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Deep UV laser etching of GaN epilayers grown on sapphire substrate

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ABSTRACT

The laser etching of GaN epilayers on sapphire substrate was carried out using a deep ultraviolet pulsed laser (157 nm wavelength, 20 ns pulse width). The quality and morphology of the etched GaN surface were evaluated by scanning electron microscopy, atomic force microscopy and scanning profilometer. Quadrate micro-hole and micro-trenches etched by the 157 nm laser exhibited clean and smooth edges, sharp side walls and very small heat affected zone (HAZ). In order to achieve controllable high-quality etching, the laser and processing parameters, such as laser repetition rate, scan speed, were systematically investigated and optimized. The mechanism analysis shows that, direct photoionization or photo-chemical reaction play predominant role within 157 nm laser etching of GaN epilayers.

1. Introduction

GaN based III-nitride semiconductor materials have been the subject of intensive study over recent years, owing to their excellent properties for use in a variety of optical devices, including light emitting diodes (LED's) and laser diodes (Huang et al., 2005). Therefore, the development of micro-fabrication techniques for GaN is very important. In general, LED's are fabricated on sapphire substrate. However, the chemical inertness and high bond strength of GaN and sapphire make it difficult to realize rapid, high-quality etching. Dry etching process, such as inductively coupled plasma (ICP) (Kim et al., 1999), electron cyclotron resonance (ECR) (Toshiki et al., 2000), reactive ion etching (RIE) (Basak et al., 1997), are applied to micro-etching of GaN based semiconductors. Comparatively, ICP process is of low cost and high selectivity, and widely used to the production of LED's device.

On the other hand, laser ablation is a promising technique for improving fabrication efficiency. The nanosecond DPSS laser (Mak et al., 2010), UV copper vapour laser (Gu et al., 2006), ArF excimer laser (Akane et al., 1999), VUV–UV multiwavelength excitation (Obata et al., 2006) have been reported to etch GaN semiconductor materials. And a new laser tool, femtosecond laser (Kim et al., 2001), was also used for the direct machining of the GaN-related materials (Kazue et al., 2001). Also, wet-chemical-assisted femtosecond-laser ablation was proved as an efficient approach for GaN etching (Nakashima et al., 2009). Comparatively, the shorter is the laser wavelength, the smaller feature size or smoother etched surface can be achieved. Because of its short wavelength (high photon energy), 157 nm fluorine laser has great potential in lithography for next generation Si-ULSI (Dai et al., 2009). This deep UV laser could offer many advantages, and drastically reduces the effects of localized heating shock such as warpage, melting, cracking, and delamination (Machavaram et al., 2007). Thus, the 157 nm laser might be a promising micromachining tool for many hard and brittle materials.

Owing to its large photon energy of 7.9 eV, the 157 nm laser can drive photochemical reaction of wide gap materials such as GaN, leading to a small HAZ (heat affected zone). This deep UV laser is very suitable for etching GaN epilayers and its sapphire substrate. In the present paper, 157 nm fluorine laser ablation performance of GaN epilayers grown on sapphire substrate is investigated, and the correlative influential factors and the etching mechanism are discussed.

2. Experimental details

A precision 157 nm micro-ablation system (Exitech Ltd., M2000) was used in the present experiments. The system is adaptive to wide variety of laser processing requirements. Fig. 1 illustrates the schematic of 157 nm laser micro-ablation system. The 157 nm laser source is the Model M-100 manufactured by Tui Laser of Germany. The pulse duration is about 20 ns. At a repetition rate of 100 Hz, the maximum output of the 157 nm laser source is 1.5 W, and the maximum pulse energy is 25 mJ. In the 157 nm laser beam delivery system, all transmissive and reflective optics are fabricated from CaF_2 and multi-layer dielectric coatings. Because 157 nm laser radiation is strongly absorbed by atmospheric oxygen – at atmospheric pressure the photon penetration of O_2 is only ~50 μm, the beam delivery system are purged with high-purity dry nitrogen gas. Two homogenizers that consist of a grid of 36 lenslets (A_1, A_2) are used.

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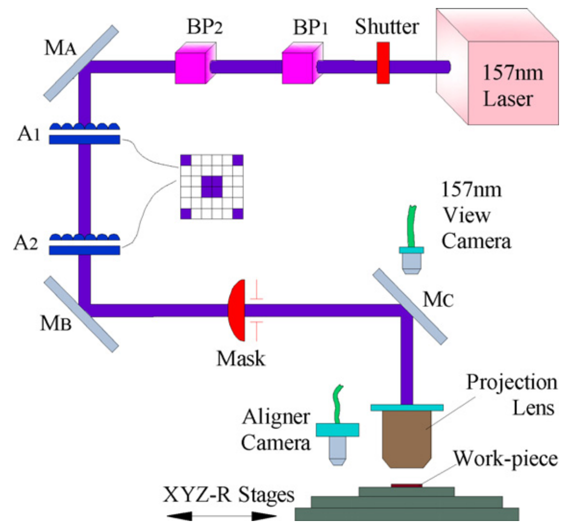

Fig. 1. Optical path of the 157 nm fluorine laser M – 45° reflective mirror; BP – Bi-prism; A – Array mirror (fly-eye homogenizer).

For monitoring the ablation procedure, a CCD camera images the sample surface through the Schwarzschild lens, which was coated for both 157 nm and visible light.

The GaN epilayers grown by MOCVD were employed as laser micromachining objective. The workpiece mounted on table can be moved by 4-axis (*X*, *Y*, *Z* and *R*) CNC (Computer Numerical Controlled) stages (300 mm × 300 mm). The resolution of *X*, *Y*, *Z*-stage is 0.5 μm, 0.5 μm and 0.1 μm, respectively. The size of laser spot can be changed by an adjustable diaphragm (Mask in Fig. 1).

