

# MONOLITHIC FABRICATION OF GAN LEDs ON SI WAFER AND GAN MEMBRANE STRUCTURE FOR COOLING SYSTEM

M.Wakui, F.R.Hu, H.Sameshima, K.Hane  
 Nanomechanics, Tohoku University, Sendai, Japan

**Abstract:** GaN-based light emitting diodes (LEDs) were fabricated by molecular beam epitaxy (MBE) grown on a GaN-on-silicon template prepared by metal organic chemical vapor deposition (MOCVD). Blue light emission with a peak wavelength of 410nm was observed. We proposed the integration of GaN LEDs and a cooling system. To flow coolant driven by micro pump, micro channel was fabricated beneath the LEDs for efficient cooling. GaN membrane structure was fabricated from the GaN template substrate for a basic element of GaN LEDs with cooling systems.

**Key words:** GaN, molecular beam epitaxy (MBE), light emitting diode (LED), micro channel, membrane

## 1. INTRODUCTION

GaN-based LEDs are widely used for many applications such as traffic signals, LCD displays and illumination. However, luminous efficiency should be improved for more general applications. Especially for high power LEDs, which generate a great deal of heat, thermal dissipation is critical problem since an increase of the junction temperature will reduce device luminosity [1].

Meanwhile, it is general that GaN film is developed on sapphire substrate. If GaN film can be deposited on Si substrate, there are two advantages for thermal management. The first one is the high thermal conductivity of silicon compared to sapphire. The second one is that silicon is most widely used semiconductor, so it is easy to fabricate any structures. Micro channel heat exchanger was proposed for very large scale integration (VLSI) by Tuckerman [2] and Kawano verified the practical micro channel heat exchanger [3].

In this paper, We propose the integration of GaN LEDs with the cooling system by fabricating micro channel from the GaN/Si substrate and flowing coolant through it. On the other hand, the etch selectivity of Si and GaN is more than 1000:1 by Inductive Coupled Plasma (ICP) etching using SF<sub>6</sub> gas [4]. So, we propose the structure that Si substrate under the LEDs is etched completely for the micro channel to reduce the thermal resistance. We fabricated GaN-based LED structure grown by MBE on the template substrate and GaN crystal was evaluated. We used commercial template substrate which GaN crystal is continuous laterally to achieve GaN membrane structure. Then, electrode was fabricated and optical properties was evaluated. Finally, we etched back side of the template until GaN film became exposed as a preliminary experiment for the cooling system.

## 2. DESIGN OF THE COOLING SYSTEM

Schematic diagram of the cooling system using micro channel is shown in Figs. 1 and 2. Coolant activated by micro pump flow under the GaN membrane directly. In general, the performance of a heat sink is measured by its thermal resistance  $\theta$  and it is given by

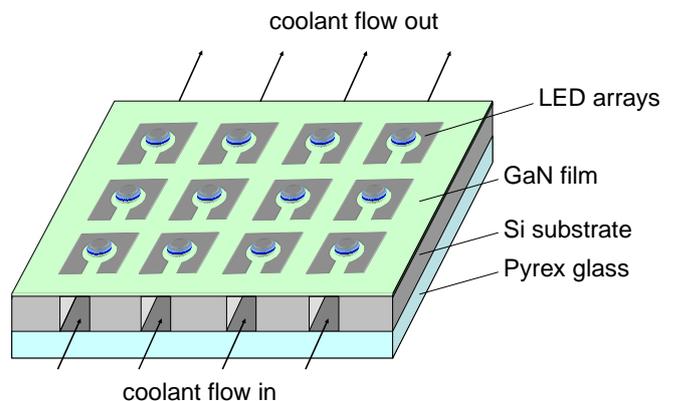


Fig. 1: Schematic diagram of the cooling system for GaN LEDs on Si substrate using micro channel.

