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Selective lift-off of GaN light-emitting diode from a sapphire substrate using 266-nm diode-pumped solid-state laser irradiation

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Abstract Selective laser lift-off of GaN from a sapphire substrate was demonstrated using 266-nm diode-pumped solid-state laser irradiation. To fabricate a single GaN light-emitting diode (LED) with a size of 100 μm × 100 μm, we used a simple direct scanning technique with a defocused beam and investigated the lift-off parameter in terms of the intensity. Two processing windows corresponding to lower- and higher-intensity regimes were observed experimentally. In the lower-intensity regime, the larger beam size worked better than with the higher regime. Although fluence is generally explained as a processing condition, the total input fluence for a single LED was not crucial to lift-off in case of the scanning technique using a defocused laser beam. However, an intensity of ~37 kW/cm^2 was required to initiate the thermal decomposition reaction in GaN at any sample position.

1 Introduction

GaN-based blue light-emitting diodes (LEDs) are rapidly growing in applicability and are widely used in the lighting industry (e.g., traffic signals, full-color displays, and signage). This is due to their high light extraction efficiency, long lifetime, and low power consumption. Furthermore, these LEDs tend to be flexible and stretchable [1–3]. GaN LEDs are generally fabricated on sapphire substrates, due to their low price and good thermal properties at high temperatures that promote GaN growth, and their transparency to ultraviolet (UV) light with respect to the laser lift-off (LLO) process [4].

The LLO technique, used to separate GaN LEDs from sapphire substrates, can be performed using a variety of lasers, including the excimer laser (248-nm KrF, 308-nm XeCl, and 193-nm ArF lasers) via the projection method at the wafer level, and frequency-doubled (355 nm) and quadrupled (266 nm) irradiation via the raster scanning method [5–7]. The reason for this is that the band gap energy of sapphire (9.9 eV) is higher and that of GaN (3.4 eV) is lower than the photon energy [3.5 eV (355 nm)–6.4 eV (193 nm)]. Thus, the photon energy of the laser beam is absorbed at the interfacial GaN surface, which induces decomposition of GaN into metallic Ga and gaseous N_2. To fabricate flexible LED devices, the GaN LED is transferred to another rigid carrier substrate, such as a Si wafer, by deposition of a metal layer on top of the GaN surface. This is used for fusion bonding between GaN and the carrier substrate. After laser lift-off, GaN LEDs on the carrier substrate are transferred to a flexible substrate such as polyimide (PI) or polyethylene terephthalate (PET) film. These are complex processes that include chemical etching.

The techniques of selective lift-off of GaN LED from sapphire substrates may be necessary to repair or replace damaged LEDs. Ideally, when an LED becomes damaged, it is removed and replaced with a new single LED in the same position. Thus, a process with a high degree of freedom is needed to manipulate a single LED.

In this study, selective laser lift-off (LLO) of GaN from a sapphire substrate was demonstrated using 266-nm diode-pumped solid-state laser irradiation, with minimal processing steps or use of chemicals. The 266-nm laser

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irradiation beam was more convenient to work with than that of the excimer laser which needs more expensive imaging optics and toxic gases. To identify the optimal conditions required for lift-off, the effect of intensity of the laser was investigated.

2 Experimental techniques

The concept of the selective LLO process is shown in Fig. 1. To verify the feasibility of selective lift-off, we used basic, undoped GaN (thickness: 2.0 μm) and n-GaN (thickness: 5 μm) samples, which were fabricated on a sapphire substrate (430 μm), without multi-quantum wells and p-GaN. The unit cell size was 100 μm × 100 μm, with a spacing of 50 μm.

A diode-pumped solid-state laser (wavelength: 266 nm; pulse width: <20 ns; and repetition rate: 30 kHz) was used. The laser beam passed through an attenuator, slit mask, objective lens (magnification: 15×), and a 0.32 numerical aperture and was then focused onto the interfacial layer between the sapphire and undoped GaN. At the focal position of the beam, the intensity was too high for lift-off, and the beam was too small to scan an area of 100 μm × 100 μm. Thus, the size of the beam was adjusted by moving the sample toward the objective lens along the *z*-axis, so that the size of the beam on the surface increased.

