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Applied Surface Science 252 (2006) 4897–4901
applied surface science
www.elsevier.com/locate/apsusc

Microfabrication in free-standing gallium nitride using UV laser micromachining

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Received 3 May 2005; accepted 13 July 2005

Abstract

Gallium nitride (GaN) and related alloys are important semiconductor materials for fabricating novel photonic devices such as ultraviolet (UV) light-emitting diodes (LEDs) and vertical cavity surface-emitting lasers (VCSELs). Recent technical advances have made free-standing GaN substrates available and affordable. However, these materials are strongly resistant to wet chemical etching and also, low etch rates restrict the use of dry etching. Thus, to develop alternative high-resolution processing for these materials is increasingly important. In this paper, we report the fabrication of microstructures in free-standing GaN using pulsed UV lasers. An effective method was first developed to remove the re-deposited materials due to the laser machining. In order to achieve controllable machining and high resolution in GaN, machining parameters were carefully optimised. Under the optimised conditions, precision features such as holes (through holes, blind or tapered holes) on a tens of micrometer length scale have been machined. To fabricate micro-trenches in GaN with vertical sidewalls and a flat bottom, different process strategies of laser machining were tested and optimised. Using this technique, we have successfully fabricated high-quality micro-trenches in free-standing GaN with various widths and depths. The approach combining UV laser micromachining and other processes is also discussed. Our results demonstrate that the pulsed UV laser is a powerful tool for fabricating precision microstructures and devices in gallium nitride.

PACS: 42.62.−b; 81.05.Ea

Keywords: Gallium nitride; Pulsed UV lasers; Micromachining

1. Introduction

Wide bandgap III-nitride semiconductor materials have been the subject of intensive study over recent years, owing to their excellent properties for use in visible optoelectronic devices. GaN-based light-emitting diodes (LEDs) and laser diodes whose emissions cover the entire visible spectrum are already commercialised for a variety of lighting and data storage applications. Much recent attention is now devoted to the development of novel GaN-based devices such as ultraviolet (UV) solid-state light sources capable of operating down to 250 nm, blue and UV vertical cavity surface-emitting lasers (VCSELs) [1–3]. The active structures used for fabricating such devices contain GaN-based multiple quantum wells (MQWs) and are normally grown epitaxially on sapphire and SiC substrates. However, due to the lattice mismatch between the nitride layer and substrate, strains are induced in the active structure, which results in the degradation of the device performances. It is expected that the device quality will be greatly improved by growing MQW structures homoepitaxially on bulk GaN substrates. Recent technical advances have made free-standing GaN substrates available and affordable, promising new development in GaN devices. However, GaN and alloys are strongly resistant to wet chemical etching and also, low etch rates restrict the use of dry etching. Thus, developing alternative high-resolution processing methods for these materials is increasingly important in the fabrication of novel optoelectronic devices.

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doi:10.1016/j.apsusc.2005.07.117

In this paper, we report the fabrication of microstructures in free-standing GaN using both a pulsed UV copper vapour laser (255 nm) and a high-intensity peak-power oscillator (HIPPO) industrial UV laser (266 nm). Our results demonstrate that the pulsed UV lasers are powerful tools for microfabrication in free-standing gallium nitride.

2. Experiment

Both UV copper vapour laser (255 nm) and HIPPO laser (266 nm) have been used to develop the processes of fabricating the microstructures in free-standing GaN. The copper vapour laser operates with a high average power and high pulse rates, making it suitable for machining materials in a controllable way [4,5]. High-resolution laser machining requires excellent beam pointing stability and power stability. The copper vapour laser (FBG*Ultra*, Oxford Lasers Ltd.) used in this study has a beam pointing stability better than 10 μrad and a power stability of 0.3% rms over 1 h. The 255 nm UV beam is generated from the 511 nm fundamental wavelength of the copper vapour laser by using a non-linear crystal BBO. The laser was operated at a pulse repetition frequency of 6 kHz with a pulse width of 30 ns. The UV laser beam was delivered to the sample surface through an objective lens ($f = 50$ mm) to produce a focal spot size of 20 μm. The laser fluence was varied from 30 to 80 J/cm^2. The GaN sample machined by the copper vapour laser was mounted on a motorised precision X–Y translation stage, with which the sample position and scan speed can be precisely controlled by a computer.