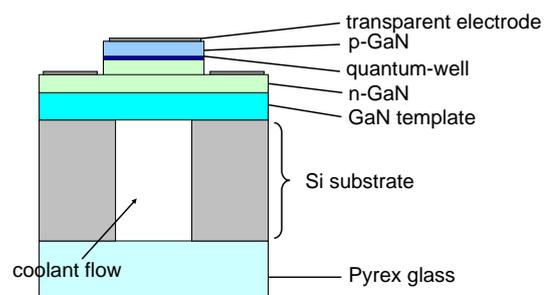


Fig. 2: Cross sectional diagram of the device.

$$\theta = T/Q \quad (1)$$

$$\theta = \theta_{\text{cond}} + \theta_{\text{conv}} + \theta_{\text{heat}} \quad (2)$$

Where  $T$  is the temperature rise of the LED above the input coolant temperature.  $Q$  is the dissipated power.  $\theta_{\text{cond}}$ ,  $\theta_{\text{conv}}$  and  $\theta_{\text{heat}}$  are due to conduction from the LED through the micro channel interface, conduction from micro channel through the coolant fluid, due to heating of fluid as it absorbs energy passing through the micro channel respectively.  $\theta_{\text{cond}}$  is given by

$$\theta_{\text{cond}} = h_{\text{GaN}}/_{\text{GaN}}A + h_{\text{Si}}/_{\text{Si}}A \quad (3)$$

Where  $h_{\text{GaN}}$  is the thickness between active layer of LED and bottom of LED and  $h_{\text{Si}}$  is the thickness between bottom of LED and the interface of micro channel. Where  $_{\text{GaN}}$  and  $_{\text{Si}}$  are the coefficient of thermal conductivity of GaN and Si. Where  $A$  is the area of LED. In our design, however, because of  $h_{\text{Si}} = 0$  and  $h_{\text{GaN}} \approx 0$ ,  $\theta_{\text{cond}}$  become almost 0. So if this structure is achieved,  $\theta$  will also decrease. It means that coolant can remove the heat from the LEDs very efficiently.

### 3. MONOLITHIC FABRICATION OF GAN LEDS ON SI SUBSTRATE

Template substrate which structure is 200 nm GaN(Si doped)/450 nm AlGaIn/200 nm AlN/500  $\mu\text{m}$  Si(111) grown by MOCVD was used. We deposited GaN-based LED structure on the template by MBE. First, the template was cleaned by buffer hydrofluoric acid (BHF) for 20 minutes at the temperature of 38 deg. The structure of GaN film is 100 nm 12-period AlN/GaN multiple layers/1250 nm Si-doped n-GaN/30 nm 3-period InGaIn/GaN quantum-wells/80 nm Mg-doped p-GaN. Total thickness of the GaN film was about 1.5  $\mu\text{m}$ .

The cross sectional scanning electron microscope (SEM) image of GaN crystal surface is shown in Fig. 3. It shows that GaN crystal grows continuously on the template without forming the column structure by MBE. In our previous research, when we fabricated GaN crystal on a Si(111) substrate by MBE, GaN nanocolumn crystal was formed because of the large mismatch of lattice constant and thermal expansion coefficient between GaN and Si [5]. Similar results were reported by other researchers[6, 7]. Good optical properties of the nanocolumn crystal was reported [8].

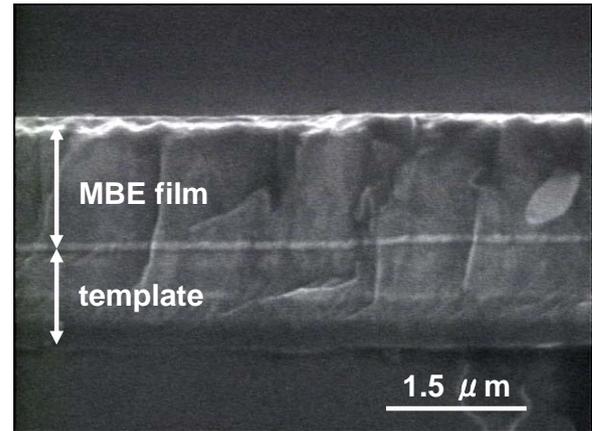


Fig. 3: Cross sectional SEM image of GaN crystal.

