Micro/nano structures induced by femtosecond laser to enhance light extraction of GaN-based LEDs

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Abstract: Surface texturing has been widely adopted to enhance the light extraction efficiency of light-emitting diodes (LEDs), and chemical etching is a technique commonly used to produce surface texturing. This study employed femtosecond lasers to apply ITO films directly onto the surface of LEDs to generate periodic micro/nanostructures and roughen the surface without contact or chemical substances. As a result, photons emitted in the active region escape into the free space, due to the scattering effect produced by texturing. This study discovered that light-emitting efficiency increases with surface roughness, and achieved an improvement of 18%. Caution regarding laser fluence was required during laser processing to avoid damaging the LED beneath the ITO film, which could detract from the electrical characteristics.

OCIS codes: (230.3670) Light-emitting diodes; (220.4000) Microstructure fabrication; (220.4241) Nanostructure fabrication; (320.2250) Femtosecond phenomena.

References and links

1. Y.-H. Sun, Y.-W. Cheng, S.-C. Wang, Y.-Y. Huang, C.-H. Chang, S.-C. Yang, L.-Y. Chen, M.-Y. Ke, C.-K. Li, Y.-R. Wu, and J. J. Huang, "Optical properties of the partially strain relaxed InGaN/GaN light-emitting diodes induced by p-type GaN surface texturing," IEEE Electron Device Lett. **32**(2), 182–184 (2011).
2. S. J. Chang, C. F. Shen, W. S. Chen, C. T. Kuo, T. K. Ko, S. C. Shei, and J. K. Sheu, "Nitride-based light emitting diodes with indium tin oxide electrode patterned by imprint lithography," Appl. Phys. Lett. **91**(1), 013504 (2007).
3. Y. C. Lee, M. J. Ciou, and J. S. Huang, "Light Output Enhancement for Nitride-based Light Emitting Diodes via Imprinting Lithography Using Spin-on Glass," Microelectron. Eng. **87**(11), 2211–2217 (2010).
4. C. F. Tsai, Y. K. Su, and C. L. Lin, "Improvement in External Quantum Efficiency of InGaN-Based LEDs by Micro-Textured Surface with Different Geometric Patterns," J. Electrochem. Soc. **159**(2), H151–H156 (2012).
5. J. H. Lee, N. S. Kim, S. S. Hong, and J. H. Lee, "Enhanced extraction efficiency of InGaN-based light-emitting diodes using 100-kHz femtosecond-laser-scribing technology," IEEE Electron Device Lett. **31**(3), 213–215 (2010).
6. P. S. Banks, B. C. Stuart, M. A. Komashko, M. D. Feit, A. M. Rubenchik, and M. D. Perry, "Femtosecond laser materials processing," Proc. SPIE **3934**, 14–21 (2000).
7. J. Bonse, M. Munz, and H. Sturm, "Structure formation on the surface of indium phosphide irradiated by femtosecond laser pulses," J. Appl. Phys. **97**(1), 013538 (2005).
8. X. C. Wang, G. C. Lim, F. L. Ng, W. Liu, and S. J. Chua, "Femtosecond pulsed laser-induced periodic surface structures on GaN/sapphire," Appl. Surf. Sci. **252**(5), 1492–1497 (2005).
9. T. H. R. Crawford and H. K. Haugen, "Sub-wavelength surface structures on silicon irradiated by femtosecond laser pulses at 1300 and 2100 nm wavelengths," Appl. Surf. Sci. **253**(11), 4970–4977 (2007).
10. C. W. Cheng, W. C. Shen, C. Y. Lin, Y. J. Lee, and J. S. Chen, "Fabrication of micro/nano crystalline ITO structures by femtosecond laser pulses," Appl. Phys., A Mater. Sci. Process. **101**(2), 243–248 (2010).
11. W. C. Peng and Y. C. S. Wu, "Enhanced light output in double roughened GaN light-emitting diodes via various texturing treatments of undoped-GaN layer," Jpn. J. Appl. Phys. **45**(10A), 7709–7712 (2006).

