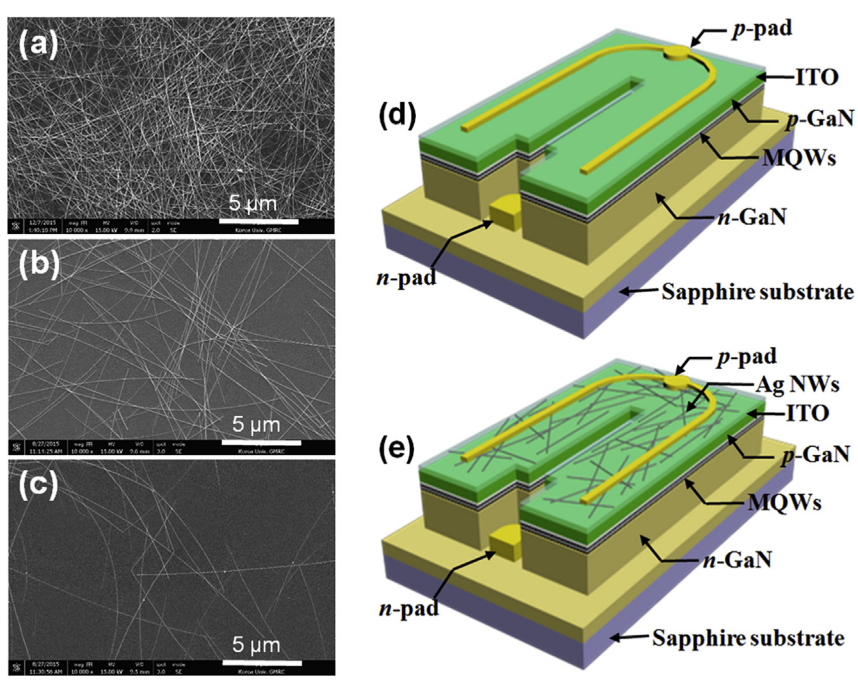

Fig. 1. SEM images of Ag NWs on ITO films (10 nm thick) coated at a speed of (a) 500, (b) 1000, and (c) 3000 rpm. Schematic of 3-D LEDs fabricated (d) with ITO-only and (e) ITO/Ag NW electrodes.