When a smaller numerical aperture was used for a large focused beam, it was difficult to find the image of the LED cell, because the image at the charged-coupled camera (CCD) was captured by the objective lens. To find the beam size, the laser power was varied between 10 and 320 mW for the sample positions of 150, 300, and 450 μm away from the focal position. The irradiation time was 500 ms throughout the experiment. For the lift-off experiments, the stage holding the samples moved at a speed of 1 mm/s; the overlap between lines was 5 μm. After laser irradiation, thermal release tape (strength: 14.4 N/20 mm) was attached to the laser-irradiated GaN, and then the tape was detached. Optical microscopy, scanning electron microscopy (SEM), and confocal microscopy were used to characterize both the beam-irradiated and detached samples.

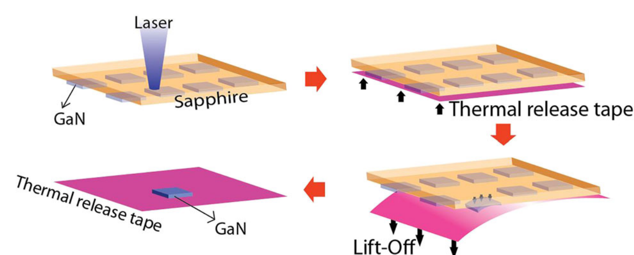

Fig. 1 Schematic illustration of selective laser lift-off (LLO)

3 Results and discussion

Figure 2 shows the spot size with respect to the laser power and focal position. The spot size increased linearly as the power and distance from the focal position increased. We determined the width of the damaged area to be the beam width, as shown in Fig. 2a. Because the spatial beam profile is Gaussian, the damaged area follows the beam profile. The narrow, deep groove area in the center may correspond to the peak power of the beam profile and we determined it as the beam width (*D*). The large damaged area appeared to be associated with a thermal crack caused by the beam edge. The beam width was determined to be 7.3 μm using linear fitting as shown in Fig. 2b, although the theoretical diffraction-limited beam width, given by 2.44 × λ × f-number, was about 1 μm.

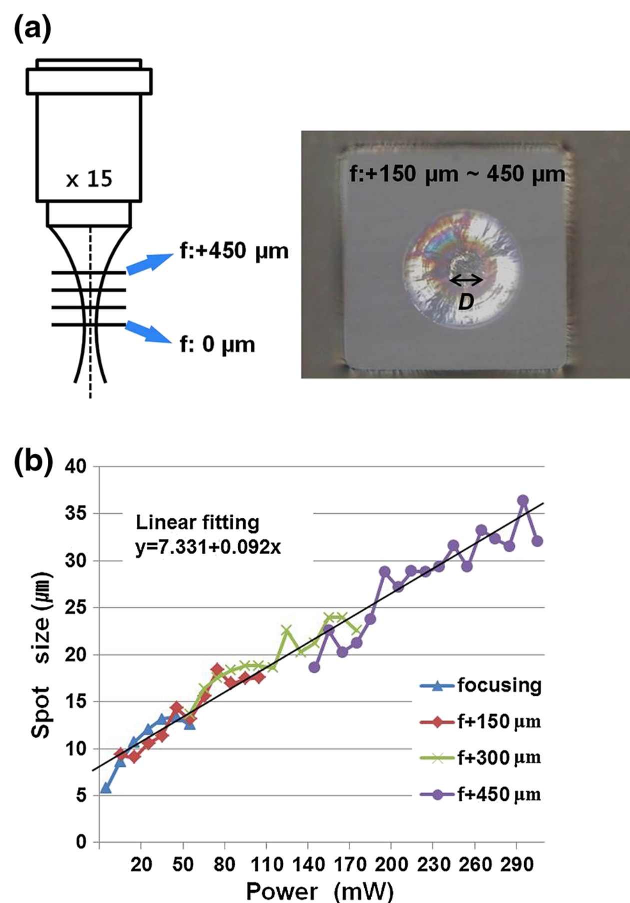

Fig. 2 **a** Sample position and beam size on the GaN surface and **b** spot size as a function of power and defocused length, with an irradiation time of 500 ms

