Strong Enhancement in Light Output of GaN-Based LEDs With Graded-Refractive-Index ITO Deposited on Textured V-Shaped Pits

Min-Shuai Wang, Lan Yang, and Xiao-Jing Huang

***Abstract*— An interesting structure of GaN-based light-emitting diodes (LEDs) with different indium–tin-oxide (ITO) films deposited on naturally textured V-shaped pits (V-pits) is fabricated and studied. The sputtered ITO assists the textured surface to get a better contact and thus reduces the forward voltage. Moreover, the ITO films prepared by different methods can serve as graded-refractive-index antireflective coatings, which can enhance the performance of the V-pits LED further. The results show that the V-pits LED with two layers ITO films have a stronger light output power than the reference LED by 52.1% at 20 mA, and the forward voltage is only a little higher than the standard LED.**

***Index Terms*— Light-emitting diode, refractive, ITO.**

I. Introduction

RECENTLY, GaN-based light-emitting diodes (LEDs) have become increasingly prevalent in light sources such as interior/exterior lighting and automotive head-lights. However, the light extraction efficiency (LEE) for GaN-based LEDs is still required to be enhanced. The LEE is limited by total internal reflection (TIR) and Fresnel reflection. The use of graded index of refraction will result in reduction in Fresnel reflection [1]. For TIR, the increase in light escape cone in LEDs can be realized by using various micro/nano-photonic structures on LED surface, such as photonic crystals [2], colloidal microlens arrays [3], and concave microstructures [4]. Among these methods, etch damage was induced in the p-GaN due to the formation of surface defects such as vacancies, impurities, and residuals as the result of the dry etching process.

Nowadays, the naturally textured V-shaped pits (V-pits) which were grown on the p-GaN surface have remarkably enhanced light extraction of LEDs [5], [6]. The uniformity of the V-pits structure is good in wafers. The non-uniformity of the V-pits in inner, middle and outer of one wafer is a problem once. By adjusting the H_2 and N_2 flow or the inner, middle and outer temperature, the non-uniformity surface will be good enough for scalable manufacturing. However, one of the most troublesome issues impeding its application is the higher forward voltage (around 3.2 V), which may be attribute to the bad contact between the V-pits and the ITO film.

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In this letter, we solved the problem and proposed that the sputtered ITO film with good compactness will reduce the higher voltage. And a new type of GaN LED with two layer graded refractive index ITO on textured surface is discussed. What is important is that there are few reports on this topic. In this letter, the improved optical and electrical properties are achieved for GaN-based LEDs with different ITO layers on V-pits surface.

II. Experiments

The GaN-based LEDs emitting at 460 nm were grown on a c-plane (0001) sapphire substrate by low-pressure metal organic chemical vapor deposition (MOCVD). The epitaxial structure consisted of a 2 μm thick undoped GaN layer, a 3 μm thick Si-doped n-type GaN layer, an MQW active layer consisting of seven periods of undoped InGaN wells and Si-doped GaN barriers, and a 300 nm Mg-doped p-GaN layer at 920 °C. The wafers were annealed at 600 °C for 10 min under air for p-type GaN dopant activation. The ITO layer was deposited by an E-beam evaporation system onto the p-GaN layer to form a p-side contact layer and a current spreading layer. The surface morphologies were examined by scanning electron microscopy (SEM, Hitachi S-4800). Four types of LED samples have been fabricated. The standard LED (denoted as the device A) is fabricated by the normal process as described above, which is a planar p-GaN surface and evaporated ITO (120 nm). The studied LED with the same evaporated ITO deposited on a V-shaped p-GaN surface is denoted as the device B. The V-shaped textured surface is made by doping a certain amount of trimethyindium (TMIn) flow. This is a new approach for forming the V-shaped pits [5], and is used in devices B to D. The In-doped p-GaN layer will generate the pure or mixed screw thread dislocations and shape the V-pits. The growth temperature of the V-pits is 920 °C, which is the same as LED A. The TMIn to TMGa flow ratio is 300/85. The V-pits density is about $8.1 \times 10^7/cm^2$. The Indium fraction inside the p-GaN is about 6% from x-ray simulation. The sputtered ITO deposited on V-shaped surface (denoted as the device C) is prepared by the same V-pits process except the ITO is deposited by RF magnetron sputtering. The device D is fabricated with V-shaped pits surface and two layers graded refractive index ITO films, which is composed of a 60 nm sputtered ITO and a 60 nm evaporated ITO. The thicknesses of the ITO layers in device A to D are all 120 nm. The sputter system was equipped with load-lock

