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Full wafer microstructure fabrication by continuous UV-assisted roller imprinting lithography to enhance light extraction of LEDs

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ABSTRACT

The ratio of the number of emitted photons from the active region of LEDs to the number of photons escaping to free space (light extraction efficiency) constitutes an essential figure for judging the performance of an LED. Fresnel loss occurs between LEDs, and air is an unavoidable factor for influencing light extraction, though the main loss channel in the LED is caused by the total internal reflection (TIR). Surface texturing ruins the TIR, and therefore enhances light extraction efficiency. This study performed UV-assisted roller imprinting to build periodical microstructures on the surface of LEDs. The results showed that the output power enhancements for LEDs with imprinting micro-cylinders at heights of 0.5, 1, 1.5, 2.5, and 5 μm were greater than conventional LEDs at 100 mA current injection by 18.79%, 25.11%, 26.34%, 22.12%, and 8.87%, respectively. The numerical simulation performed using the ray tracing method was also useful for obtaining the microstructure with optimal light efficiency extraction. The 2″ full wafer imprinting was fabricated through the flexible mold adopted by reversal imprinting.

1. Introduction

A light-emitting diode (LED) is an electroluminescent device with a broad selection of emission wavelengths (colors). The unique properties of LEDs, such as compactness, low power consumption, long lifetime, and fast turn-on time have made LEDs an indispensable component in modern traffic lighting, display, car lighting, and cell phones applications. In recent years, LED usage has grown more rapidly due to the application of backlights in large-size flat panel displays, a market previously dominated by cold cathode fluorescent lamps (CCFL). In addition, wide speculation foresees that the next boom for LEDs could arise from the interior/exterior lighting market. However, the light extraction efficiency of LEDs is low due to the Fresnel loss and total internal reflection (TIR). Some studies have found that light extraction efficiency could be significantly enhanced by the application of a surface texture [1,2]. Chang et al. [3] performed a thermal embossing technique to pattern polymethyl methacrylate (PMMA) onto the indium tin oxide (ITO) layer of an LED, and used an inductively-coupled plasma (ICP) etcher to remove the residual PMMA layer. The PMMA pattern was then transferred onto the ITO layer using dilute hydrochloric acid. Hong et al. [4] produced a moth eye structure on *p*-GaN by UV imprinting lithography and an ICP process with a Cr etching barrier. The master imprinting mold was fabricated by laser interference lithography and electroforming. Huang et al. [5] fabricated *p*-GaN nanostructures on the surface of a $1 \times 1\ mm^2$ high-power green LED chip. An SiO_2 thin film was first deposited onto *p*-GaN, and a silicon mold was used for the hot embossing imprint process. Reactive ion etching (RIE) was used for cleaning the residues of the imprinting material and SiO_2, to complete the transferring of the structure using SiO_2 as the resist. A *p*-GaN nanostructure of 75 nm depth was later produced via ICP etching. Finally, an ITO thin film was deposited onto *p*-GaN.

Continuous imprinting process is demonstrated using the roller imprint method. Instead of imprinting the entire surface at once, the roller and the substrate are imprinted progressively, rendering the roller imprint useful for the fabrication of structures on a large surface [6–9]. In this study, we propose to build SU-8 microstructures on the LED surface by UV-assisted roller imprinting, rather than by etching with ITO or *p*-GaN. A soft polymer such as polydimethylsiloxane (PDMS) is used as the mold to duplicate the pattern of hard mold, and the imprinting material was sprayed onto PDMS mold. By compressing the PDMS soft mold and the substrate, the pattern of the mold is imprinted to the substrate. UV-assisted roller imprinting is a continuous room-temperature imprinting process which also can avoid the trapped-air phenomenon. The imprinting material SU-8, with a refractive index of ~1.5, is suitable as a buffer layer to reduce Fresnel loss, and SU-8 microstructures are also useful in destroying TIR to enhance light extraction efficiency.

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2. Experiments

2.1. LED epitaxy

The GaN-based LED structure in this study was grown using a metal organic chemical vapor deposition (MOCVD) system on a C-face (0001) in 2 in. diameter sapphire substrates. The LED layer structure consists of a low-temperature GaN nucleation layer, a thick unintentionally doped GaN layer, a n-type GaN layer grown on an active region with 10 periods of InGaN/GaN multiple quantum wells (MQWs), a Mg doped p-$Al_{0.15}Ga_{0.85}N$ cladding layer ($p = 5 \times 10^{17}\ cm^{-3}$), and a Mg-doped p^+-GaN contact layer ($n = 7 \times 10^{17}\ cm^{-3}$) [10].

2.2. Chip process and imprinting procedure

Fig. 1 shows the chip process of a GaN-LED. The fabrication of 10 mm × 10 mm LED sample was first to evaporate a 240 nm thick layer of indium tin oxide (ITO) onto the sample as a transparent conductive layer, followed by partial-etching about 1 μm deep by ICP in a gas mixture of $Cl_2/SiCl_4/Ar$ to expose the n-GaN. The ITO pattern is defined by optical lithography and through wet etching to reveal the p-GaN. Cr/Au was then deposited both on the p-GaN and n-GaN surfaces by a thermal evaporator with rapid thermal annealing for p-electrode and n-electrode.

