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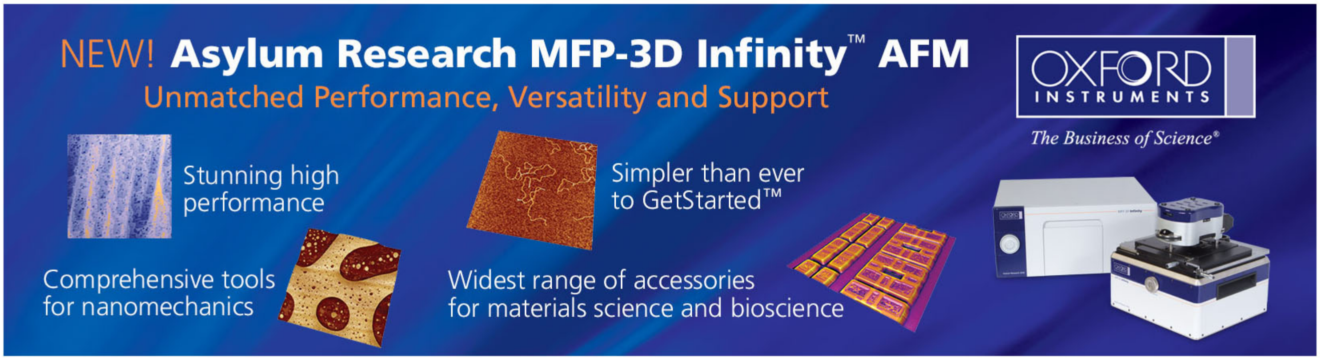
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Effects of laser sources on the reverse-bias leakages of laser lift-off GaN-based light-emitting diodes

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The KrF pulsed excimer laser (248 nm) and the frequency-tripled neodymium doped yttrium aluminum garnet laser (355 nm) have been used to separate GaN thin films from sapphire substrates and transfer to bond other substrate. However, these processes would increase the dislocation density, resulting in an increase of the leakage current. In this study, the effects of these two laser sources on the reverse-bias leakages of InGaN–GaN light-emitting diodes were studied. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2749866]

Despite the lack of a lattice-matched substrate and high defect density, GaN-based light-emitting diodes (LEDs) have improved extremely quickly due to the rapid development of the GaN growth techniques. The current progress may be further extended by combining the GaN-based LEDs with other materials such as Si, Cu, and diamond. A less direct integration method is laser lift-off and transfer to bond dissimilar materials. Several laser sources have been demonstrated to separate GaN thin films from sapphire substrates including the frequency-tripled Nd:YAG (yttrium aluminum garnet) laser (355 nm) (Refs. 1 and 2) and the KrF pulsed excimer laser (248 nm).[3] However, effects of these two laser sources on GaN thin films were never been compared. Therefore, the principal goal of this research has been to investigate the effects of these two laser sources on the reverse-bias leakages of GaN-based LEDs.

Three kinds of LED were investigated in this study. Samples designated as "CV-LED" were conventional LED without any laser treatment. Samples designated as "KrF-LED" were LEDs with KrF pulsed excimer laser treatment, while "YAG-LED" were LEDs with Nd:YAG laser treatment. The basic processes of these LED were almost the same. The InGaN–GaN films were grown by low-pressure metal organic chemical vapor deposition on a sapphire substrate. The LED structures were consisted of a 5-nm-thick Si-doped n^+-InGaN tunnel contact structure, a 0.4-μm-thick Mg-doped GaN layer, an InGaN–GaN multiple quantum well (MQW), a 2-μm-thick Si-doped GaN layer, a 2-μm-thick undoped-GaN layer film, and a buffer layer on a sapphire substrate. The Si-doped n^+-InGaN layer was used to form the Ohmic contact between indium thin oxide (ITO) and p-GaN.[1,4]

For the CV-LED, the device mesa with a chip size of 350×350 μm^2 was then defined by an inductively coupled plasma to remove Mg-doped GaN layer and MQW until the Si-doped GaN layer was exposed. Then, the ITO layer deposited on the n^+-InGaN layer using an e-beam coater to form a p-side contact layer and a current spreading layer. The Cr/Au layer was deposited onto the ITO layer to form the p-side and n-side electrodes.