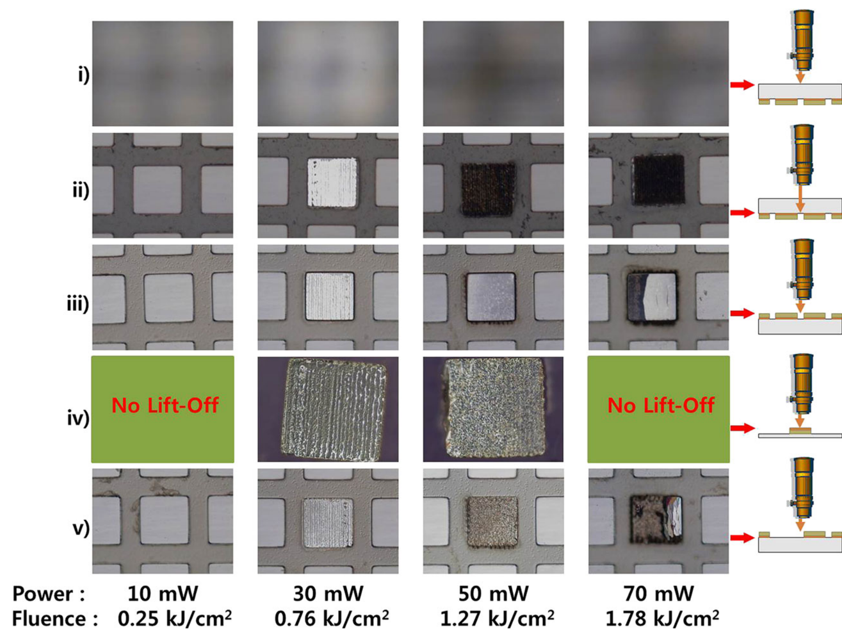

Fig. 3 Images of sapphire surface (*row i*), interfacial layer from sapphire (*row ii*), n-GaN on the sapphire substrate (*row iii*), u-GaN surface on thermal release tape (*row iv*), and the sapphire surface after lift-off (*row v*). In each case, the power varied from 10 to 70 mW (0.25–1.78 kJ/cm^2) at the defocused lengths of 150 µm

Table 1 Lift-off power and fluence for a given sample position

Sample position (µm)	Lift-off power (mW)	Lift-off fluence (kJ/cm^2)
f: +150	—, 30–50, —	—, 0.76–1.27, —
f: +300	—, 90, —, 130, —	—, 2.29, —, 3.31, —
f: +450	—, 130–150, —, 230–310, —	—, 3.31–3.82, —, 5.86–7.89, —

— indicates the power range where no lift-off was observed

Figure 3 shows the microscope images when the sample was irradiated and scanned at the defocused length of 150 µm, with power ranging from 10 to 70 mW which induce the total fluence of 0.25–1.78 kJ/cm^2 because the beam size is calculated to 10 µm. The images in row i) of Fig. 3 correspond to the sapphire surface; no damage was observed. This indicated that the 266-nm ultraviolet (UV) laser beam passed through the sapphire without significant absorption. In row ii), the interfacial layer between the sapphire and the undoped GaN layer through the sapphire is shown. Row iii) shows the n-GaN surface after the sample was turned upside down. A bright metallic silver color appeared at 0.76 kJ/cm^2; the same phenomena have been observed using KrF excimer laser irradiation [4]. Row iv) shows n-GaN on the thermal release tape after LLO, and row v) shows the surface of the undoped GaN on the sapphire substrate. LEDs processed at 0.76 and 1.27 kJ/cm^2 were lifted off. The lift-off results from the other power and fluence regimes are summarized in Table 1. Figure 4 shows the results of lift-off when the sample was placed 450 µm from the focal position of the laser; a cleaner surface was observed at 3.82 kJ/cm^2 than with 6.37 kJ/cm^2. Each fluence was calculated from the power of 150 and 250 mW with the beam size of 23 µm.

Two processing windows, with lower and higher power regimes, were discovered experimentally. To interpret the two regimes, the intensity and fluence were calculated based on the measured power and focal position. The intensity distribution at the focal position was derived from the Gaussian spatial beam profile. Intensity changes along the optical axis can be obtained from the beam propagation, using the measured power P (FWHM) and the beam size which is related to the beam radius at the focal position, the length from the focal position, and the Rayleigh length. The total fluence in case of laser scanning method was derived from the fluence per pulse and overlap pulses for the beam size along in-line and cross-direction.

