Control of Mesa Shape by ICP-RIE Condition to Fabricate Monolithically Integrated Micro-LEDs

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ABSTRACT

We assessed dry etching conditions to form a gentle slope for the side surface of GaN mesa structure. The technique enables us to prevent the electrode disconnection when the top-down monolithic integration method is employed to fabricate the micro-LED displays.

1 Introduction

Micro-LED display is considered as a promising technology for development of next-generation displays [1]. In the prototype, flip-chip LEDs are integrated on a circuit board. However, significant challenges still remain in cost-effective mass production technology to accurately handle the huge number of LED chips. In contrast, top-down monolithic integration method enables miniaturization and alignment of the LEDs, simultaneously. The technique is realized by etching the LED wafer by the inductively-coupled-plasma reactive-ion-etching (ICP-RIE) method. In general, highly anisotropic dry etching condition is conventionally employed for LED isolation by using a gas mixture of BCl_3, Cl_2, and Ar. However, due to high perpendicularity of the LED sidewall, electrode disconnection occurs if line electrodes are formed on the corrugated surface. In this study, first, we assessed dry etching conditions to form a gentle slope for the LED side surface. Then, the condition was employed to form micro-LED pixels.

2 Experiment

First, to assess the dry etching conditions, 3-μm-thick GaN template on (0001) sapphire was used. Resist pattern was formed on the GaN template by photolithography. Then, ICP-RIE was conducted using a gas mixture of BCl_3 and Cl_2 with flow rates of 15 and 20 sccm, respectively [2]. The Ar gas was not used to avoid anisotropic dry etching condition. The RF ICP power was 150 W, process pressure was 0.8 Pa, and RF bias power was varied from 10 to 40 W.

Second, the etching condition was employed to form micro-LED pixels as follows. Blue LED wafer was prepared on (0001) sapphire substrate by metalorganic vapor phase epitaxy. It consists of a 2.5-μm-thick unintentionally-doped (UID) GaN, 1.0-μm-thick Si-doped n-type GaN, a total of 100-nm-thick five periods of GaInN/GaN multiple quantum-well emission layer, and a 100-nm-thick Mg-doped p-type

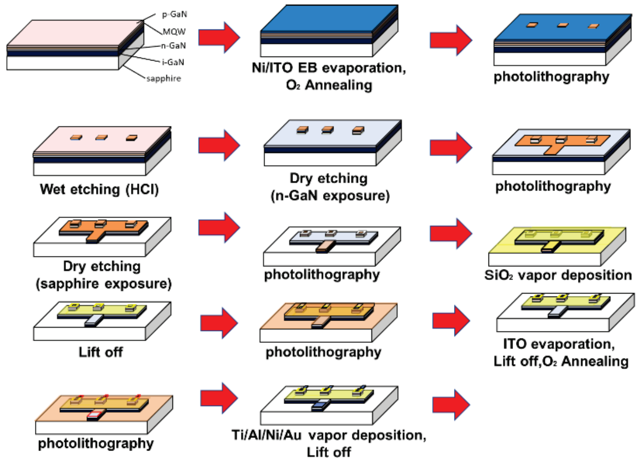

Fig. 1 Schematic diagram of fabrication processes for micro-LED pixels.

GaN. Fabrication processes for μ-LED pixels are schematically shown in Fig. 1. After annealing the LED wafer in a nitrogen atmosphere to activate acceptors in the p-type GaN, a 5-nm-thick Ni metal and 100-nm-thick ITO were deposited by an electron beam (EB) evaporation method. The ITO was annealed in an oxygen atmosphere to make it transparent. After patterning the Ni metal and ITO by photolithography and wet chemical etching, the LED wafer was selectively etched by the ICP-RIE method to expose the n-GaN contacting layer. Here the optimized condition was employed to form a gentle slope for the LED side surface. Then, to form the LED mesa, the LED wafer was again patterned by photolithography, and the LED wafer was selectively etched by the ICP-RIE method. Here the optimized condition was again employed to form a gentle slope for the side surface. After that, to form the isolation layer, the LED wafer was patterned by photolithography and a 300-nm-thick SiO_2 was deposited by the EB evaporation, and it was patterned by the lift-off technique. To form the p-type electrode, the LED wafer was patterned by photolithography and a 5-nm-thick Ni metal and 100-nm-thick ITO were deposited by the EB evaporation. ITO was annealed in an oxygen atmosphere to make it transparent. Finally, to form the electrode pads, the LED wafer was patterned by photolithography and a total of 80-nm-thick Ti/Al/Ni/Au