The fabrication processes of KrF-LED and YAG-LED were shown in Fig. 1. CV-LED wafer was bonded to a host substrate covered with adhesive layer. The sapphire substrate was then removed by laser lift-off process with various energy densities. As shown in Table I, the energy densities of KrF laser were in the range between 700 and 1000 mJ/cm^2, while those of YAG laser were in the range between 100 and 400 mJ/cm^2. The pulse length of KrF laser is 35 ns, which is longer than that of YAG laser (5 ns). As a result, a higher pulse energy of typically 800 mJ/cm^2 is necessary to heat the GaN above the sublimation threshold, whereas pulse en-

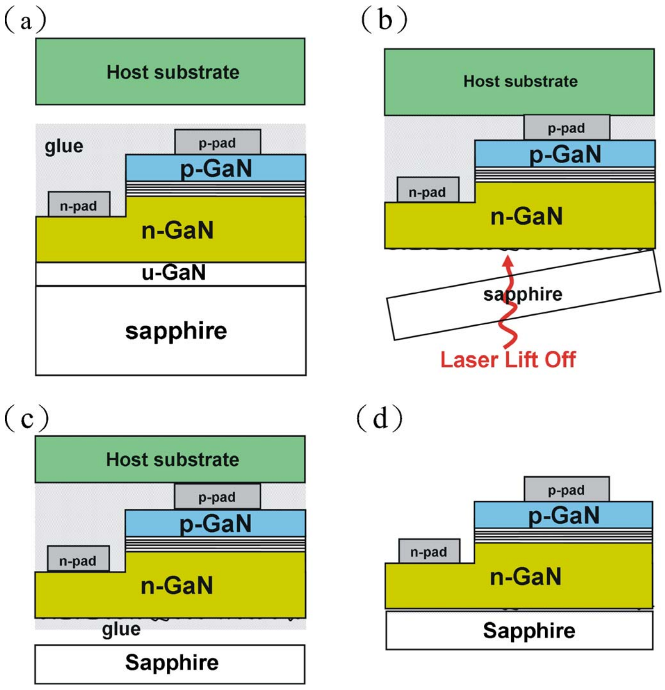

FIG. 1. (Color online) Schematic diagram of the YAG-LED and KrF-LED transfer process: (a) CV-LED bonding to host substrate, (b) laser lift-off process, (c) bonding to sapphire substrate, and (d) removal of host substrate and glue layer.

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TABLE I. Average leakage currents of LEDs under a reverse bias of −5 V.

Laser source	KrF				YAG			
Energy density (mJ/cm^2)	700	800	900	1000	100	200	300	400
Leakage current (nA)	NS[a]	0.17	4.02[b]	6.25×10^{1}[b]	NS[a]	1.65×10^{3}	1.11×10^{6}[b]	1.24×10^{6}[b]

[a] GaN layer not separated.

[b] Most LED devices failed.

ergies of 200 mJ/cm^2 are sufficient in the case of the YAG laser. The Ga residues were subsequently removed by a wet chemical etch using diluted $HCl:H_2O$ (1:1) solution for 60 s. These wafers were then bonded to a sapphire substrate with an adhesive layer that consisted of a polycyclic aromatic hydrocarbon (C_8H_6) composed of a benzene ring fused to a cyclobutene ring. Wafers were annealed at 200 °C for 60 min with a comprehensive load of 10 kg/cm^2. The host substrate and glue layer were subsequently removed. For base line comparison the performance of the CV-LED, sapphire was chosen as the substrate of KrF-LED and YAG-LED. With the same sapphire substrate, we could investigate the influence of various laser lift-off techniques on the performance of the LED chips. The samples described herein were only cut into chips without encapsulation.

