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Liquid-immersion laser micromachining of GaN trenches and its application in device fabrication

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Trench formation for device isolation on GaN light-emitting diode (LED) wafer via nanosecond pulsed laser micromachining in deionized (DI) water is demonstrated. The basis of this technique relies on the large difference between the ablation thresholds of GaN and sapphire, so that the ablation can automatically terminate at the GaN/sapphire interface to produce a smooth and tapered trench. Compared with micromachining in ambient air, re-deposition and re-solidification of ablated material on the sidewalls are found to be greatly reduced in DI water. In addition, liquid immersion admits a larger focus offset tolerance and a better control of the trench width through adjustment of pulse energy. As an application in rapid device prototyping, a 5 × 7 dot-matrix microdisplay with laser-micromachined trenches for pixel separation is demonstrated, illustrating the effectiveness of this processing technique.

1 Introduction The typical epitaxial structure of GaN-based light-emitting diode (LED) wafer consists of p-GaN, InGaN/GaN multi-quantum well (MQW), n-GaN and sapphire layers. By selectively removing certain regions of the GaN layers, on-chip LEDs that are electrically isolated from each other can be fabricated on top of the insulating sapphire substrate. Since GaN is a hard and stable material, etching techniques that combine ion bombardment with chemical processes are usually employed. Currently, inductively coupled plasma (ICP) etching is the prevalent technique for this purpose. Although an appreciable etch rate of 1 μm/min can be achieved [1], etch selectivity poses a limitation to the thickness of GaN that can be removed by ICP. Although hard masks such as SiO_2 and Ni masks can be used to achieve a higher etch selectivities [2], strong acids are often required to remove the remaining masking layer after ICP etching. This might not be possible when the material under the hard mask is also reactive towards the acids.

In view of this, we previously introduced a direct-write nanosecond-pulsed laser micromachining technique for the formation of trenches in GaN-on-sapphire wafer [3]. The principle is based on the large difference between the ablation thresholds of GaN and sapphire. According to two previous studies, the ablation thresholds of GaN and sapphire are 0.25 J/cm^2 [4] and 4.5 J/cm^2 [5] respectively. By setting the laser fluence between these two ablation thresholds, GaN will be removed by laser ablation while sapphire can be left intact. The control of laser fluence can be achieved by shifting the wafer away from the best focus plane (termed as focus offset), so that the laser spot size is altered. This idea is illustrated in Fig. 1. GaN trenches can be generated by placing the wafer at the optimal focus offset position and scanning the laser beam across the wafer. Our technique is particularly useful for the rapid prototyping of GaN devices [6].

In order to ensure that interconnects run conformally across the trenches, re-deposition and re-solidification of ablated material on the sidewall and bottom surface have to be minimized. However, this is not easy to achieve even at the optimal focus offset. In our previous study, it is found that re-deposition could be minimized by high pulse repetition rates [3]. However, increasing pulse repetition rate could also reduce the adjustable range of pulse energy (given the same range of pump current). This is not desirable since pulse energy can be used to control the trench width (to be detailed in Section 3).

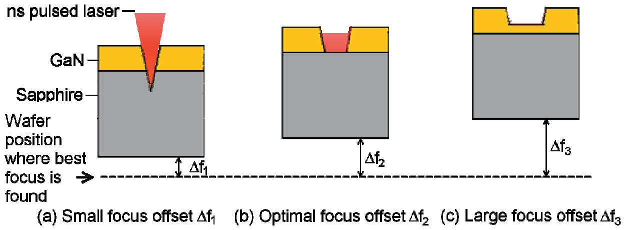

Figure 1 Principle of laser micromachining of trenches on GaN/sapphire material.

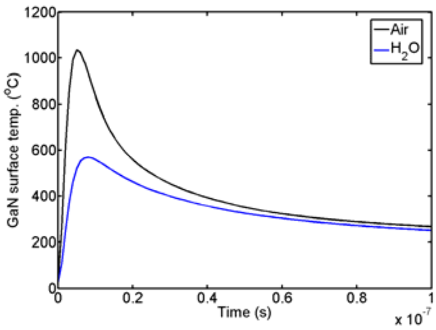

Figure 2 Temperature variation against time at the trench edge, where the beam is assumed to be Gaussian with a pulse energy of 25 µJ, a spot radius of 20 µm and a wavelength of 349 nm.

