Laser slicing: a thin film lift-off method for GaN-on-GaN technology

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A femtosecond laser focused inside bulk GaN was used to slice a thin GaN film with an epitaxial device structure from a bulk GaN substrate. The demonstrated laser slicing lift-off process did not require any special release layers in the epitaxial structure. GaN film with a thickness of 5 µm and an InGaN LED epitaxial device structure was lifted off a GaN substrate and transferred onto a copper substrate. The electroluminescence of the LED chip after the laser slicing lift-off was demonstrated.

Keywords: laser slicing; lift-off; InGaN LED; GaN-on-GaN

Bulk GaN substrate is a crucial element in the production of reliable, high-current density GaN-based devices. However, the widespread use of GaN substrates is currently limited due to their high cost. Separation of the epitaxial device structure from the bulk GaN substrate allows the reuse of the expensive substrate multiple times and thus reduces the effective cost. Also, the separation of the epitaxial structure is necessary to create heterogeneously integrated devices [1–3], as well as to improve heat dissipation [2, 4] and light extraction [5].

To lift-off GaN films from foreign substrates multiple methods were developed: laser lift-off [6]; natural stress-induced separation [7, 8]; controlled spallation [9]; chemical etching of ZnO [10], GeO2 [11], CrN [12], AlN [13] and Nb2N [14] sacrificial layers; doping-selective electrochemical etching [15]; substrate removal by grinding or etching [16–19]; void-assisted separation [20]; growth over patterned masks [21–24]; the use of weakly bonded release layers like graphene [25, 26], BN [27], carbon [28]; and the use of substrates with easy cleavage along the c-plane of a GaN epilayer [28, 29].

To separate a GaN film from a native GaN substrate several approaches were proposed: chemical lift-off process [30]; porous release layers created by chemical [31], electrochemical [32, 33] or dry [34] etching of GaN substrate; controlled spalling [35]; laser lift-off with an InGaN release layer [36]; ion implantation [37, 38]; and free-carrier-absorption laser lift-off [39].

The lift-off methods based on the use of intermediate layer require a complicated epitaxy process. The ion implantation method does not allow separating epitaxial device structures due to a large number of point defects formed by the implantation process [38, 39, 41]. The free-carrier-absorption LLO method is limited to separating undoped films from a heavily doped substrate [40].

We have proposed a laser slicing lift-off (LSLO) method for separating an epitaxial structure from a bulk GaN substrate, one that does not require any special release layers and can be used both for lifting off pure GaN films and for lifting off GaN films with device structure [42]. The method is based on the effect of GaN decomposition induced by an ultra-short laser pulse focused inside a bulk GaN material. The use of femtosecond lasers is preferable as it allows to reduce the heat-affected zone and the corresponding damage in the surrounding material [43]. This effect was earlier used to create hollow 3D-channels inside bulk GaN [44] and to dice transparent wafers with laser stealth dicing technology [45].

The principle of the LSLO method is as follows. To lift-off a thin GaN film with an InGaN multiple quantum well (MQW) device structure from a bulk GaN substrate, the pulses of a near-infrared femtosecond laser are focused inside the GaN layer, several microns under the surface (fig. 1). The laser photon energy is less than the InGaN bandgap, so both the InGaN device structure and the GaN substrate are transparent at the wavelength of the laser. The laser pulse energy is adjusted so that the non-linear breakdown threshold is exceeded only in the focus area and the GaN material in this area is decomposed. Scanning of the focus position is performed in the X-Y-plane until a continuous layer of decomposed material is created inside the wafer.

In this work, a proof-of-concept LED chip fabrication using the LSLO method is described. First, a 5-µm thick GaN film with an InGaN LED structure was grown homoepitaxially on a bulk GaN layer. After that, the film with the LED structure was lift-off from the substrate and transferred to a copper carrier (fig. 2). The electroluminescence of the LED chip after the lift-off was demonstrated. A detailed study of the LED chip for possible damage caused by the LSLO process will be published separately.

A GaN-on-sapphire HVPE template was employed as a bulk-like substrate for the InGaN LED structure epitaxy. The template was grown on a 2-inch c-plane (0001) sapphire substrate using a two-stage growth process [46]. The thickness of the bulk-like HVPE GaN layer was 50 µm. The surface of the HVPE GaN template was epitopolished by a chemical-mechanical polishing process. After that, the InGaN MQW LED structure was deposited using a metal-organic chemical vapor deposition system. The LED structure consisted of a 5-µm thick n⁺ doped GaN:Si (n=4·10^18 cm⁻³) layer; five pairs of InGaN quan-
Figure 1. Experimental setup for the laser slicing lift-off process: a beam of Yb-doped femtosecond laser with a pulse width of 350 fs and a pulse energy of 0.24 µJ is focused inside a GaN wafer, 6 µm below the surface. The decomposition of GaN takes place in the focus area of the laser beam. The wafer is scanned in the X-Y plane until a continuous layer of decomposed material is created inside the wafer.

Figure 2. Schematic diagram of thin-film InGaN LED chip fabrication using the laser slicing lift-off process.
Figure 3. a) A photograph of the InGaN LED chip on a copper substrate with a current probe connected, electroluminescence at 1 mA operating current. The inset shows a microphotograph of the Ga-face of the chip after the LSLO process. b) SEM image of the Ga-face of the chip after the LSLO process. c) SEM image of the N-face of the chip after the LSLO process.

layers. The light emitting image of the LED chip on a copper substrate is shown in fig. 3(a). The operating current was 1 mA. Blue-light emission was observed under the probe, confirming that the MQW LED structure was not destroyed during the LSLO process. A detailed study of the I-V characteristics and the electroluminescence spectrum, as well as a detailed comparison of the LED performance before and after the LSLO process will be published separately.

The SEM image of the top side (Ga-face) of the LED chip after the LSLO process is shown in fig. 3(b). No signs of damage caused by the LSLO were observed on the surface. The SEM image of the bottom side (nitrogen-face) of the LED chip after LSLO and debonding is shown in fig. 3(c). The remains of the decomposed layer were observed. The surface roughness of the bottom side of the chip was estimated using a tilted-view SEM image (not shown) to be about 1 µm, which corresponds to the focus depth of the laser beam. The thickness of the separated film was measured using a side-view SEM image (not shown) and was 5 µm, which corresponds to the position of the focus below the surface.

Following is a brief discussion of the technological limits and possible improvements of the method. The maximum thickness of the lifted-off layer is limited by the defocusing of the laser beam caused by spherical aberration and optical inhomogeneity of the material. Recent advances in the growth of pure GaN [47] make it possible to obtain an optically homogeneous material, and the adaptive optics techniques can compensate for spherical aberration when focusing to a depth of hundreds of microns [48]. The minimum thickness of the decomposed layer is limited by the depth of focus of the laser beam, which can be reduced by the use of high-numerical-aperture objectives, such as solid immersion lenses [49]. Processing throughput is mainly limited by the scanning speed, therefore the use of parallel multi-beam machining methods [50, 51] is highly desirable. Wafers with already deposited metallization layers can also be processed. For this, the focused laser beam is directed from the underside of the wafer. Other materials that decompose irreversibly under the action of laser breakdown can also be processed. The greatest practical interest of such materials is diamond, which is graphitized by laser breakdown [52].

In conclusion, a 5-µm thick GaN film with the InGaN LED MQW structure was lifted off from the bulk GaN layer by focusing near-infrared femtosecond laser pulses 6 µm under the surface of the GaN wafer. The film was transferred to a copper carrier and the electroluminescence of the LED structure was demonstrated.

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