The HIPPO laser system (Spectra Physics) has a compact optical cavity that uses high-gain Nd:YVO$_4$ laser. HIPPO laser provides high beam quality ($M^2 < 1.2$) and stability for improved process control and fine feature resolution. The laser's 1064 nm output can be frequency-quadrupled to 266 nm using pre-aligned harmonic modules. At this UV wavelength, an output power of 2 W is achieved. The laser beam is translated in X and Y using a galvanometer scanning head (HurryScan, Scanlab) and is focussed to a spot size of 20 μm using an *f*-theta lens. Software was developed for the scanhead, which provides precise control of the beam position and scan speed. The HIPPO laser was operated at a very high repetition rate of 50 kHz so as to achieve high-speed micromachining. The short UV laser pulses produced from both lasers enable material processing with minimal heat effects, which is critical for precision micromachining of brittle materials such as gallium nitride.

Commercially available free-standing GaN substrates with a typical thickness of 250–300 μm were used for this study. The laser micromachining was conducted in air.

In this work, the nature of the re-deposited material due to laser ablation was characterised by using wavelength dispersive X-ray (WDX) analysis. The measurements were carried out using a Cameca SX100 electron probe micro-analyser (EPMA). This EPMA is designed for quantitative elemental analysis and composition mapping by three WDX spectrometers. The high spectral resolution and peak-to-background ratios of the spectrometer ensure excellent composition detection.

3. Results and discussion

3.1. Removal of re-deposited materials

During laser micromachining, the ablated materials are re-deposited around the machined areas. These re-deposited materials must be removed prior to any further processing. Thus, we first investigated what the re-deposited materials are and how to remove them.

Fig. 1 shows the results of the EPMA taken from the machined surface of a GaN substrate. A secondary electron image of the region over which the analysis was taken is shown in Fig. 1(A) (the machined trench is approximately 420 μm wide). It can be seen that there is a lot of re-deposited material at the bottom and edges of the trench. The remaining images in Fig. 1 show the composition of the re-deposited material under electron excitation. From images (B) and (C) which were taken

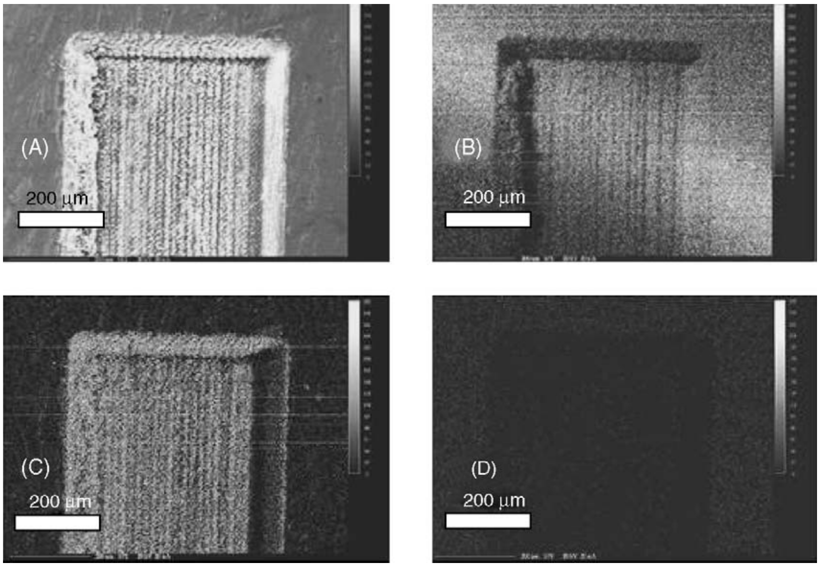


Fig. 1. EPMA images taken with a 20 keV electron beam: (A) secondary electron image of the area scanned, (B) gallium signal, (C) oxygen signal and (D) nitrogen signal.

