Structural Modifications in Free-Standing InGaN/GaN LEDs after Femtosecond Laser Lift-Off [†]

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[†] Presented at the Eurosensors 2018 Conference, Graz, Austria, 9–12 September 2018.

Published: 29 November 2018

Abstract: A laser lift-off (LLO) process has been developed for detaching thin InGaN/GaN lightemitting diodes (LED) from their original sapphire substrates by applying an ultrafast laser. LLO is usually based on intense UV irradiation, which is transmitted through the sapphire substrate and subsequently absorbed at the interface to the epitaxially grown GaN stack. Here, we present a successful implementation of a two-step LLO process with 350 fs short pulses in the green spectral range (520 nm) based on a two-photon absorption mechanism. Cathodo- and electroluminescence experiments have proven the functionality of the LLO-based chips. The impact of radiation on the material quality was analysed with scanning (SEM) and transmission electron microscopy (TEM), revealing structural modifications inside the GaN layer in some cases.

Keywords: GaN; LED; laser lift-off; ultrashort pulse laser

1. Introduction

In recent years, the performance of GaN-based LEDs in terms of output efficiency, brightness and longevity has steadily been advanced, manifesting their importance in all fields of illumination, from general lighting to advanced sensor systems. In commercial LED production, sapphire is usually taken as a low-cost substrate for epitaxial InGaN/GaN heterostructure growth. However, sapphire provides poor electrical and thermal conductivities, limiting its practicability for sophisticated LED architectures. Therefore, a transfer of thin LED dies from the original sapphire substrate to tailored environments, based on e.g., silicon or flexible polyimide, is required. An effective method for detaching the LED stack from the sapphire is LLO, where intense UV light is directed to the backside of the wafer. The light is transmitted through the sapphire, then absorbed in the first GaN layers at the interface, leading to local decomposition [1]. In conventional lift-off processes, high-power laser sources with photon energies above the GaN bandgap of 3.4 eV (corresponding to 365 nm) are utilized, usually excimer lasers (emission wavelength of 248 for KrF and 308 nm for XeCl) or frequency-tripled Nd:YAG lasers (355 nm) with pulse widths in the nanosecond regime and energy densities of several 100 mJ/cm² [2].

In this work, we present an LLO process based on a 520 nm laser source with a pulse width of 350 fs. Even though GaN is not directly absorbing at this wavelength, the provided high pulse

energies cause non-linear two-photon absorption in the semiconductor material. We demonstrate the feasibility to create free-standing LED chips with a size of $1 \times 1 \text{ mm}^2$ in a two-step laser ablation process and have proven chip functionality by cathodo- and electroluminescence measurements.

Although the required energy densities are an order of magnitude higher than for conventional liftoff [2], the mostly non-thermal nature of the material decomposition at the interface may lead to a gentle lift-off. Moreover, extension of the process to UV LED structures is conceivable, as the lift-off is not directly dependent on the band gap of the semiconductor material.

2. Material and Methods

For our experiments, we employed a commercial laser machining system (LMS) from Newport, equipped with a regenerative amplifier containing an Ytterbium doped Potassium Gadolinium Tungstate (Yb:KYW) crystal. The center wavelength is 1040 nm or 520 nm with integrated frequency doubling, respectively. The laser provides a maximum output power of 8 W at 520 nm emission wavelength with a repetition rate of 200 kHz and a pulse length of <400 fs. Unlike with many other lift-off processes presented in literature, the beam profile in our setup is not widened using a beam shaper [2,3]. Instead, the beam is guided through a focusing objective and scanned across the sample by a galvanometer scanner. It works at high velocities up to 2 m/s, enabling quick processing of the surface. The working distance, i.e., the distance between the objective and the sample, can be adapted by a linear positioner, at which the telecentric f -theta objective with $f = 100 \text{ mm}$ is mounted, as shown in Figure 1a. The focused laser spot is somewhat elliptical with different focus positions for the two main axes, where the spot diameter in focus is between 20 and 30 μm (see Figure 1b).

Figure 1. (a) Sketch of the beam path in the LMS, showing the three different possibilities of movement: (1) adjusting of working distance d , (2) beam scanning in x and y -direction by galvanometer scanner, (3) lateral movement of sample stage. (b) Beam characteristics, revealing different focus positions and beam diameters for the two main axes of the elliptical beam profile.

The LED structures for lift-off experiments were fabricated in-house in the epitaxy competence center (ec²) by metalorganic vapour phase epitaxy (MOVPE). On 430 μm thick double-side polished sapphire substrates, the 5 μm thick LED structures with an InGaN/GaN multi quantum well (MQW) were grown. Prior to lift-off, no additional treatment was executed.