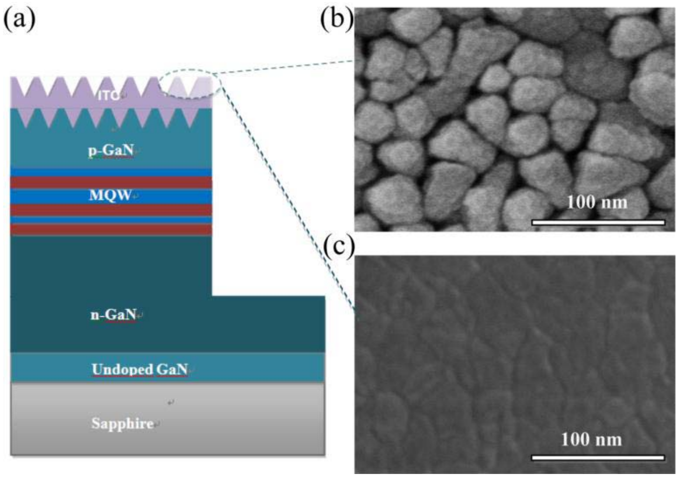

Fig. 1. (a) The schematic structure of the V-pits LED. (b) SEM image of evaporated ITO layer. (c) SEM image of sputtered ITO layer.

system, and the base pressure in the chamber was maintained below 1.3×10^{-4} Pa. ITO sputtering was done in an Ar–O_2 (3.0 vol. % O_2) gas mixture at pressure of 7×10^{-3} mbar. The Hall test was measured at room temperature using an Accent HL5500 Hall System. The LED wafers were processed into $350 \times 350\ \mu m^2$ LED chips. The current-voltage, light-output power and optical transmittance measurements were carried out using an integrating sphere on bare die.

III. Results and Discussion

Fig. 1(a) is the schematic of the textured V-pits LED. Fig. 1(b) and (c) shows the SEM images of evaporated and sputtered ITO films. In Fig. 1(b) and (c), the sputtered ITO film is very dense and smooth and the evaporated ITO film is roughness and porous. In RF sputtering process, there is an enhanced substrate bombardment by plasma ions (mainly Ar+) of moderate energy, because of the higher difference between plasma and floating potential in a RF discharge. Such a moderate energy ion bombardment can assist the film growth and lead to a better and denser film [7]. The poor quality of evaporated ITO film is the reason for higher forward voltage in V-pits LEDs. The sputtered ITO film has a better surface and is more suitable for the contact with V-pits surface.

Fig. 2 shows the refractive index and optical transmittance of the two ITO films measured by ellipsometry and spectrophotometer. The refractive indexes of these two ITO films were measured after annealing. The anneal temperature is 260 °C under air condition for about 15 minutes. In Fig. 2, the refractive index of sputtered ITO (about 1.80 in 460 nm) is larger than the one of evaporated ITO (about 1.45 in 460 nm). The Fig. 2 also presents the optical transmittances of ITO films. The transmittances are about 48% and 54% in 460 nm wavelength for the evaporated and sputtered ITO. The higher transmittance of sputtered ITO film is related with the refractive index and will enhance the light extraction for LEDs with sputtered ITO film.

However, what is the physical reason for different refractive index when the films are deposited by different approaches?

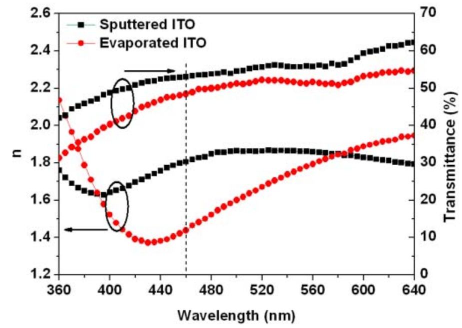

Fig. 2. The refractive index and optical transmittances of the sputtered and evaporated ITO films.

The refractive index can be influenced by film density, carrier concentration and so on. On one hand, there is the prevalent refractive index equation of ITO film, which can be express as:

$$n^2 = \varepsilon_{opt} - \frac{4\pi N e^2}{m^* \omega_0^2} \qquad (1)$$

where n is refractive index, ε_{opt} is the optical frequency dielectric constant, N is the carrier concentration, m* is the carrier effective mass and ω_0 is the carrier plasma oscillation frequency [8]. We also measured the hall test. The carrier concentration, mobility, resistivity data for the evaporated and sputtered ITO layers are, -2.03×10^{20} cm^{-3}, 34.1 cm^{2}V^{-1}s^{-1}, $9.02 \times 10^{-4}\Omega$·cm, and -1.24×10^{21} cm^{-3}, 27.7 cm^{2}V^{-1}s^{-1} 1.82×10^{-4} Ω•cm. The ITO films were deposited on the glass substrate for the Hall measurements. The ITO films thickness are all 120 nm. One can see that the carrier concentration in sputtered ITO is higher than the one in evaporated ITO, and based on equation (1) the refractive index in sputtered ITO should be smaller. The contradiction offers another perspective that the influence of carrier concentration on refractive index is not decisive in our case. The comparison of carrier concentration is more appropriate in the same kind of material or forming by the same deposited method.