#168372 - $15.00 USD Received 10 May 2012; revised 8 Jun 2012; accepted 20 Jun 2012; published 28 Jun 2012

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 indispensable components in modern traffic lighting, display, car lighting, and cell phones applications. In recent years, LED lighting has accelerated, due to its application of backlights in flat panel displays, a market previously dominated by CCFL. The lighting market for LEDs is also booming for both interior and exterior applications and the efficiency of LEDs is continuously being pushed. One approach involves improving the internal quantum efficiency by increasing radiative recombination and decreasing non-radiative recombination. Another approach involves the enhancement of light extraction efficiency by causing the photons generated in the active regions to escape into free space. A number of studies have found that light extraction efficiency can be significantly enhanced through the application of surface texturing to LEDs, which helps to eliminate the total internal reflection (TIR) occurring between the semiconductor and air. Sun et al. [1] used inductively-coupled plasma-reactive ion etching (ICP-RIE) in the presence of silica nanoparticles as an etching mask to create the p-type GaN roughened surface. The etch depth was 50 nm. The light output power of the textured InGaN/GaN LED was 17% higher than that of the device without roughening. Chang et al. [2] employed a thermal embossing technique to pattern a 0.8 μm diameter hole array PMMA onto the ITO layer of a nitride-based LED, using ICP etching to remove the residual PMMA layer. The PMMA pattern was then transferred onto the ITO layer to a depth of 90 nm using dilute hydrochloric acid. The light output power of the textured LED was 14% higher than that of the conventional device. Lee et al. [3] created various micro-structures made of SOG directly on the ITO surfaces of the LEDs using an imprinting method. The output intensity of the micro-cylinder structure on GaN-based LEDs increased by 26.2%, compared with conventional LEDs. Tsai et al. [4] used photolithgraphy and wet etching to fabricate micropatterns on the surface of the ITO. Compared with conventional LEDs, the concave and convex patterned ITO LEDs enhanced light output power by 7.9% and 16.3%, respectively. J. H. Lee et al. [5] used nanosecond and femtosecond lasers to scribe grooves on the backside of the sapphire substrates. Compared with the LEDs scribed by the nanosecond laser, the LEDs scribed by the femtosecond laser showed 11% output power enhancement. The power improvement is attributed to the femtosecond laser reduced less debris and thermal damage on the sapphire.

Laser etching is a non-contact, chemical-free ablation method. This study employs a femtosecond laser with a wavelength of 517 nm for micro/nanofabrication of an ITO layer on InGaN/GaN LEDs. The femtosecond laser produces extremely fine surface structures in the target material with very little thermal damage and enables the processing of transparent materials with multiphoton absorption characteristics. The textured ITO surface helps to lead photons generated in the multiple quantum wells (MQW) into escape cone to free space, thereby increasing light extraction efficiency.

2. Experiments

Figure 1 shows the sample prepared through epitaxy, a conventional chip fabrication process, and laser etching. The GaN-based LED structure in this study was grown using metal organic chemical vapor deposition (MOCVD) on a C-face (0 0 0 1) of a sapphire substrate with a diameter of 2 in. The structure of the LED layer comprised a low-temperature GaN nucleation layer, a thick undoped GaN layer, a n-type GaN layer, 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}).

The wafer was cut to 10×10 mm^2 for the preparation of 300×300 μm^2 LED chips. The fabricated LED sample had a 240 nm thick layer of indium tin oxide (ITO) evaporated onto it

Received 10 May 2012; revised 8 Jun 2012; accepted 20 Jun 2012; published 28 Jun 2012

as a transparent conductive layer. Partial-etching was performed to approximately 1 µm deep using ICP etcher in a gas mixture of Cl_2/$SiCl_4$/Ar to expose the n-GaN. Optical lithography defined the ITO pattern, and wet etching exposed the p-GaN layer. Thermal evaporation with rapid thermal annealing to create the p- and n-electrodes deposited Cr/Au on the p-GaN and n-GaN surfaces.