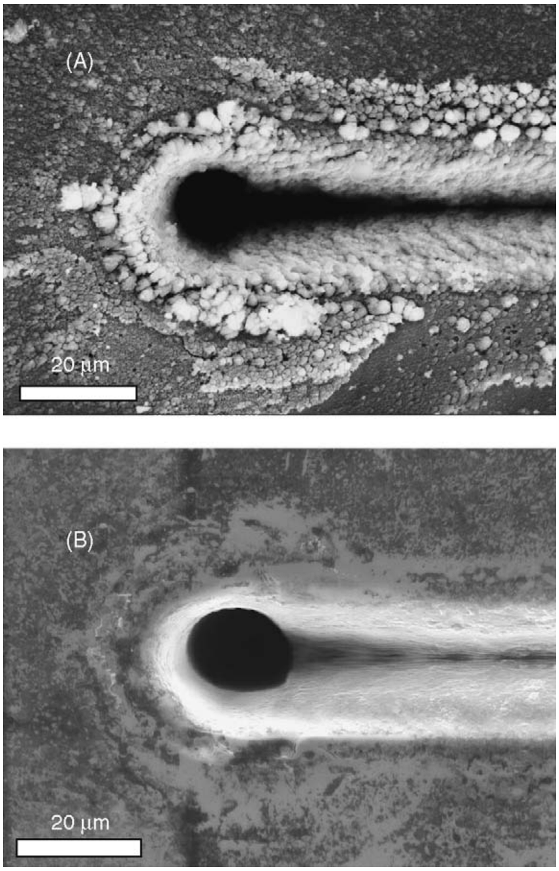


Fig. 2. (A) Re-deposited material around a micro-trench machined in GaN. (B) After cleaning, the same trench shows no evidence of re-deposited materials.

at the characteristic wavelength of gallium and oxygen, respectively, we can see definite evidence that both gallium and oxygen are present on the surface. No nitrogen signal was detected from the surface (Fig. 1(D)). These results suggest that the gallium oxide is the material re-deposited on the surface during the machining process. Gallium oxide was also found in the re-deposited materials produced by femtosecond laser ablation of GaN [6].

Hydrochloric acid (HCl) was then selected to etch away the re-deposited material as gallium oxide is soluble in HCl. Cleaning was performed by immersing the sample in concentrated HCl (12 M) for 5 h, after which the sample was placed in an ultrasonic bath for 5 min to enhance the removal process. The sample was then cleaned in deionised water and dried using nitrogen gas. Our results show that HCl acid etching removes the re-deposited material effectively. The scanning electron microscopy (SEM) images of a micro-trench taken before and after HCl etching are shown in Fig. 2. It can be seen that the re-deposited material around the trench has been removed completely by this treatment.

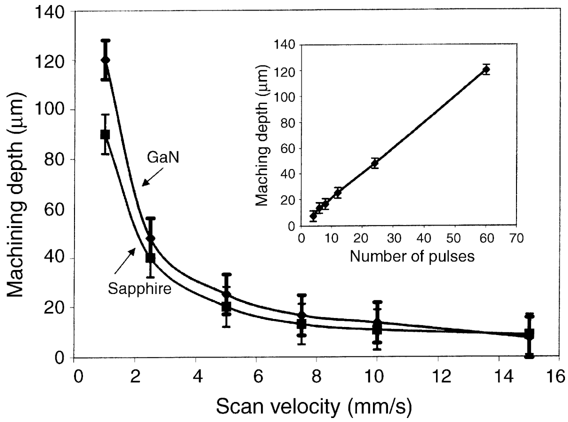
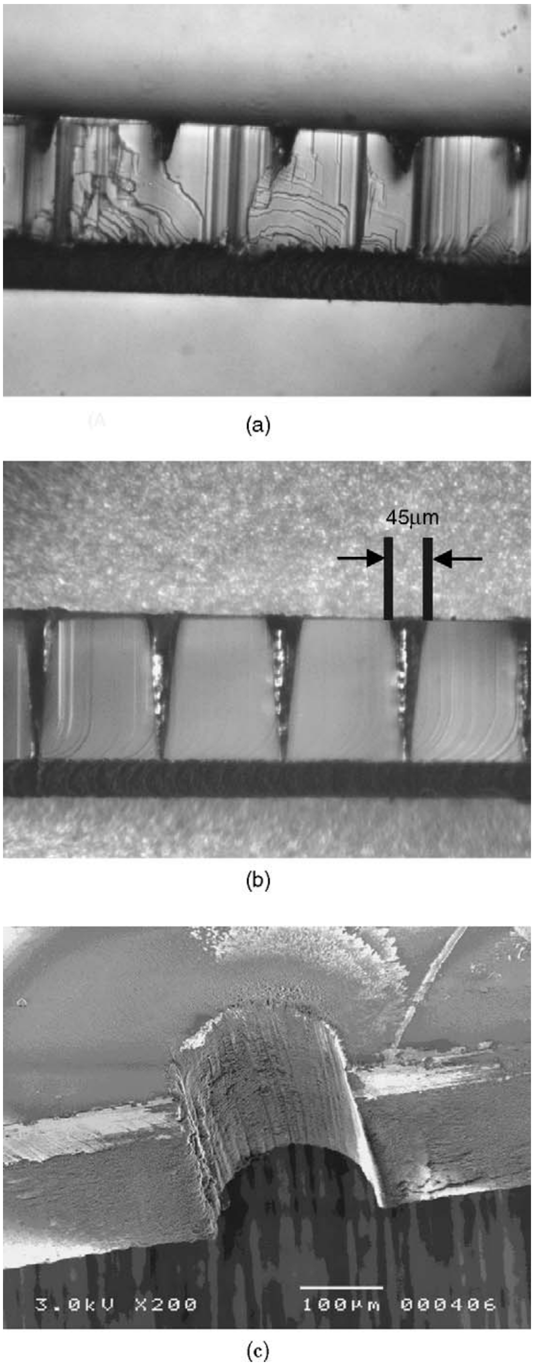