On the other hand, the refractive index of a material can be calculated by an empirical formula:

$$n = 1 + \rho \sum_i P_i K_i \qquad (2)$$

where n is refractive index, ρ is the film density, P and K_i is the mole fraction and coefficient of refraction of the i-th component. From the equation (2), we know that the density or compactness of the film is a foremost factor. In Fig. 1, the better compactness surface in sputtering ITO indicated the larger refractive index of sputtering ITO. Besides, the carrier concentrations of the deposited ITO layers vary with the different approaches which may be associated with the process condition of sputtering such as the degree of target oxidation, oxygen presence in gas mixture and the reduction of oxygen content during the sputtering process [9].

Fig. 3 shows the L-I, I-V and far-field plots of the standard LED (device A), the V-pits LED with evaporated ITO (device B), the V-pits LED with sputtered ITO (device C) and the V-pits LED with graded refractive index ITO films (device D).

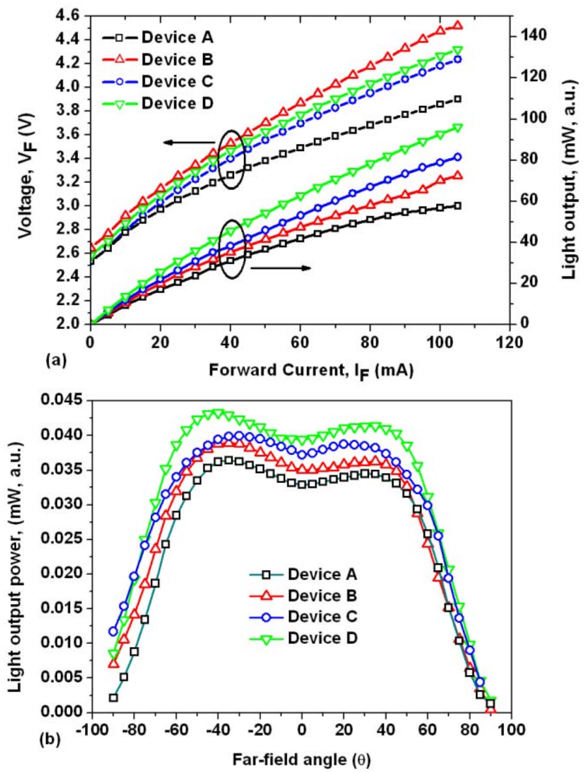

Fig. 3. The comparison of (a) light output power–current (L-I), forward current–voltage (I-V) plot and (b) far-field emission patterns for device A, B, C and D.

In Fig. 3(a), compared to device A, the other three V-pits LEDs both show a better light-output power. At a current of 20 mA, device D shows 52.1% higher light-output power than device A, whereas the device B and device C only shows 19.5% and 30.3%. Firstly, the higher output power in three V-pits LED is due to the reduction of total internal reflection. The V-pits structure increase more lights emitted into the escape cone by providing the oblique plane. Secondly, the light output in device C is higher than device B, which may be attributed to the refractive index and higher optical transmittance of the sputtered ITO. Finally, device D shows a strong enhancement in light output power compared to the standard LED. The destructive interference of the three reflected lights and the constructive interference of the emitting lights amplified the effect of the antireflective coatings and reduced the Fresnel reflection.

The average I-V characteristics of the LEDs are also shown in Fig. 3(a). The forward voltage of device A is around 3.0 V at 20 mA. The device C and D is a little higher forward voltage (about 3.06 V), but the forward voltage in the device B is high up to 3.15 V. This is attributed to the rough and grainy surface of the evaporated ITO, which caused poor contact with the V-pits surface. The reverse leakage of the four LEDs are all around 1.5×10^{-8} A under an operation voltage of -10 V and there is no obvious higher reverse leakage in V-pits LEDs. Fig. 3(b) shows the far-field emission patterns of the four LEDs at the current density of 20 A/cm^2. The far-field measurements were taken from $\theta = -90°$ to $\theta = 90°$. The top and side lights of device D shows a stronger radiant intensity than the other three LEDs, which is in accord with the L-I result.

IV. Conclusion

In summary, we show the surface of sputtered ITO film is smooth and dense, and it is more suitable for the contact with V-pits surface other than the evaporated ITO film. The finding of different refractive indexes in sputtered and evaporated ITO films is important. And an interesting LED is formed by surface V-pits and two layers graded refractive index ITO films, which exhibits 52.1% enhancement in light output power compared to the standard LED due to a strongly reduced total internal reflection and Fresnel reflection. Moreover, the forward voltage is only a little higher than the standard LED. It is suggested that we can achieve a better optical and electrical performance in any optoelectronic devices by using the graded refractive index ITO films.

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