Micro/nanostructures were fabricated using an all-in-one femtosecond regenerative amplifier (UC-1035-2000, High Q Laser) with a visible wavelength of 517 nm, a pulse duration of 350 fs, and a repetition rate of 100 kHz. The laser source was a Yb:KYW (ytterbium-doped potassium yttrium tungstate) laser. The laser beam was focused using a 20 × objective lens with a numerical aperture of 0.4 at room temperature. Prior to the lasing process, a chemically amplified epoxy based negative resist SU-8 (SU-8 2000.5, MicroChem Corp.) was spun onto the LED sample as an absorption layer to reduce the power of the incident laser striking the ITO layer. Hence, the femtosecond laser based on a SU-8 coating layer is considered as a buffer approach, which facilitates the formation of structures at constant laser energy. The sample was then placed on the translation stage and moved perpendicularly to the direction of the laser beam. The electric field of the laser was linearly polarized normal to direction of motion of the translation stage.

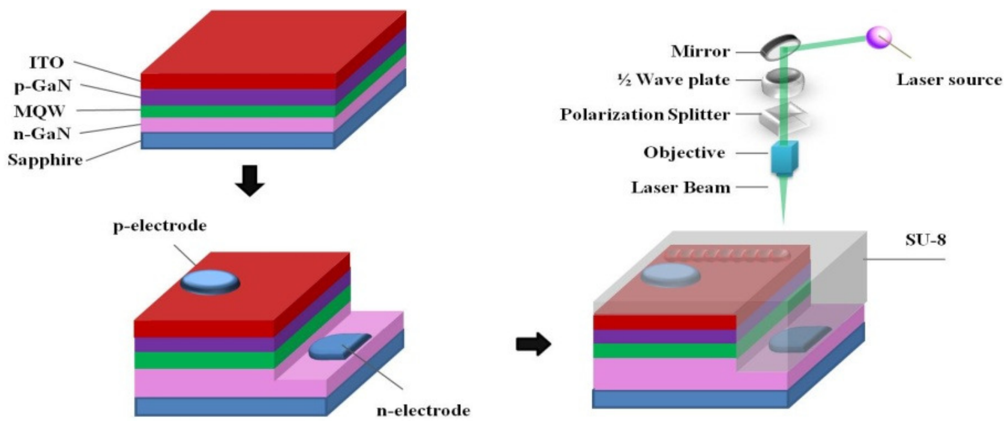

Fig. 1. Process flow to prepare surface texturing of GaN-based LED.

3. Results and discussions

3.1. Surface morphology

Figure 2 presents the results of adjusting the laser power to 2 mW for a continuous process (i.e., line process) with single-pulsed laser irradiation. A stage moving speed of 130 mm/s and laser ablation spot size of ~0.9 µm prevented the laser pulses from overlapping. The width between lines was 1.2~1.5 µm. An ITO band gap of 3.65 eV far exceeded the photon energy of 2.4 eV in the wavelength of the laser. Ablation of the target material was caused by multiphoton absorption resulting from ultrashort laser pulses in which the material absorbed the energy of the laser, bonds were broken, and high-density surface plasma was formed [6]. Laser-induced ripple structures were not observed within the craters (Fig. 2); and the maximum etching depth of the structures was 71 nm with an RMS roughness of 21 nm.

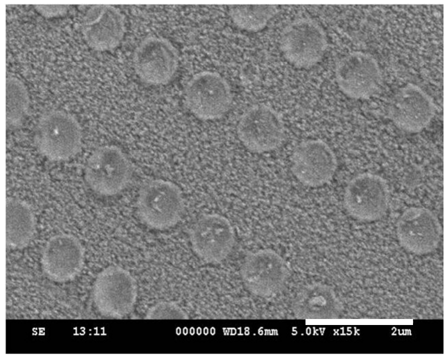

Fig. 2. SEM image of ITO etching at femtosecond laser power of 2 mW moving speed of 130 mm/s.

Figure 3 (a) shows SEM results of ITO films textured using a femtosecond laser at a power of 10 mW, with an ablation spot size of ~3 μm. The width between fabricated lines was 3.7~4.5 μm. It shows ripple structures perpendicular to polarization of the laser beam throughout most of the laser scan area. These ripple structures are called laser-induced periodic surface structures (LIPSS). The average period of the ripple structures in Fig. 3(a) is 120 nm, which is considerably less than the 517 nm wavelength of the incident laser and thus considered sub-wavelength. The generation of these ripple structures can be attributed to the influence of second-order harmonic waves created by the incident laser [7–9], and its period $\Lambda = \frac{\lambda}{2n}$, where λ is the wavelength of the incident laser, and n is the index of refraction within the material. We adopted a wavelength of 517 nm in the formula, $\Lambda = \frac{517\,\text{nm}}{2\times 2} = 129\,\text{nm}$, the result of which is very close to measurement results in the experiment. Similarly, Cheng et al. [10] etched ripple structures onto ITO surfaces using a laser with wavelength of 800 nm and pulse duration of 120 fs, to produce ripples with period of 200 nm, which was also close to calculated values.

