Fabrication and characterization of freestanding circular GaN gratings

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Abstract: It's of significant interest to combine freestanding nanostructure with active gallium nitride (GaN) material for surface-emitting optoelectronic application. By utilizing bulk micromachining of silicon, we demonstrate here a promising way to fabricate freestanding GaN nanostructures using a GaN-on-silicon system. The well-defined nanoscale circular GaN gratings are realized by fast-atom beam (FAB) etching, and the freestanding GaN gratings are obtained by removing silicon substrate using deep reactive ion etching (DRIE). The freestanding GaN slab is thinned from the backside by FAB etching to reduce the confined modes inside the GaN slab. The measured microphotoluminescence (micro-PL) spectra experimentally demonstrate significant enhancements in peak intensity and integrated intensity by introducing freestanding circular grating. This work represents an important step in combining GaN-based active material with freestanding nanostructures for further increasing light-extraction efficiency.

OCIS codes: (160.6000) Semiconductor materials; (310.6628) Subwavelength structures, nanostructures; (220.4241) Nanostructure fabrication

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1. Introduction

Gallium nitride (GaN) material is very promising for short-wavelength surface-emitting optoelectronic devices. In conventional planar-surface structure, the extraction cone is governed by a critical angle of $\theta_c = \arcsin(n_{air}/n_{GaN}) \approx 24.6°$, n_{air} and n_{GaN} being the refractive indices of the air and the GaN, respectively. Most of the emitted light is confined inside thick GaN slab due to total internal reflection caused by the large refractive index difference between the GaN layer and air. The confined modes propagate within the GaN slab and their number increases with GaN slab thickness. Freestanding GaN nanostructures are apromising way to overcome this challenging issue: (1) freestanding GaN slab gives the ability to work as thinGaN and flip-chip light-emitting diodes (LEDs) [1,2]. The suspended GaN slab in space features good optical confinement in the vertical direction and avoids the light loss into the substrate due to the freestanding characteristic [3–5]; (2) nanostructures break the total internal reflection condition at the GaN surface to enhance the light-extraction efficiency [6]. Additionally, a resonant nanostructure can also function as an optical cavity for the emitted light at a specific wavelength for obtaining a GaN surface-emitting laser.

However, well-controlled and low-damage processing techniques are still deficient for the fabrication of freestanding GaN nanostructures. A variety of techniques are developed to overcome the manufacturing issue of GaN slabs. Yang *et al.* introduced GaN-on-patterned-silicon method to obtain suspended GaN microstructures [7,8]. Rosenberg *et al.* illustrated a simple way to fabricate partially freestanding GaN photonic crystal slab using an isotropic wet etch of silicon [9]. In order to realize the suspended structures on the active material, Hu *et al.* fabricated partially freestanding GaN structures including microdisks and photonic crystal nanocavities using selective photoelectrochemical (PEC) etching [10–12]. Noda *et al.*

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demonstrated novel "air holes retained over growth" method to construct suspended GaN photonic crystal structures for surface-emitting lasers at the blue wavelength [13]. Recently, Wierer *et al.* presented a two-dimensional photonic crystal into freestanding GaN-based LEDs to increase the light-extraction efficiency significantly [14]. The freestanding GaN photonic crystal was realized by removing the sapphire substrate using a laser lift-off technique. The high extraction efficiency and the low thresholds were demonstrated in these successful freestanding GaN-based structures.

In recent years, high quality a GaN-on-silicon system has been developed by using an intermediate AlGaN/AlN buffer layer to reduce the crack density [15–17]. Silicon micromachining is also a mature technique for removing silicon substrate under GaN to generate freestanding GaN slabs. It is thus promising to fabricate optical components on thin freestanding GaN slabs using the GaN-on-silicon system. The fabrication process might be compatible with the microelectronics manufacturing line. This is, in combination with the growth on the highly available and cost-efficient silicon substrate, a very interesting approach. Here, we fabricate the freestanding circular GaN gratings to combine their freestanding characteristic with circular grating on the active GaN material. Circular-grating structures are able to couple the emitted radiation by multi-directional diffraction. They have also been widely employed to achieve polarization-independent optical property, small-divergence output beam, and vertical emission perpendicular to the device plane [18–21].