To create free-standing GaN LEDs, we applied a two-step recipe as shown in Figure 2. In both steps, the wafer was placed with sapphire side up on the sample stage. At first, an outer quadratic frame around the to-be-lifted LED chip was removed by applying high power pulses (1.5 W, 30 J/cm²) as depicted in Figure 2b. Afterwards, the detachment of the inner LED-chip from the sapphire substrate was conducted with less power (500 mW, 9 J/cm²). In contrast to the first step, the pulse energy is mainly absorbed at the interface, resulting in a controlled detachment of the LED chip. Both processing steps were conducted at a working distance that is well out of focus with a laser spot of $\sim 50 \mu\text{m}$ in diameter. The distance between two impinging pulses on the surface, following a quadratic pattern (see Figure 2d), was set to be 5 μm . Thus, a homogenous energy distribution is ensured.

Figure 2. Sketch of the two-step laser lift-off process. (a) Initial GaN LED wafer with sapphire on top side, (b) selection of a free-standing LED chip area by removing an outer frame at high laser power, (c) lift-off of inner LED chip with less laser power, (d) applied scanning pattern, where each green dot marks the position of an impinging laser pulse.

3. Results and Discussion

3.1. Creation of Free-Standing GaN LED Chips

In Figure 3a, an SEM image of a lifted, free-standing LED chip is depicted. For SEM analysis, the chip was mounted on a conductive carbon pad. It can be seen that the thin LED layer is free of cracks. In Figure 3b, the *n*-GaN surface, i.e., the original interface to the sapphire, is shown with higher magnification. The lift-off process leads to a rather rough interface in comparison to the *p*-GaN surface (Figure 4). In cathodoluminescence measurements, a broad emission peak at 430 nm appears (Figure 3c), which corresponds to the emission wavelength of the InGaN/GaN LED before lift-off.

Figure 3. SEM images of a lifted LED chip, applying the 520 nm femtosecond laser. (a) Crack-free substrateless LED with 1 × 1 mm in size, (b) closer view on the *n*-GaN surface of another sample where the crack occurred during mounting of the structure onto a carbon pad, (c) cathodoluminescence spectrum clearly revealing the quantum well emission around 430 nm.

Figure 4. Laser induced holes on the *p*-GaN side after laser treatment. (a) Overview picture, showing three laserinduced holes, (b) close-up cross-sectional view of a hole under 30° tilt, which has a depth of several 100 nm, meaning that the *p*-GaN layer and the multi quantum well are locally destroyed. (c) TEM image revealing a local accumulation of threading dislocations underneath the hole.

3.2. Laser Induced Damage during Lift-Off

Closer SEM investigations of the *p*-GaN side of the lifted LED chips revealed that in some cases laser induced damage appears. An observed phenomenon is the creation of small holes as depicted in Figure 4. Their diameters are typically $<1\ \mu\text{m}$, hence much smaller than the diameter of the laser spot (Figure 4b). From the TEM image (see Figure 4c), the depth of the holes can be quantified to several 100 nm, meaning that the *p*-GaN and the MQW are locally destroyed. On the bottom of the hole, ripple-like structures appear (Figure 4c), which are typical for semiconductor surfaces after treatment with intense laser radiation [4].

The allocation of the holes is not related to the laser pulse pattern, as the positions of the three holes in Figure 4a imply. Densities of the holes range from 10^4 to $10^8\ \text{cm}^{-2}$, depending on the laser power. We assume that the mechanism of hole formation is somehow connected to locally increased energy deposition in the crystal, enhanced by previously existing defects. The TEM image in Figure 4c reveals a strong accumulation of dislocations underneath a hole. Most probably, these are threading dislocations, which run out of the tapered TEM lamella [5]. To what extent this accumulation was also triggered by the lift-off process or existed beforehand remains open at this point. Thus, further investigation and experiments will be conducted for a better understanding of this phenomenon.

4. Conclusions

Selective laser lift-off (LLO) of GaN-based LEDs from their sapphire substrates by applying a fs laser source with 520 nm emission wavelength has been demonstrated. The absorption process is based on non-linear two-photon absorption. Free-standing LED pieces with proven functionality and size of up to $1 \times 1\ \text{mm}^2$ could be lifted.

Characterization results by means of SEM and TEM indicate a strong impact of the laser radiation not only on the interface where ablation takes place, but also on the bulk material of the LED stack. As several other studies reveal, an increase in defect density is commonly observed with laser lift-off, though often only slightly influencing LED performance [6]. To what extent laser treatment affects LED quality in case of the presented femtosecond laser lift-off and how it compares to existing laser lift-off strategies needs to be further investigated.

Author Contributions: S.B. and N.Y. designed and conducted the experiments; C.M. grew the samples; T.M. performed TEM measurements; J.G. assisted during data acquisition; H.S.W., A.W. and M.S. had a supervisory role; S.B. wrote the paper; H.S.W. revised and provided inputs for writing improvement; All authors read and agreed on the written paper.

Acknowledgments: This work has been partially performed within LENA-OptoSense funded by the Lower Saxony Ministry for Science and Culture (N-MWK), European project of ChipScope funded by the European Union's Horizon 2020 research and innovation program under grant agreement no. 737089, and the joint collaboration of Epitaxy Competence Center (ec²), funded by Osram Opto Semiconductors GmbH. T.M and M.S. acknowledge funding by the German Research Foundation (DFG), project SE560-6/1.

Conflicts of Interest: The authors declare no conflict of interest.

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