The effects of laser energy densities on the macroscopic optical appearance of thin GaN layers on sapphire are shown in Fig. 2. Below a critical intensity (approximately 700 mJ/cm^2 for KrF laser and 100 mJ/cm^2 for YAG laser), no visible alteration of the GaN layer occurs. For higher intensities, however, the absorbed photon energy leads to local heating of the layer above the critical sublimation temperature of Ga, causing the destruction of the GaN. Most LED devices were failed after such high-energy laser treatment. When the YAG-laser energy densities were greater 300 mJ/cm^2, samples were broken into pieces, like that shown in Fig. 2(c). On the other hand, when the KrF-laser energy densities were greater 900 mJ/cm^2, GaN layer was peeled off, like that shown in Figs. 2(d) and 2(e).

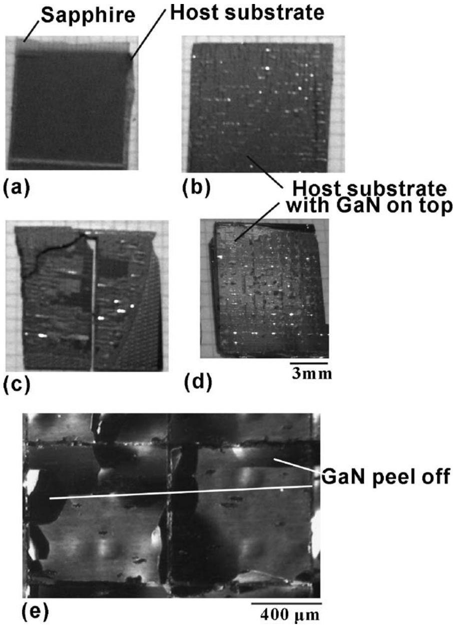

FIG. 2. Images of bonded LEDs after laser lift-off with various laser sources and energy densities. (a) is the YAG laser with 100 mJ/cm^2. (b) is the YAG laser with 200 mJ/cm^2. (c) is the YAG-laser with 300 mJ/cm^2. (d) is the KrF laser with 1000 mJ/cm^2. (e) is the high magnification of Fig. 2(d).

Table I shows the average leakage currents of LEDs under a reverse bias of −5 V. It was found that the measured leakage currents increased with the laser energy densities in both cases. No leakage current data for KrF laser with 700 mJ/cm^2 and YAG laser with 100 mJ/cm^2 because no alteration of the GaN layers occurred. For those high-energy laser treatment devices, the average leakage currents were measured form survived LED devices (most devices failed after high-energy laser treatment). Only those devices with median energy density (approximately 800 mJ/cm^2 for KrF laser and 200 mJ/cm^2 for YAG laser) have good yields (>90%), and were therefore ideal for elucidating the effects of laser sources on the reverse-bias leakages of LEDs.

Under a reverse bias of −5 V, the leakage current of CV-LED was only 0.05 nA. However, the leakage current of YAG-LED was 1.65×10^{3} nA, which was 10 000 times higher than that of the KrF-LED (0.17 nA). These degradations must be caused by the laser lift-off processes, which generated the screw dislocations, which had been demonstrated as the primary culprit in reverse-bias leakage paths in GaN.[5,6]

Transmission electron microscopy (TEM) image with a two-beam condition was used to identify the screw dislocations. Furthermore, the low-loss region of transmission-electron-energy-loss spectroscopy was used to estimate the sample thickness in order to obtain accurate dislocation density. A simple integration was used to compare the area I_0 under the zero-loss peak with the total area I_t under the whole spectrum.[7] The thickness t is given by

$$t=\ln(I_0/I_t)\lambda,$$

where λ is a total mean free path for all inelastic scattering which was estimated to be 72 nm in this work.[7]

Figure 3 shows the TEM images of LEDs. The screw dislocation density of YAG-LED was much higher than that of KrF-LED. The screw dislocation densities were obtained by counting the number of penetrating dislocation, then divided by the thickness and width of sampling regions. In this case, only those dislocations penetrated through MQW region were counted because they could affect the leakage current of LED. The screw dislocation density of YAG-LED was 2.9×10^{9} cm^{-2}, which was ten times higher than that of the KrF-LED (3.75×10^{8} cm^{-2}). Therefore, YAG-LED's leakage current was higher than KrF-LED's.