To overcome the fabrication issue, we develop fast-atom beam (FAB) etching for manufacturing the GaN slab [22,23]. The FAB is made up of energetic neutral particles and has good directionality of the beam flux [24]. As a neutral dry etching technique, FAB etching is able to etch GaN layer with high lateral resolution. The silicon substrate under GaN grating region is completely removed in our proposed freestanding circular GaN gratings. FAB etching from the backside is also developed to thin the freestanding GaN slab. This novel technique functions to reduce the number of optical modes inside GaN slab and to improve the light-extraction efficiency.

2. Device fabrication

The starting material, consisting of 200nm GaN layer, 450nm AlGaN layer, 200nm AlN buffer layer and 200μm silicon handle layer, is a commercial GaN template grown on silicon substrate by metal organic chemical vapor deposition (MOCVD). The InGaN/GaN multiple quantum-well (MQW) heterostructures are deposited on the GaN template by molecular beam epitaxy (MBE) with radio frequency nitrogen plasma as gas source [25,26]. The structure incorporates 6nm AlN layer, twelve pair 3nm AlN/3nm GaN superlattice sacrificial layer, 12nm GaN layer, 950nm n-type GaN layer, three pair 3nm InGaN/9nm GaN active layer, 6nm p-type AlGaN layer and 50nm p-type GaN layer. The epitaxial structure of material is shown in Fig. 1.

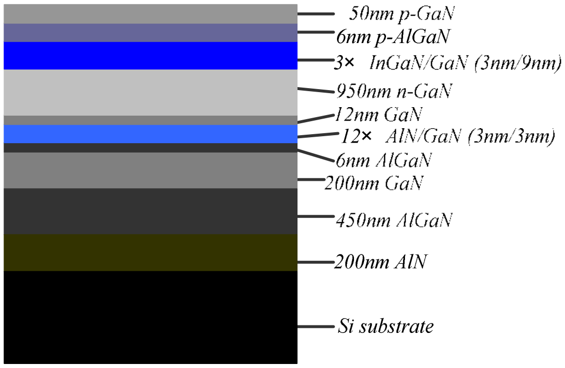

Fig. 1. The schematic layer structure of material used to make freestanding circular GaN grating.

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The proposed freestanding circular GaN gratings are implemented on the prepared GaN substrate. The schematic fabrication process of freestanding circular GaN gratings is illustrated in Fig. 2. Nanoscale circular gratings were first patterned in ZEP520A resist using electron beam lithography (steps *a*-*b*). The grating patterns were then transferred to GaN slab with a grating height of approximately 200nm by FAB etching (steps *c*). FAB etching generated by the neutralization of ions extracted from direct current Cl_2 plasma was performed with an etching rate of about 11.5nm/min at the high voltage of 3.0KV and the accelerated current of 10mA. After removing the residual resist, the processed patterns were protected by thick photoresist. The silicon substrate under the circular-grating region was then patterned from the backside by photolithography and etched down to the AlN layer by deep reactive ion etching (steps *d*-*e*), which made the circular grating suspend in space. The freestanding circular GaN gratings were finally generated by removing the residual photoresist (steps *f*). FAB etching from the backside was developed to thin the freestanding GaN slab to a thickness of ~1000nm (steps *g*-*h*).

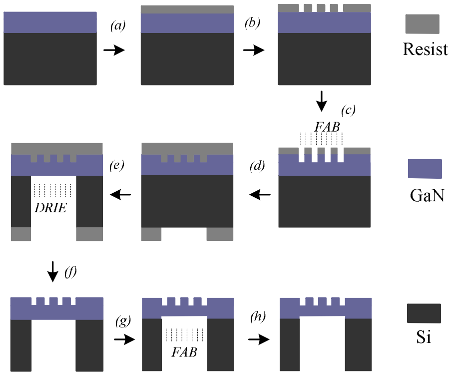

Fig. 2. Fabrication process of freestanding circular GaN grating.

3. Experimental results and discussion

Figure 3(a) shows a scanning electron microscope (SEM) image of freestanding GaN slab obtained from the silicon substrate side. The size of the square freestanding GaN slab is about 300µm × 300µm. The three-dimensional surface profile illustrated in Fig. 3(b) is measured by an optical interferometer. The surface deflection regarding the freestanding GaN slab is downward due to the residual stress, and the peak-to-valley (PV) value is measured around 3.25µm at the centre of the 300µm × 300µm GaN slab. Figure 3(c) illustrates one optical micrograph of fabricated circular gratings on the freestanding GaN slab. These results indicate that it is promising to fabricate freestanding GaN lighting devices using the GaN-on-silicon system.