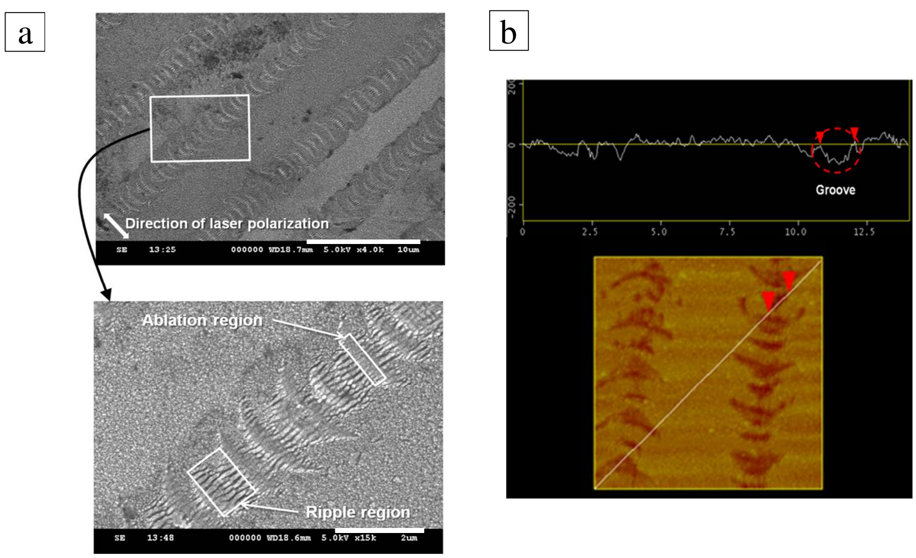

Fig. 3. (a) SEM images of ITO etching using a femtosecond laser power of 10 mW and moving speed of 40 mm/s and (b) AFM image and line scanning of laser processing region.

#168372 - $15.00 USD Received 10 May 2012; revised 8 Jun 2012; accepted 20 Jun 2012; published 28 Jun 2012

Bonse et al. [7] observed the influence of the gradual accumulation of laser fluence on single-spot processing using repeated femtosecond laser pulses with pulse duration of 130 fs on InP material. When laser fluence surpassed the single-pulse ablation threshold, a single pulse generated craters, similar to those in Fig. 2 of this study. With a gradual increase in the number of laser pulses, wavelength-sized ripple structures (low-spatial-frequency LIPSS) were created. In this study, at higher laser energy of 10 mW, sub-wavelength structures (high-spatial-frequency LIPSS), were achieved as shown in Fig. 3(a). Excessive pulse overlap usually results in an expansion of the processed area. Here, high overlapped pulse of the femtosecond laser energy resulted in the ablation of the ripple structures. In Fig. 3(b), the dimensions of the ripple structures (top-view and cross-sectional images) were obtained by the AFM measurement of the laser processed region in Fig. 3(a), illustrating that excessive laser energy causes the ablation of ITO resulting in grooves.

3.2. Electrical and Optical Properties of laser-texturing LEDs

Figure 4 compares the current (I) to voltage (V) curves of conventional LEDs, Hole-LEDs (laser power: 2 mW; stage moving speed: 130 mm/s), and Ripple-LEDs (laser power: 10 mW; stage moving speed: 40 mm/s). The I-V curves of LEDs with surface roughening by femtosecond laser etching are similar to those of conventional LEDs. At an injection current of 20 mA, the forward voltage of conventional LEDs is 3.1 volts; those of hole-LEDs and ripple-LEDs are 3.2 volts. A small portion of the laser fluence passed through the ITO causing minor damage to the p-GaN, such that forward voltage was increased slightly.

