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Deep etch of GaN by laser micromachining

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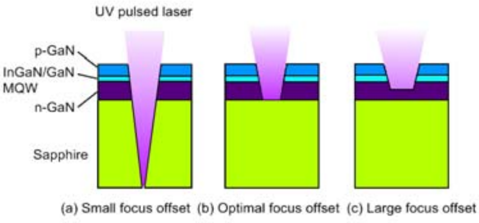
Trench formation for device isolation on GaN light-emitting diode (LED) wafers via nanosecond ultraviolet laser micromachining is demonstrated. Owing to the dissimilar ablation thresholds between GaN and sapphire, the etch process terminates automatically at the GaN/sapphire interface. It was found that optimal focus offset, optimal pulse energy and high repetition rate are essential for obtaining a trench with tapered sidewall and smooth bottom surface, which is suitable for the conformal deposition of interconnects across the trench. This technique has been successfully applied to the rapid prototyping of interconnected LED arrays on a single chip.

1 Introduction Gallium nitride (GaN) has been widely adopted for fabricating optoelectronic and electronic devices. Despite the lattice mismatch, GaN is often grown as an epitaxial layer on sapphire substrates [1]. In order to fabricate an integrated circuit on the same GaN LED wafer, selective-area complete removal of GaN is an indispensable process step. As GaN is highly resistant to wet etch, dry etch technique, such as inductively coupled plasma (ICP) etch, is the conventional technique for the removal of GaN. Although ICP etch offers an attractive etch rate of up to 1 μm/min [2], etch selectivity poses a limit to the effectiveness in creating high-aspect-ratio features. Typically, with photoresist as an etch mask, the highest etch selectivity that can be achieved is about 1:1 [3]. As the typical thickness of a complete LED structure (comprising p-GaN, InGaN/GaN multi-quantum wells (MQWs) and n-GaN layers) is 3 to 4 μm, a layer of photoresist of equal thickness has to be spin-coated. Nevertheless, handling of thick photoresist layers is often cumbersome (such as edge bead effects [4]), coupled with the fact that thicker photoresists generally offer lower resolutions. Therefore, it is desirable to develop a maskless direct-write deep etch technique for overcoming the above-mentioned problems.

In this paper, we introduce an ultraviolet (UV) nanosecond (ns) laser micromachining technique for the formation of deep trenches in GaN films, suitable for device isolation on GaN LED wafers. The basis of this technique lies on the large difference between the ablation thresholds of GaN and sapphire. According to the findings of two previously published papers, the ablation threshold of GaN is 0.25 J/cm^2 [5], whereas that of sapphire is 4.5 J/cm^2 [6], due to their large difference in absorption coefficient at UV wavelengths. If the laser fluence (pulse energy divided by irradiated area) can be controlled to a level between these two ablation thresholds, the GaN layer will be ablated while the sapphire substrate is left intact.



(a) Small focus offset (b) Optimal focus offset (c) Large focus offset

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

Figure 1 illustrates how such control of laser fluence can be achieved through focus offset adjustment. Near the best focus, the laser energy is concentrated into a tiny spot, so that the laser fluence is high enough to cut through both the GaN and sapphire layers. This is the mode of operation for LED die separation (Fig. 1(a)). As the sample is translated vertically to attain a larger focus offset, the laser spot on the sample surface is enlarged and the laser fluence is reduced. Upon careful adjustment, a range of focus offset planes can be found such that the laser fluence is just sufficient to ablate GaN but not sapphire. This “auto-stop” mechanism allows trenches with tapered sidewall and flat bottom surface to be formed (Fig. 1(b)), with controllable trench width. If the focus offset is further increased, the laser fluence will not be sufficient for ablating the whole layer of GaN (Fig. 1(c)).

In our experiments, focus offset, pulse energy and pulse repetition rate were varied in order to optimize the trench quality. By enclosing a region with laser micromachined trenches, GaN mesa structures can thus be formed. This technique is suitable for the rapid prototyping of devices [7], whereby only a small area needs to be processed each time.

2 Experimental details

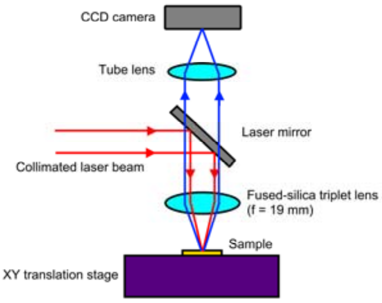


Figure 2 Schematic diagram of the laser micromachining setup.