Figure 5 shows the intensity profile along the z-axis for an average laser power of 150 mW. The intensity rapidly decreases with distance from the focal position. From the experiments, the beam size was determined to be 7.3 µm, which resulted in an intensity of 390 kW/cm^2 at the focal position, and 188, 74, and 37 kW/cm^2 for the defocused lengths of 150, 300, and 450 µm, and the beam size of 10, 16, and 23 µm, respectively.

The intensity with sample position and lift-off power is summarized in Table 2. The two lift-off regimes can be classified according to the intensity. The lower regime is

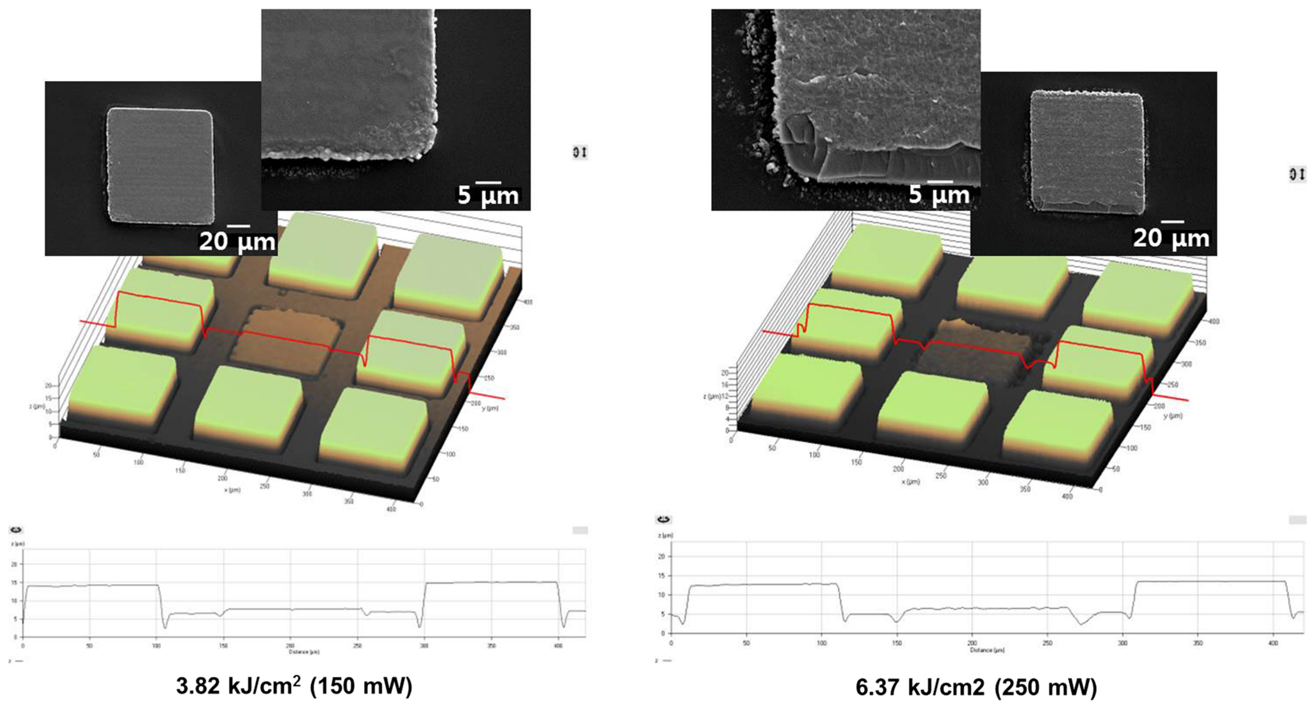

Fig. 4 Images of the GaN surface and profile contour of sapphire the defocused lengths of 450 µm with the fluence of 3.82 kJ/cm^2 (150 mW) and 6.37 kJ/cm^2 (250 mW)