In this study, we propose a change of the ambient medium from air to liquid. This approach not only reduces redeposition, but also offers several advantages to the process tolerance. Deionized (DI) water was chosen as our preliminary object of study due to the following reasons. First, liquid water is weakly absorbing in the near-UV and visible regions [7]. This property not only allows us to observe the micromachining process easily by a visible light source and a CCD camera, but also allows the energy from the UV laser to be transferred efficiently to the sample surface. Secondly, liquid water has a relatively high specific heat capacity (4.18 J/(g K) at 25°C, comparing with 2.44 J/(g K) for ethanol and 1.012 J/(g K) for air at 23 °C). The heat generated during the laser micromachining process can be dissipated quickly into the water without causing a large temperature rise. The size of heat affected zone (HAZ) is minimized, resulting in an improvement in the trench quality. The simulated temperature variation against time around the trench edge can illustrate this point, where the maximum temperature reached in air is much higher than that in DI water (Fig. 2).

2 Experiments Liquid-immersion laser micromachining was performed with the optical setup shown in Fig. 3. It was similar to that detailed in [3], except that the sample was immersed in a DI water bath where the meniscus was ~1mm above the sample surface. The water bath was placed on a motorized XY translation stage, where a nanosecond pulsed laser beam (λ = 349 nm) was focused on top by a UV focusing lens (f = 19 mm). Focus offset was achieved by adjusting the level of the Z translation stage.

3 Results and discussions Liquid-immersion laser micromachining significantly reduces the amount of stalagmite-like structures over the trench sidewalls and improves the smoothness of the bottom surfaces. This is demonstrated from the atomic force microscope (AFM) scans of two trenches which were laser-micromachined under the same conditions, except for different ambient media (Fig. 4). The sidewall roughness R_a for the trench micromachined in ambient air is 312 nm, contrasting sharply with 27.65 nm for the trench produced in DI water. The rms roughness of the bottom surfaces also reveals the superiority of liquid immersion (87.49 nm for air vs. 13.42 nm for DI water).

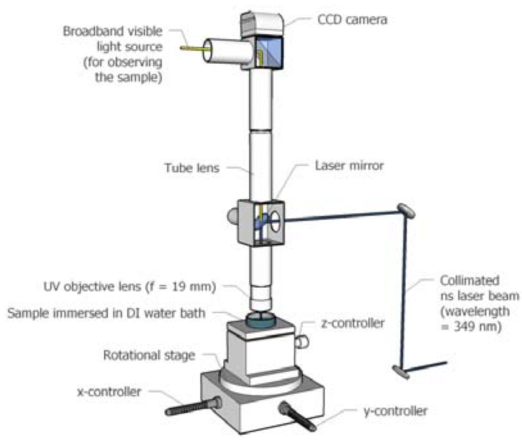

Figure 3 Experimental setup for liquid-immersion laser micromachining.

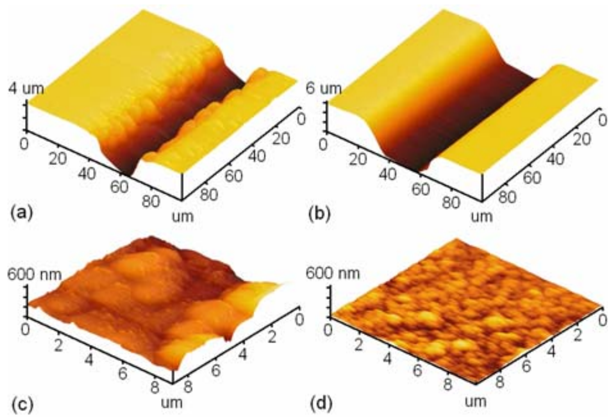

Figure 4 AFM images of trenches that are generated in: (a) and (c) air; (b) and (d) DI water. (c) and (d) Zoomed images of the bottom surfaces.

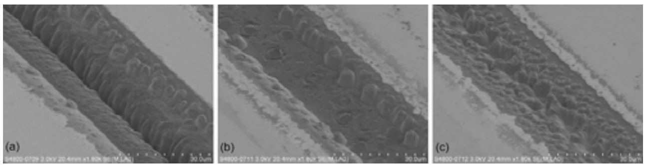

Figure 5 SEM images of trenches laser-micromachined at different focus offset planes in ambient air: (a) 300 μm; (b) 450 μm; (c) 600 μm, where 450 μm is the optimal focus offset.