Fig. 3. GaN machining depth as a function of scan velocity. The inset shows the dependence of machining depth on number of pulses.



(a)

(b)

(c)

Fig. 4. (a and b) Wedge trepanned micro-holes in the free-standing GaN. The holes were drilled by rotating the laser beam. Drilling times of: 150 ms (a) and 1 s (b). (c) Trepanned holes drilled by rotating the GaN sample under the stationary laser beam.

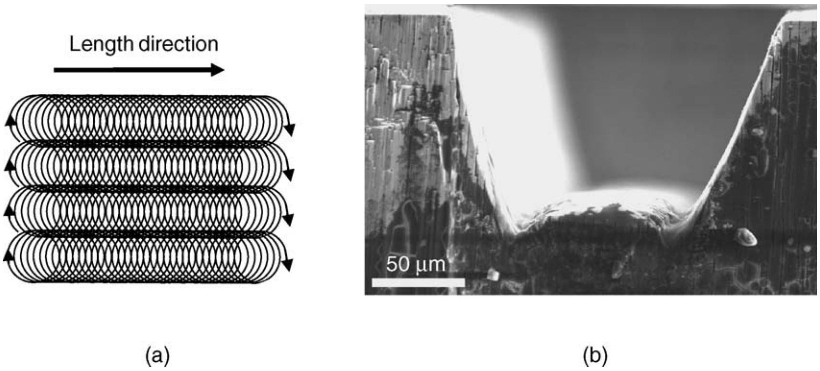


Fig. 5. (a) Laser process strategy to fabricate micro-trenches in GaN. (b) SEM image of a micro-trench in GaN.

3.2. Micromachining of free-standing GaN

Free-standing GaN substrates were first machined by using the copper vapour laser with a fluence of 74 J/cm^2. The dependency of machining depth on the scan velocity is shown in Fig. 3. For comparison, machining depths of sapphire using the same laser fluence as the GaN are also shown in Fig. 3.

It can be seen that under the same condition, the machining depths for GaN are larger than those for sapphire, which is an expected result. The defect density in GaN ($\sim 3 \times 10^7$ cm^{-2}) is much higher than that in the single crystal sapphire. Thus, more seed electrons are produced in the GaN due to the defects, making the laser fluence threshold for GaN machining lower than that for sapphire machining. The inset in Fig. 3 shows the machining depth as a function of the number of laser pulses. It can be seen that the machining depth of GaN increases in a linear manner as the number of pulses increases.