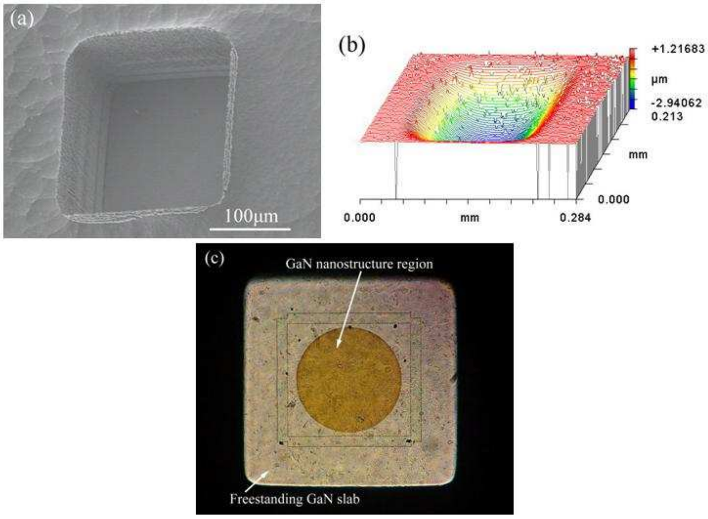

Fig. 3. (a) Sample of freestanding GaN slab obtained from Si substrate side; (b) three-dimensional surface profile of freestanding GaN slab; (c) optical micrograph of nanostructures on freestanding GaN slab.

Figure 4(a) illustrates scanning electron microscope (SEM) image of fabricated freestanding circular GaN gratings, where the grating period is 300nm. Figures 4(b), 4(c) and 4(d) show close-up views of freestanding circular GaN gratings, where the grating periods are 300nm, 600nm and 800nm, respectively. The duty ratio $d(= a/p)$, which is defined as the ratio of the grating width a with respect to the grating period P, is designed to be 0.5. The duty ratio d generated in reality deviates slightly from the designed value of 0.5 due to the fabrication issues. The tilting view of the freestanding GaN gratings exhibits their well defined circular symmetry, and the GaN crystal defects are also observed, degrading the internal quantum efficiency of the GaN material. In the whole device area, the circular gratings are well fabricated, and no broken grating beams are observed.

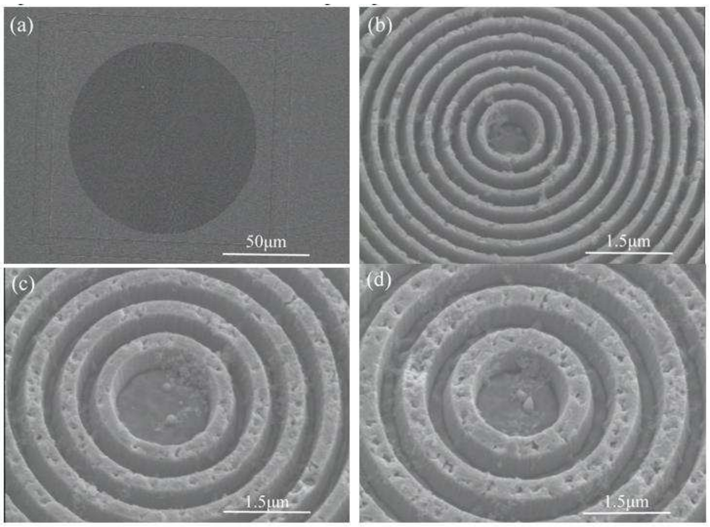

Fig. 4. SEM images of fabricated freestanding circular GaN gratings. (a) Whole grating region for 300nm-period circular grating; (b), (c) and (d) the close-up view of circular grating with grating period of 300nm, 600nm and 800nm, respectively.

The emission properties of fabricated samples are characterized using a microphotoluminescence (micro-PL) system at room temperature. The excitation source is a continuous wave He-Cd laser with a peak wavelength 325nm, and the pump light is focused on the sample through a UV-compatible objective lens (20 × and numerical aperture:0.36). The emitted light is collected by the same objective lens and measured using a multichannel analyzer system (Hamamatsu C10027).