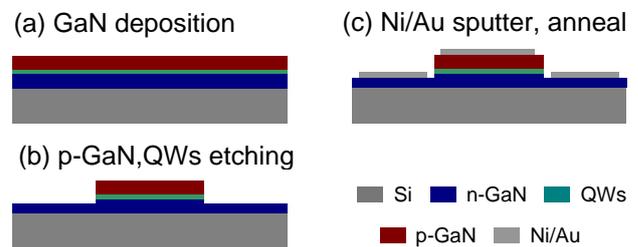


Fig. 4: Fabrication process of electrode.

When it comes to fabricating GaN membrane, however, it is likely that the mechanical strength of nanocolumn crystal is lower than that of continuous crystal. So, the laterally continuous GaN film is good for fabricating the GaN membrane.

We fabricated electrode using this GaN film. Figure 4 shows the fabrication process of the electrode. We fabricated electrodes for both p-GaN and n-GaN on the surface of GaN film because the conductivity of Si substrate used in the template is not high. It is known that Ti/Al form ohmic contact for n-GaN, however, we used Ni/Au electrode for both p-GaN and n-GaN to simplify the fabrication process. After GaN deposition by MBE (a), GaN film was etched until n-GaN became exposed (b). 5nm Ni/15nm Au was sputtered on the both p-GaN and n-GaN by lift-off process, and the device was annealed at the temperature of 500 deg in air (c).

We applied voltage between n-GaN electrode and p-GaN electrode. The micrograph of LED when voltage is not applied is shown in Fig. 5(a). Inside the smallest circle, the Ni/Au transparent electrode is deposited. The micrograph when voltage of 10 V is applied at room temperature is shown in Fig. 5(b). When the micrograph of Fig. 5(b) was taken, we exposed for 1 min because the light intensity was low.

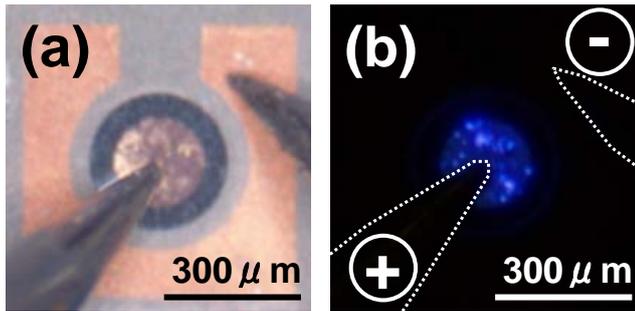


Fig. 5: Micrograph of LED before voltage is applied(a) and voltage of 10 V is applied(b).

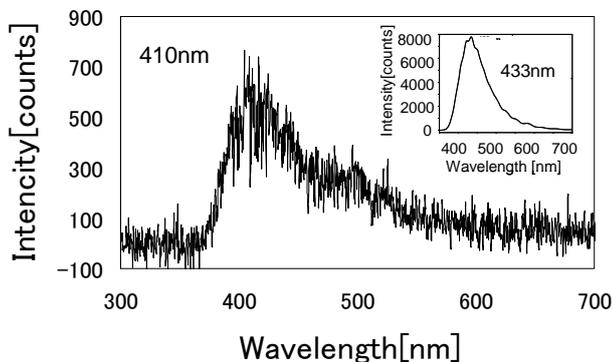


Fig. 6: EL and PL spectrum of GaN-based LED.