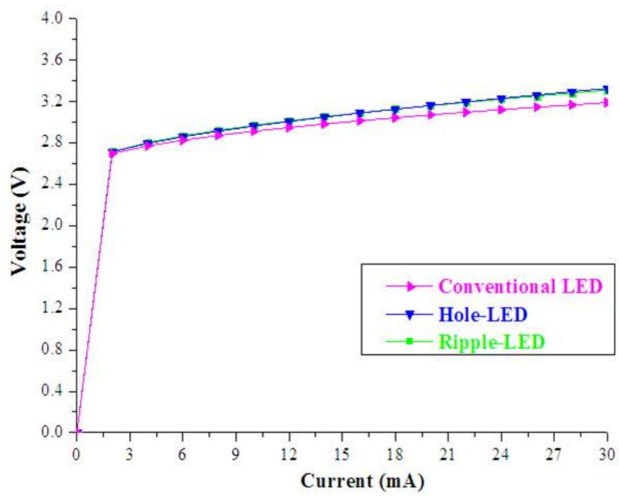

Fig. 4. Comparison of I-V curves for conventional LEDs and other LEDs etched by femtosecond lasers.

Figure 5 compares the output power of the three types of LEDs. Our results reveal that texturing ITO surfaces through laser etching can enhance the light extraction efficiency of conventional LEDs. The optical and electrical properties before and after laser texturing at an operating current of 20 mA are listed in Table 1. The light output power of conventional LEDs, Hole-LEDs, and Ripple-LEDs are 8.0 mW, 8.9 mW, and 9.4 mW, respectively. A comparison of mean roughness verified that LEDs with rougher surfaces provide stronger surface scattering, thereby increasing efficiency. These results are consistent with those of previous studies [11].

Table 1. Comparison of Forward Voltage, Light Output Power, and Light Enhanced Efficiency of Various Laser Texturing Conditions and Those of Conventional LEDs with Injection Current of 20 mA

LED types	Recipe (Laser power/ Stage speed)	RMS Roughness (nm)	Forward Voltage (V_f)	Output Power (mW)	Enhanced Efficiency (%)
Conventional LED	——	3.7	3.1	8.0	——
Hole-LED	2 mW/ 130 mm/s	21	3.2	8.9	11
Ripple-LED	10 mW/ 40 mm/s	23	3.2	9.4	18

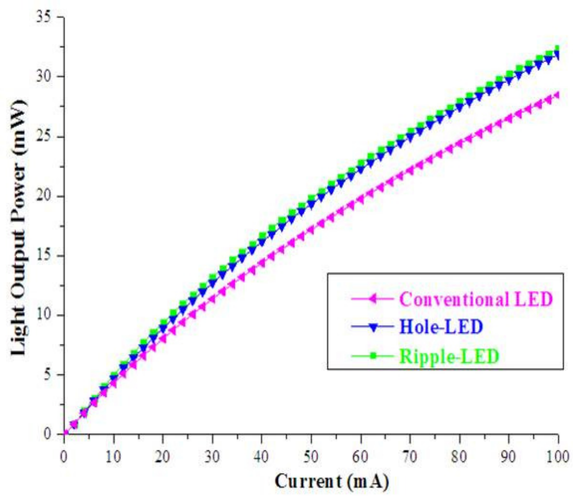

Fig. 5. Comparison of L-I curves for conventional LED and other LEDs etched by femtosecond laser.

4. Conclusions

This study employed femtosecond lasers to manufacture periodic micro/nano-structures on the ITO surface of LEDs. A specific energy threshold must be reached to produce sub-wavelength ripples of LIPSS; otherwise, only a crater would be produced through the partial ablation of material. Excessive laser energy destroys the structure of ripples and ablates more material. LED surface texturing contributes to an enhancement of the efficiency of LEDs and a higher degree of roughness implies better enhancement. Texturing encompassed ~40% of the entire surface in this study. These efforts increased light-emission efficiency by 18% through partial surface texturing; complete surface texturing would no doubt increase this further.

#168372 - $15.00 USD Received 10 May 2012; revised 8 Jun 2012; accepted 20 Jun 2012; published 28 Jun 2012