A schematic diagram of the laser micromachining setup is shown in Fig. 2. A third-harmonic neodymium-doped yttrium lithium fluoride diode-pumped solid-state laser (Spectra Physics) was used as the laser source. The centre wavelength is 349 nm and the pulse repetition rate can range from single pulse to 5 kHz. The nominal pulse duration is 4 ns, while the pulse energy (of the order of µJ) can be varied by changing the diode pumping current. The expanded and collimated beam was guided by several laser mirrors and focused onto a piece of GaN LED sample (emission wavelength = 470 nm, thickness of GaN layer ~ 3 µm) placed horizontally on an x-y motorized stage. The fused-silica focusing triplet lens allows UV and visible light to pass through and has a focal length of 19 mm. As the stage translates while keeping the laser spot stationary, trenches can be scribed onto the sample. The scan speed is controlled by software with a precision up to 25 µm/s. In order to shift the sample away from the focal point, the stage height can be manually adjusted relative to the best focus position. The precision of height adjustment is 10 µm. A charge-coupled device (CCD) camera was installed confocal to the optical path for real-time observation of the micromachining process.

One of the side-effects of laser ablation is the formation of sedimentary by-products on the surface of GaN [8]. These substances were effectively removed by sonifying the sample in dilute hydrochloric acid (HCl) (18% by mass) for 15 minutes. The scanning electron microscope (SEM) images were acquired using a Hitachi S4800 SEM system.

3 Results and discussion

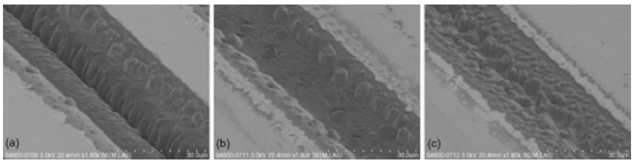


Figure 3 SEM images of trenches laser micromachined at different focus offset planes: (a) -300 µm; (b) -450 µm; and (c) -600 µm. The pulse energy, pulse repetition rate and scan speed are fixed at ~23 µJ, 1 kHz and 25 µm/s respectively.

Figures 3(a) to (c) show SEM images of micromachined trenches at three different focus offset levels while keeping the pulse energy and repetition rate constant. The focus offset level is defined as the distance shifted away from the focal plane. In Fig. 3(a) where the sample is positioned near the focal plane (-300 µm from focal plane), the laser beam ablates both the GaN and sapphire layers. A V-shaped valley is formed in the sapphire layer due to the Gaussian beam shape. Although trenches like these serve the purpose of electrical isolation between adjacent devices, the deep V-shaped valley is not suitable for the subsequent deposition of metal interconnect across the trench. The metal interconnect will become discontinuous at the sharp corners of the valleys. At the optimal focal offset plane of -450 µm as shown in Fig. 3(b), the ablation terminates automatically at the GaN/sapphire interface as the laser fluence drops below the ablation threshold value for sapphire, resulting in a flat and smooth sapphire bottom surface being exposed. At a larger focus offset plane of -600 µm, the GaN layer is not completely removed, leaving a shallow and rugged trench on the surface (Fig. 3(c)).

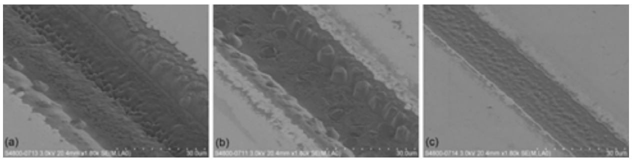


Figure 4 SEM images of trenches under different pulse energy: (a) 45 µJ; (b) 23 µJ; and (c) 7 µJ. The focus offset level, pulse repetition rate and scan speed are fixed at -450 µm, 1 kHz and 25 µm/s respectively.

The SEM images in Figs. 4(a) to (c) illustrate laser micromachined trenches processed at three different pulse energies of between 7 to 45 µJ, while keeping all other parameters constant. The focus offset is kept at the optimal value of -450 µm as determined from the previous set of experiments. When the pulse energy is set too high, the effect is similar to that of having a small focus offset, whereby the GaN as well as sapphire are ablated to form a V-shaped trench (Fig. 4(a)). Similar correspondence between low pulse energy and large focus offset can be observed in Fig. 4(c).