As shown in Fig. 5 (b), blue light was observed through the whole of the p-GaN electrode. It seems that much current flow in the bright part. It may cause the breaking of GaN crystal at the bright part when much voltage is applied. More research should be done to solve this problem. Figure 6 shows the electroluminescence (EL) spectrum and the inset is the photo luminescence (PL) spectrum. The peak emission of EL is obtained at the wavelength of 410 nm with a full width at half maximum (FWHM) of about 80 nm. On the other hand, the peak emission of PL is the wavelength of 433 nm with a FWHM of about 65 nm. Almost the same EL as PL was observed.

#### 4. FABRICATION OF GAN MEMBRANE

To fabricate the GaN membrane, the back side of the template substrate was polished to make the thickness of the template substrate 200  $\mu\text{m}$ . Then photoresist was spin coated and patterned. Circular and linear pattern mask was used. The diameter of the circles was ranged from 150  $\mu\text{m}$  to 500  $\mu\text{m}$  and width of the lines were 50  $\mu\text{m}$  and 100  $\mu\text{m}$ . Both of

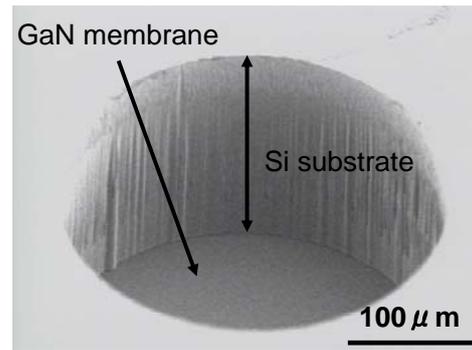


Fig. 7: SEM image of the GaN membrane.

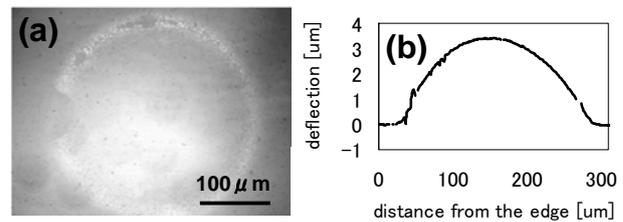


Fig. 8: Micrograph of the GaN membrane(a) and cross sectional profile of the membrane(b).

length of the lines were 9 mm. We etched the substrate by ICP reactive ion etching (ICP-RIE) using  $\text{SF}_6$  gas until GaN film become exposed.

The SEM image of the membrane is shown in Fig. 7. It shows that Si is completely etched and only the GaN membrane existed in the circular area. As for the circular membranes, although a few membranes of the diameter from 300  $\mu\text{m}$  to 500  $\mu\text{m}$  were broken, a large number of membranes existed after etching. As for the linear membranes, few lines remained completely at the length of 50  $\mu\text{m}$ . All lines broke partly at the length of 100  $\mu\text{m}$ . The resistance of GaN film is dependent on the diameter of the membrane [9] and the thickness of the GaN film [10]. In our template, the total thickness of 850 nm, the circular diameter of the membranes less than 300  $\mu\text{m}$  can be suitably fabricated. On the other hand, the linear width should be shortened less than 50  $\mu\text{m}$ .

The micrograph and the cross sectional profile of the membrane are shown in Fig. 8 (a) and Fig. 8 (b). The diameter of the membrane is 300  $\mu\text{m}$ . A deflection was observed from the membrane. The maximum deflection was 3.4  $\mu\text{m}$ . The deflection indicates a residual compressive stress in GaN film. The larger the diameter of the circle becomes, the larger the deflection becomes. It seems that large deflection caused the wreck at the large diameter of membranes.

## 5. CONCLUSION

GaN-based light emitting diodes (LEDs) were fabricated by molecular beam epitaxy (MBE) grown on the GaN template. Blue light emission with a peak wavelength of 410nm was observed when it was applied voltage of 10 V. GaN membrane structure was also fabricated from the template. A large number of membranes existed after etching at the circular membranes. As for the linear membranes, lines of 50  $\mu$ m remained. Based on these results, GaN LED with cooling system is now being designed and fabricated as the future work.

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