The variation of two LED's dislocation densities is due to the fact that the absorption coefficient of GaN at 248 nm (for KrF-LED) is 2×10^{5} cm^{-1}, which is 3.33 times higher than that at 355 nm (for YAG-LED) (6×10^{4} cm^{-1}).[8] In other words, the absorption depth of YAG laser was much thicker than that of KrF excimer laser. The absorption of laser energy induces a highly localized, rapid thermal decomposition

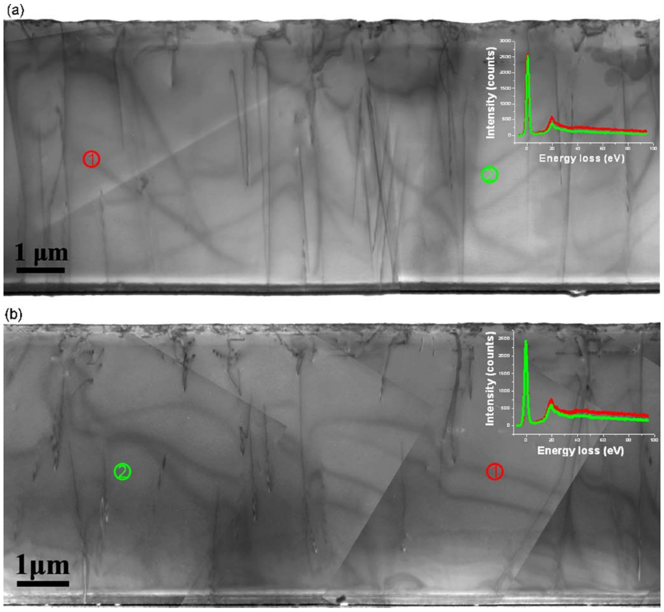

FIG. 3. (Color online) TEM images of (a) YAG-LED and (b) KrF-LED.

of the GaN, and yielding metallic Ga and N_2 gas during the laser lift-off process. Therefore, this decomposition introducing a biaxial compressive stress can cause the deformation (formation of the dislocations) of the GaN as well as delamination of the GaN film from the sapphire substrate. Compare with KrF excimer laser, YAG laser had thicker absorption depth, which cause more formation of the dislocations and resulted in an increased of reverse-bias leakage current.

In summary, effects of the KrF pulsed excimer laser (248 nm) and the frequency-tripled Nd:YAG laser (355 nm) on the reverse-bias leakages of GaN-based LEDs were investigated. It was found that, below a critical energy intensity, no visible alteration of the GaN layer occurs. For higher intensities, the absorbed photon energy leads to local heating of the layer and causes the destruction of the GaN. Only those devices with median energy densities (approximately 800 $\mathrm{mJ/cm^2}$ for KrF laser and 200 $\mathrm{mJ/cm^2}$ for YAG laser) have good yields ($>90\%$). Under a reverse bias of -5 V, the leakage current of YAG-LED was 1.65×10^3 nA, which was 10 000 times higher than that of the KrF-LED (0.17 nA). These degradations were caused by the laser lift-off processes, which generated the screw dislocations. The screw dislocation density (penetrated through MQW region) of YAG-LED was $2.9\times10^9\ \mathrm{cm^{-2}}$, which was ten times higher than that of the KrF-LED ($3.75\times10^8\ \mathrm{cm^{-2}}$). This is because the absorption coefficient of GaN at 248 nm (for KrF-LED) is $2\times10^5\ \mathrm{cm^{-1}}$, which is 3.33 times higher than that at 355 nm (for YAG-LED).

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