In fact, the laser spot diameter required for the complete removal of GaN without damaging sapphire can be estimated theoretically. Assuming that the average pulse energy applied is 23.5 μJ and the ablation thresholds of GaN and sapphire are the values given in Section 1, the laser fluence F J/cm^2 has to satisfy the following condition: $0.25 < F < 4.5$. From the relationship between laser fluence and spot area, the required laser spot diameter is found to be between 26 μm and 109 μm. The lower bound 26 μm correlates well with the width of the trench shown in Fig. 4(b), which is measured to be 20.74 μm.

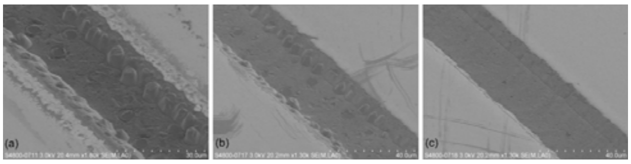


Figure 5 SEM images of trenches under different pulse repetition rate: (a) 1 kHz; (b) 3 kHz; and (c) 5 kHz. The focus offset, pulse energy and scan speed are fixed at -450 μm, 23 μJ and 25 μm/s respectively.

Trenches laser-micromachined under an increasing pulse repetition rate are shown in the SEM images of Figs. 5(a) to (c); all other parameters are kept constant. It is observed that when the pulse repetition rate increases from 1 kHz to 5 kHz, the sidewall and bottom surface become increasingly smoother. Formation of stalagmite GaN structures rarely occurs. This observation can be understood by noticing that an increasing pulse repetition rate raises the probability of a particular location being hit by an incident photon. The photons collide more frequently on the surface of the stalagmite-like structures, causing a stronger abrasion effect. Another observation is that the trench width remains approximately unchanged.

From the above sets of experiments, we can develop the conditions for laser micromachining of an optimal trench, which can be obtained by tuning the focus offset level, pulse energy and pulse repetition rate. One of the major applications of this laser micromachining technique is the rapid prototyping of interconnected LED arrays on a single chip. An example of such a device is the alternating-current LED (ac-LED) as shown in Fig. 6(a), whereby the device consist of multiple interconnected LEDs which form the rectifying circuit and the emissive components. Details of this device will be reported elsewhere. In order to interconnect the LEDs in an array, trenches must be formed between the mesa regions of individual devices. The trenches must have smooth and inclined sidewalls for conformal coverage of the metal interconnects. Figure 6(b) illustrates a 500 nm thick Ti/Al bi-layer interconnect being deposited across two laser-micromachined trenches. The deposition was performed by electron-beam evaporation. The LEDs are electrically isolated from each other by the trenches, and connected in series by the Ti/Al interconnect (with an underlying SiO_2 layer for isolation). The smooth tapered sidewall and flat bottom allow the Ti/Al layer to run smoothly across the trenches.

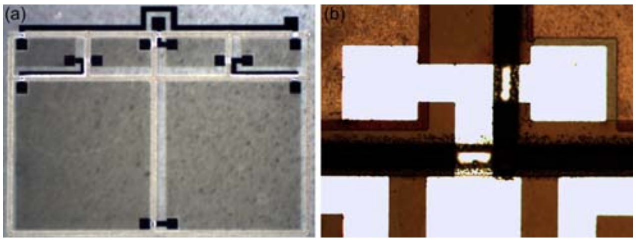


Figure 6 (a) Alternating-current LED: an example of interconnected LED array. (b) Optical microscope image of a 500 nm Ti/Al interconnect deposited across laser-micromachined trenches.

4 Conclusion

Laser-micromachined trenches in GaN/sapphire wafers with smooth sidewalls and flat bottom surfaces using nanosecond UV pulses are demonstrated. When process conditions are optimized, laser ablation terminates automatically at the GaN/sapphire interface, making use of the difference in ablation thresholds of GaN and sapphire. Several parameters that affect the trench quality have been investigated. It is found that a trench with inclined sidewall and smooth bottom surface can be obtained by optimizing the focus offset, pulse energy and pulse repetition rate. The process has been successfully applied to the interconnection of LED arrays on a single chip.

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