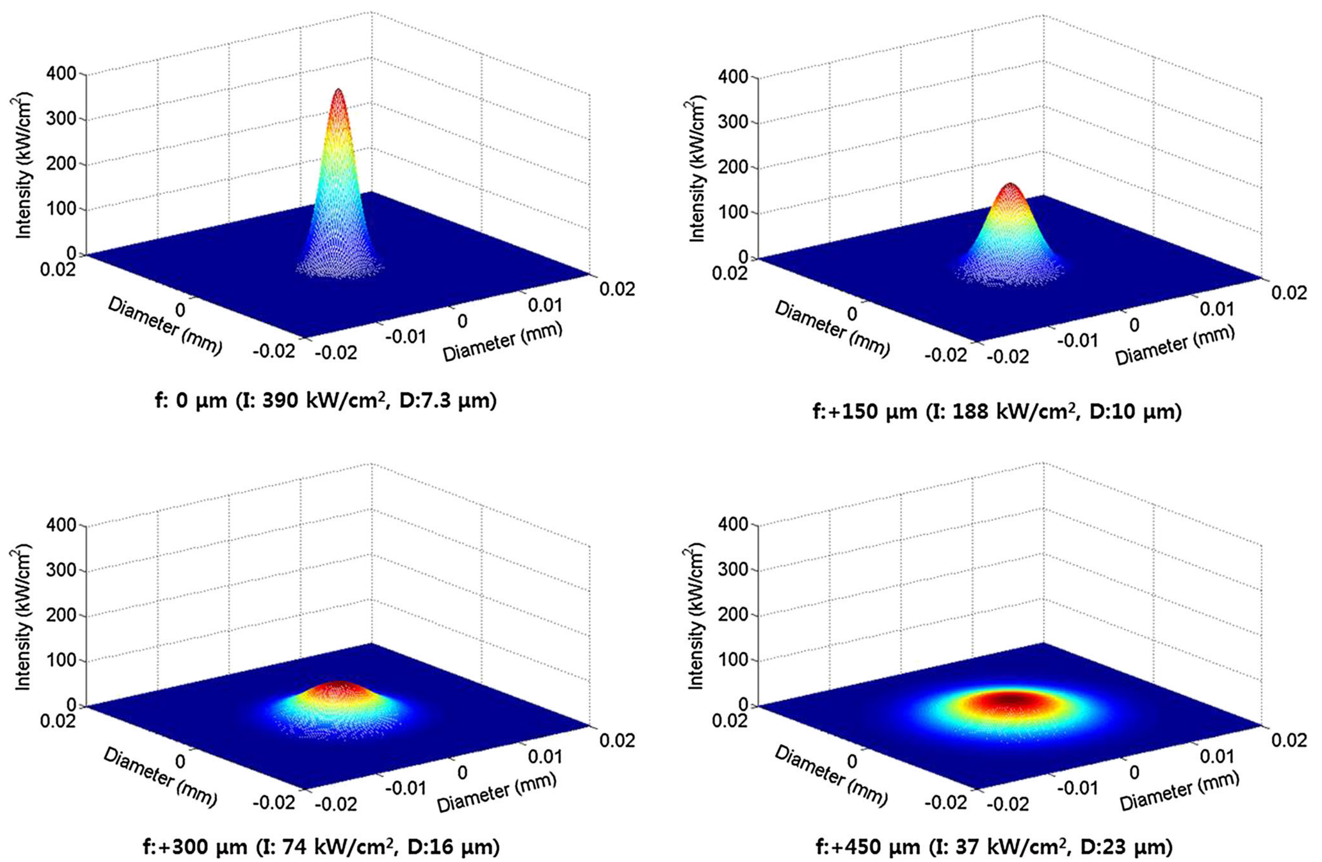

Fig. 5 Intensity distribution changes with respect to the defocused length, with a power of 150 mW and a focal beam size of 7.3 µm

Table 2 Comparison data of intensity with sample position and lift-off power

Sample position (μm)/ beam size (μm)	Lift-off power (mW)	Intensity at sample position (kW/cm^2)
f: +150/10	30	38
	50	63
f: +300/16	90	44
	130	64
f: +450/23	150	37
	250	61