The soft nanoimprint lithography, similar to the UV-curing nanoimprint lithography, has the advantages of fast production, simple process, and low equipment cost. The key benefit of the soft nanoimprint lithography is its flexible mold, which makes it suitable for the non-planar imprint process, thereby having wider application. The disadvantage is that the mechanical strength of the mold is relatively weak compared to that of the others, resulting in easy wearing of the imprint patterns or the molds. To improve the imprint technique, a reversal imprint is developed. As shown in Fig. 2, the aforementioned imprint techniques place the imprinting materials on the substrate surface. Conversely, the reversal imprint technique places the imprinting material on the surface of the mold before the entire material is pressed for transferring to the substrate. This procedure is similar to "planting" structures on the substrate, and the pressure required for the reversal imprint is 4 kgf/cm^2 in this experiment. Micro-cylinder array with a diameter of 3 μm and periodicity of 4.65 μm was fabricated on the surface of the LED samples by roller reverse imprinting as shown in Fig. 2. Polytetrafluoroethylene (PTFE) was first sprayed onto the PDMS soft mold at 2000 rpm for 30 s before being cured at 200 °C for 10 min to obtain a lower surface energy, and hexamethyldisilazane (HMDS) was sprayed onto the LED substrate at 6000 rpm for 30 s before being cured at 110 °C for 1 min to increase adhesion. Thus the imprinting materials have a better adhesion to the LED substrate and can be successfully detached from the PDMS mold. We used SU-8 (SU-8 2000.5, MicroChem Corp.) as the imprinting material for spinning onto the PDMS mold at 3000 rpm for 30 s at room-temperature, after which micro-cavities in the mold were filled with SU-8. The imprinting material was then cured at 95 °C for 1 min. The LED sample was fixed at the translation stage by a vacuum holder, and sent for roller imprinting as a translation speed 2 mm/s. As a curing source we used a UV lamp, the optical energy of which could pass through the quartz cylinder and PDMS mold to focus on the imprinting contact area during the imprinting process.

2.3. Light extraction analysis using the ray tracing method

For calculating extraction efficiency, this study used Monte Carlo ray tracing to analyze the light propagation in LED chips [11]. Ray tracing simulates emission, absorption, refraction,

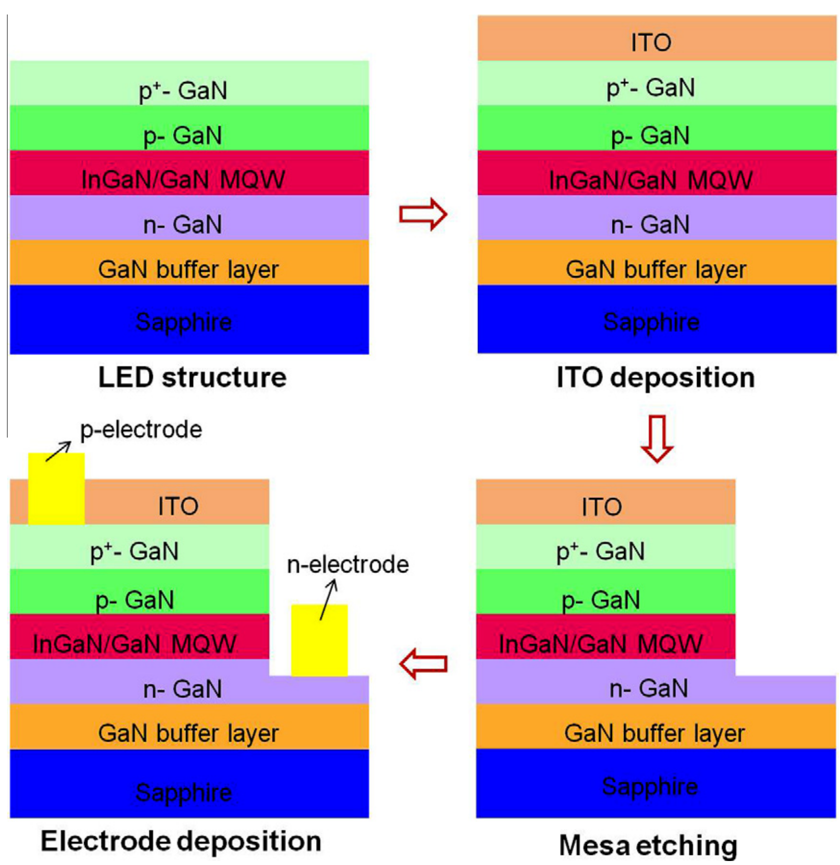

Fig. 1. Chip process of a conventional GaN-LED.