The development of techniques to fabricate precision features in free-standing GaN, such as holes and trenches, is increasingly important to make novel GaN-based devices. In this work, precision holes of different diameters and depths were fabricated in the free-standing GaN using laser trepanning technique. By the trepanning method, the laser beam or sample is rotated during the beam exposure period to produce round holes [4]. Fig. 4(a and b) shows the cross-sectional SEM images of the holes in the GaN, which were machined by rotating the laser beam. The drilling times were 150 ms (Fig. 4(a)) and 1 s (Fig. 4(b)), respectively. It took 1.2 s to drill through this 250 μm thick GaN. As shown in the images, these holes have good quality wall finish. From the depth of the holes drilled with different times, the drilling speed can be estimated. The results show that drilling speed decreases with increasing depth. Since the laser beam used by this trepanning technique is not perpendicular to the sample surface (inclination angle 6.5°), the holes drilled are tapered as shown in the images. Alternatively, if a small taper is required, holes can also be drilled by rotating the sample under a perpendicular beam. A hole drilled in this way is shown in Fig. 4(c). Clearly, this hole has a very small taper and is almost dross free.

Micro-trench structures were fabricated in free-standing GaN by using the HIPPO (Nd:YVO$_4$) laser. The machining strategy for micro-trench fabrication consists of an array of beam scan lines with built in beam ''wobble''. Beam wobble is circular motion superimposed onto linear motion resulting in a spiral movement of the laser beam. This technique is shown in Fig. 5(a). A cross-sectional image of a micro-trench made by this way is shown in Fig. 5(b). It can be seen that the micro-trench fabricated has smooth side walls. However, the bottom of the trench is not flat and the maximum depths are located at the edges of the trench as shown in the image. In order to improve the flatness, the laser and machining parameters were further optimised. In particular, we added extra ''wobble'' passes at the centre area of the trench to achieve better flatness. Micro-trenches fabricated in this way are shown in Fig. 6. It can be seen that these micro-trenches have a flat bottom surface and almost vertical sidewalls (>85°). Since the trenches were fabricated by multi-beam scanning, a ''ripple'' structure is observed at the bottom of the trenches. As the laser beam translated across the surface, adjacent beam lines might overlap at the edges creating an over machined area and thus leading to

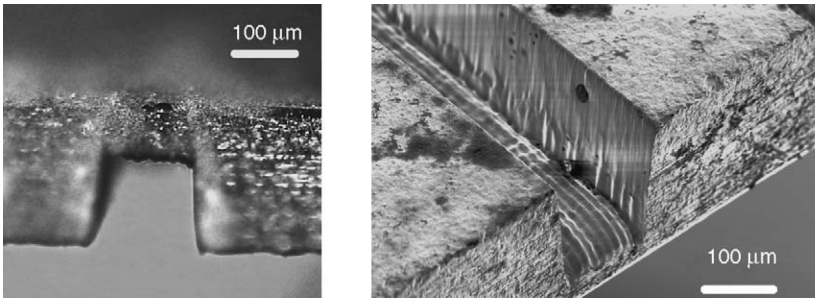


Fig. 6. Micro-trenches in GaN fabricated with extra ''wobble'' passes at the centre of trenches.

a ‘‘ripple’’ effect. These ripples can be minimised or even eliminated by further adjusting the lateral translation between the scan passes.

In order to finely adjust the depth of the trenches and further improve their surface qualities, such as flatness and smoothness, we have explored the further etching of the micro-trenches fabricated by laser micromachining using an inductively coupled plasma (ICP) etching tool. It was found, the depth of trench could be accurately controlled by ICP etching. However, the flatness and smoothness were not improved, which may be due to the local non-uniform etch resulting from high threading dislocation density of the GaN ($\sim 3 \times 10^7$ cm^{-2}). It is expected that using bulk GaN substrates with low defect densities, the high-quality micro-trenches will be fabricated by the combined techniques of laser machining and ICP etching.

4. Summary

In summary, we have investigated the processes of UV laser machining to fabricate microstructures in free-standing GaN which is a new and important semiconductor material for developing UV/blue optoelectronic devices. It was found that HCl etching is an effective method to remove the re-deposited materials due to the laser machining. In order to achieve controllable high-resolution micromachining, the machining strategy, important laser and machining parameters, such as laser fluence, scan velocity, were investigated and optimised. Our work demonstrates that by using UV pulsed lasers, clean and well-defined microstructures such as holes and trenches can be fabricated in free-standing GaN. Microfabrications using pulsed UV laser therefore provide a new approach in the development of GaN-based devices.

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