The workpiece is commercially available GaN wafer (Made from Fangda Int. Ltd. Co.) with 6 μm GaN/AlGaN epilayers and 430 μm sapphire substrate. Before tests, the surface of the workpiece was cleaned by Ethanol. The GaN wafer was fixed on table. After laser etching, the etched surface was cleaned by ultrasonic in acid solution. The morphology of the etched surface or micro-structures was inspected by a scanning electron microscope (SEM, JSM-5610), sometimes observed rudely using a conventional optical microscope (Keyence Ltd.). The ablation depth and surface roughness were measured by a Tencor/KLA P-16 scanning profilometer.

3. Results and discussions

The shape of laser spot focused onto work-piece depends on the shape of the mask (referring to Fig. 1). The mask is placed before the projective lens, instead of placing above the workpiece directly. Here, the mask is set as square pattern, the length or width of the square can be adjusted by micro-motor severally. Fig. 2 shows a typical AFM image of GaN surface ablated by 157 nm laser. The size of laser spot was adjusted as ~25 μm × 25 μm. The other conditions were: laser fluence ~2.0 J/cm^2, pulse repetition rate 1 Hz, number of pulses 45. After laser ablation, the work-piece was cleaned 15 min with ultrasonic in 18 vol.% hydrochloric acid solution. It can be seen that, the shape of the square pattern is considerably regular. One of the side-walls is of slight disfigurement at its bottom edge (swell), but other side-walls are highly regular and sharp. On the whole, the bottom is smooth. However, the homogenization of laser fluence is very difficult within the whole spot range, leading to an imperfect bottom surface. From AFM measured results, the bottom roughness is 35 nm-Ra and 138 nm-Ry, indicating that the flatness of the bottom is not so good. That might result from disfigurement of the laser spot. From the AFM image, it can be also found, there is no obvious melting traces left in the micro-structure. That strongly indicates little thermal influence during the 157 nm laser process.

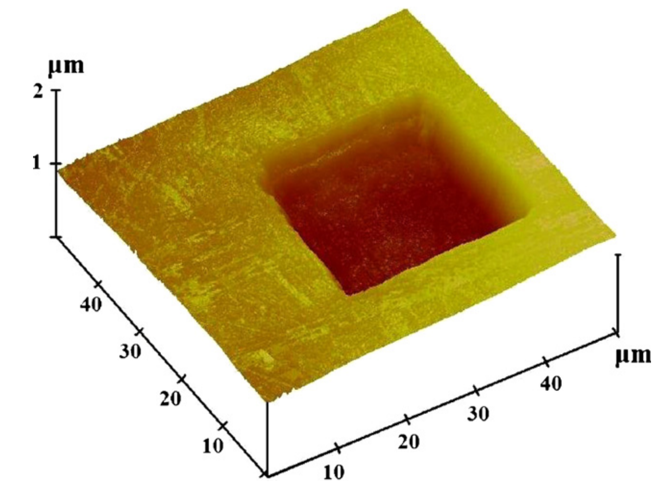

Fig. 2. AFM image of GaN film etched by 157 nm laser (the beam size ~25 μm × 25 μm).

To test the 157 nm laser ablation efficiency, a series of square micro-structures like shown in Fig. 2, were produced by 157 nm laser etching. Fig. 3 shows the ablation rates of GaN epilayers under different pulse number. Here, the ablation rate was calculated as the total etched depth divided by the total number of laser pulses. The GaN ablation rates are relatively high during the first 20–40 pulses. With increased number of pulses, the ablation rates are slightly decreased. In fact, as the laser pulses increased, the photo-chemical decomposition would generate debris, which impeded the further etching of GaN partially. On the other hand, the GaN ablation rates are significantly affected by laser fluence. Higher laser fluences provided higher ablation rates. However, the amplitude was decreased gradually with increased laser fluence.

In general, the ablation rate is largely affected by absorption coefficients α of materials and laser fluences F. In the 157 nm laser ablation, the material removal is predominantly photon-chemical process. For incident laser fluences just above an ablative threshold value F_T, the etch depth per pulse t is approximately:

$$t = \frac{1}{\alpha} \ln \left[\frac{F}{F_T} \right] \tag{1}$$

For photon absorption, the penetration depth of $1/\alpha$ is dependent on laser wavelength, bandgap energy of materials and so on.

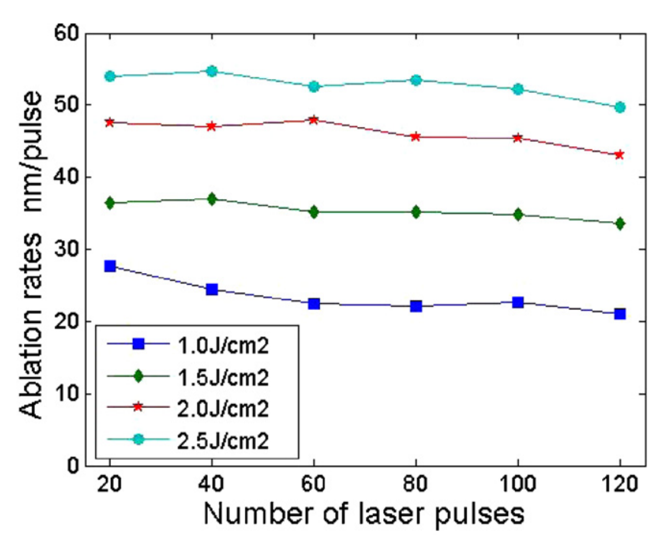

Fig. 3. The ablation rates of GaN film etched by 157 nm laser.