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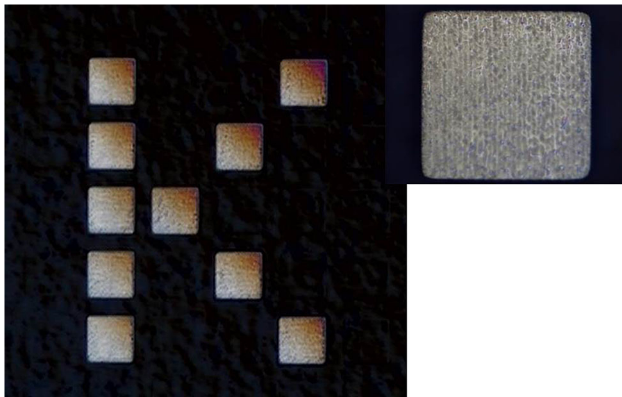

Fig. 6 Light-emitting diodes (LEDs) lifted off selectively onto thermal release tape in the shape of the letter "K"

around 37 kW/cm^2 and the higher 63 kW/cm^2. However, as shown in the optical images in Fig. 3 and SEM images in Fig. 4, the surface quality of the higher regime is worse than that of the lower regime. In the lower power regime, the larger beam size makes the surface quality clean at the same intensity. The smaller beam size in the higher power regime has a sharp beam profile, and the temperature of the surface follows. There are many papers on lift-off conditions, which mostly represent fluence as 0.6–0.9 J/cm^2 for the KrF laser [4, 7, 8] and 0.26 J/cm^2 for the Nd:YAG third-harmonic laser [9]. However, the intensity, rather than the total fluence, contributed most to the lift-off observed in LED cells in the experiments discussed in this paper. That is, an appropriate definite intensity for lift-off exists at any sample position regardless of the total fluence. For example, lift-off occurs with the intensity of around 38 ± 6 kW/cm^2 at any sample position compared to the total fluence of 0.76, 2.29, and 3.31 kJ/cm^2 at the sample position of 150, 300, and 450 μm, respectively.

As we can adjust the beam position by moving the stage in the *xy*-plane to a certain *z* position, a specific GaN cell can easily be lifted off, as shown in Fig. 6. The shape of the image represents the letter "K." Furthermore, after working LEDs were fabricated on a sapphire substrate, single LEDs, transferred to a flexible thermal release tape after lift-off, were confirmed to emit blue light with a current of 4 mA and a voltage of 3.2 V. This is shown in Fig. 7. This provides supporting evidence for the feasibility of selective lift-off using a defocused laser beam and the potential applicability to single LED replacement.

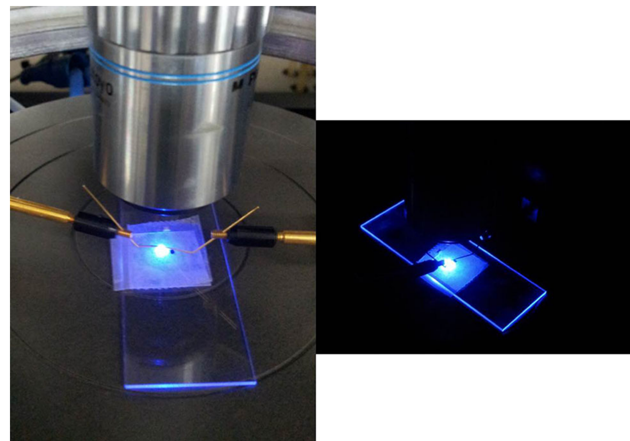

Fig. 7 Single LED on a flexible substrate emitting *blue* light

4 Conclusions

Selective laser lift-off (LLO) of GaN from a sapphire substrate was demonstrated using 266-nm diode-pumped solid-state laser irradiation. The direct scanning technique, which works by moving the samples away from the focal position of the laser, was found to be applicable to the lift-off of single GaN LEDs from sapphire substrates onto flexible thermal release tape. The intensity, in two regimes, played an important role in the lift-off process, regardless of fluence. A large beam size with intensity of about 37 kW/cm^2 provided better quality surfaces than a small beam size. Finally, we demonstrated lift-off of a single LED to a flexible substrate to confirm the feasibility of the technique.

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