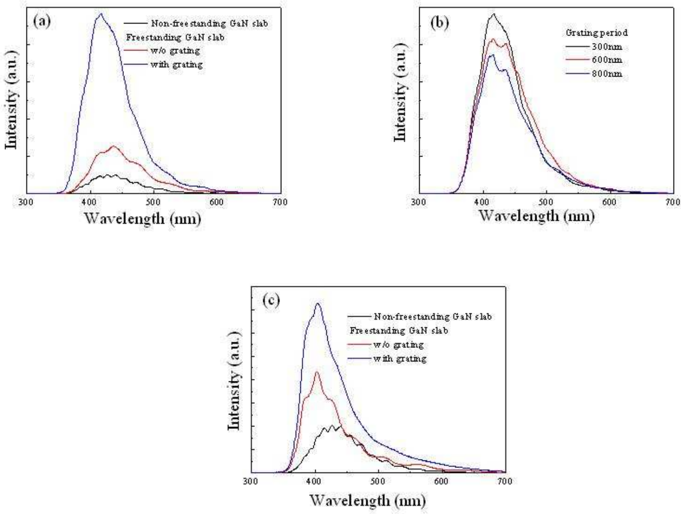

Fig. 5. (a) PL spectra of fabricated samples obtained from top surface; (b) PL spectra versus grating period obtained from top surface; (c) PL spectra of fabricated samples obtained from silicon substrate side.

Figure 5(a) shows the micro-PL spectra of fabricated samples, where the pump light is focused on the sample from top surface. The micro-PL spectra of freestanding GaN slab are first compared with those of non-freestanding GaN slab. The luminescence peak of the non-freestanding GaN slab at 426nm is normalized to 1, and a 2.5-fold enhancement in micro-PL peak intensity is observed from the freestanding GaN slab. The luminescence intensity integrated over the emission spectrum is increased by about 2.5 times. The measurements confirm the improvement in the light-extraction efficiency of freestanding GaN slab, and these results can be explained that the light loss into the silicon substrate is avoided in the freestanding GaN slab.

The freestanding GaN slab is able to function as thin GaN LEDs when a metal reflector is deposited on the bottom surface [2,27,28]. In the thin GaN case, circular gratings on top surface are useful in enhancing the light-extraction efficiency. The fabricated circular gratings have a periodic distribution of the refractive index. Therefore, a modification of the direction of light propagation occurs by multi-directional diffraction effect, which breaks the total internal reflection condition at the surface of the GaN slab. When the MQW layer is excited by the pump laser source, the circular grating helps some of the emitted photons avoid total internal reflection, which would trap them in the emitting layer. More photons can leave the device, and the micro-PL intensity is significantly improved. As illustrated in Fig. 5(a), the micro-PL intensities measured from the top side are significantly increased with the assistance of circular grating patterns, 10-fold peak intensity and 8-fold integrated intensity enhancements are obtained from 300nm-period circular grating, respectively. The micro-PL spectra also show a clear dependence on the periodicity of circular gratings, as illustrated in Fig. 5(b). The luminescence peaks are observed around 416nm, and the peak intensities are 7-fold, 8-fold and 10-fold enhancements for circular grating with grating period of 800nm, 600nm and 300nm, respectively. By varying the grating period it is shown, that the best extraction efficiency is achieved for gratings with a period below 300nm, as expected from the emission wavelength and effective refractive index of the material system.

Figure 5(c) illustrates a clear enhancement in PL intensity when the pump light is focused on the sample from silicon substrate side. In comparison with the micro-PL intensities of non-freestanding GaN slab obtained from top surface, the luminescence peak is observed around 403nm, and the integrated intensity enhancement is about 2-fold for freestanding GaN slab measured from the backside. It is a little bit lower than those obtained from top surface, which may be caused by the thicker GaN slab under MQW layer. The freestanding GaN slab can also work as flip-chip GaN LEDs [1,2,29]. In this case, circular gratings functions as patterned substrate to increase the light-extraction efficiency. By introducing circular grating with grating period of 300nm, 4-fold peak intensity enhancement is obtained. These results indicate that the micro-PL intensity is significantly improved by using circular gratings and thinning GaN slab.

4. Conclusions

We demonstrate a promising way to fabricate freestanding GaN nanostructures using the GaN-on-silicon system. FAB etching of GaN slab realizes the well-defined nanoscale circular gratings, and silicon DRIE technique makes the GaN gratings freely suspend in space. Thinning the freestanding GaN slab is performed by FAB etching to reduce the confined modes inside the GaN slab. The measured PL spectra experimentally demonstrate 10-fold peak intensity and 8-fold integrated intensity enhancements for freestanding circular grating with a grating period of 300nm. This work represents an important step in combining GaN-based active material with freestanding nanostructures for further increasing light-extraction efficiency.

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