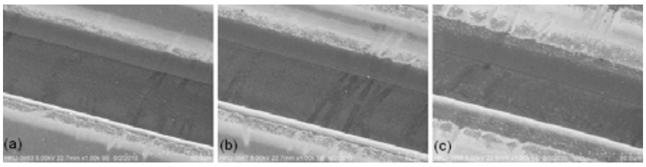

Figure 6 SEM images of trenches laser-micromachined at different focus offset planes in ambient DI water: (a) 550 μm; (b) 700 μm; (c) 950 μm. Smooth trenches were generated in all three cases.

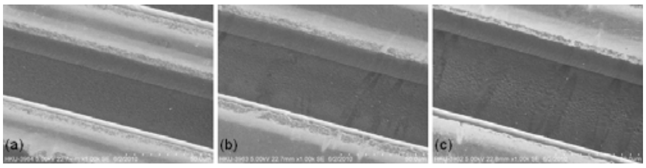

Figure 7 SEM images of trenches laser-micromachined at the same focus offset plane but with different pulse energies in ambient DI water: (a) 25-26 μJ; (b) 52-54 μJ; (c) 79-81 μJ.

Besides improved surface quality, liquid-immersion laser micromachining also offers several advantages over process control. The first one is the increased focus offset tolerance. For micromachining in ambient air, when the focus offset deviates from the optimal value by a few tens of microns (+/- 150 μm in our experiment), either damage to the sapphire layer (Fig. 5(a)) or incomplete ablation of GaN (Fig. 5(c)) will be resulted. For micromachining in DI water, a large focus offset deviation is allowed (as large as +/-200 μm in Fig. 6), albeit a slight decrease in the trench width. There is no obvious degradation in the trench quality. The second advantage of liquid immersion is a better control over the trench width by pulse energy. When the pulse energy is increased, HAZ will be enlarged, causing the trench to be widened. For micromachining in ambient air, it is difficult to control the trench width just by altering the pulse energy. It is often necessary to search for a new value of optimal focus offset in order to produce acceptable trenches again. However, owing to the enhanced focus offset tolerance of liquid-immersion laser micromachining, even the focus offset is not optimal for the new pulse energy, smooth trenches can still be generated. This is illustrated in Fig. 7(a)-(c), where the trench widths were measured as 41.7 μm, 52.1 μm and 69 μm, respectively.

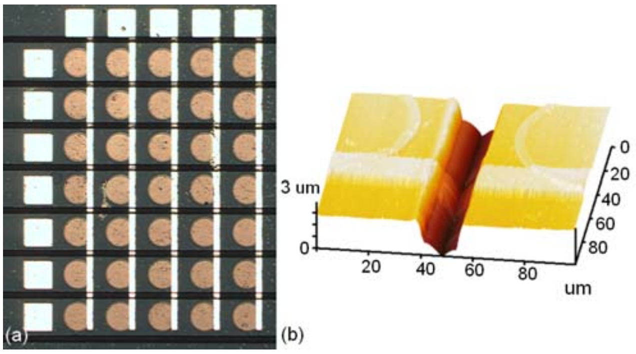

Figure 8 (a) 5 × 7 dot matrix microdisplay with trenches from liquid-immersion laser micromachining to separate each row of circular pixels. (b) AFM scan of a trench.

As an application of this technique, a 5 × 7 dot matrix LED microdisplay was demonstrated in Fig. 8(a). Rows of circular LED pixels are electrically isolated between trenches which have been formed by liquid-immersion laser-micromachining. They are then passivated by SiO_2 layer and interconnected by Ti/Al layer. The AFM scan in Fig. 8(b) shows how the interconnect runs conformally across one of the trenches, testifying to the smoothness of the sidewalls.

4 Summary The characteristics of liquid-immersion laser micromachining of GaN trenches have been investigated. Comparing with ambient air, immersion in DI water can help to reduce re-deposition, increase the focus offset tolerance and control trench width by pulse energy. This technique has been successfully applied to the fabrication of dot matrix microdisplay.

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