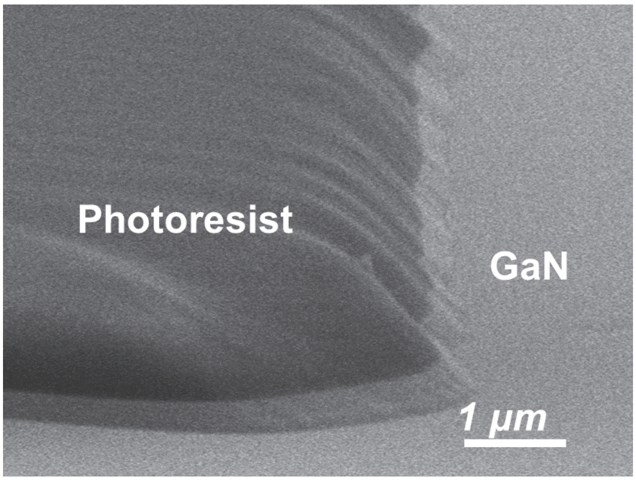

Fig. 2 Bird's-eye view SEM image (×10,000) of the mesa structure formed on the GaN template.

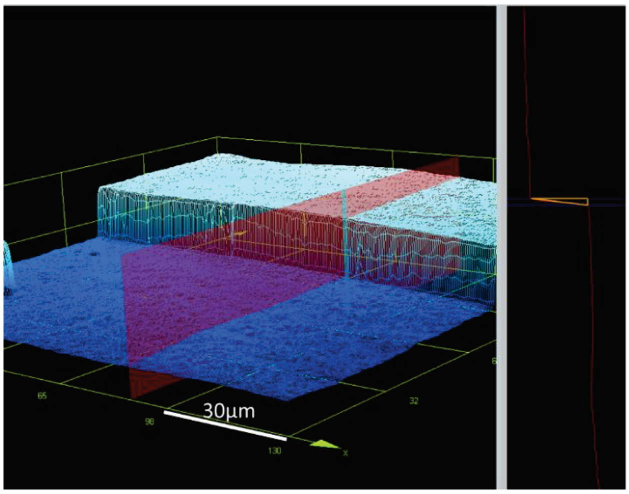

Fig. 3 Laser microscope image (x100) of the mesa structure formed on the GaN template.

metal were deposited by the EB evaporation, and it was patterned by the lift-off technique.

Side surface of the mesa structures were evaluated for six locations each using FE-SEM, contact profilometer, and laser microscope.

3 Results

Figure 2 shows a representative bird's-eye view SEM image of the mesa structure formed on the GaN template by etching for 300 sec. with RF bias power of 30 W. Formation of the gentle slope was confirmed for the LED sidewall. Here the slope angle is defined as the angle between the surface plane and the sidewall. The slope angle was evaluated by the laser microscope as shown in Fig. 3. The RF bias power dependence of the slope angle is shown in Fig. 4. The slope angles were determined to be 88.3°, 84.3°, 83.4°, and 86.0° at the RF bias power of 10 W, 20 W, 30 W, and 40 W, respectively. Figure 5 shows a representative bird's-eye view SEM image of the micro-LED pixel after forming the SiO_2 isolation layer. It was confirmed that a continuous SiO_2 film was successfully deposited on the gentle slope with a slope angle of 78°.

4 Discussion

As mentioned in the introduction, physical anisotropic etching occurs when the gas mixture of BCl_3, Cl_2, and Ar is used during the ICP-RIE. The vertical sidewall is obtained due mainly to the physical sputtering effect. In contrast, chemical etching dominantly occurs when the gas mixture of BCl_3 and Cl_2 is used. Formation of the gentle slope for the mesa structure is attributed to the isotopic etching. Here, surface damage is known as another critical issue when the gas mixture of BCl_3, Cl_2, and Ar is used during the ICP-RIE. As shown in Fig. 5, the sidewall exhibits a fairly smooth surface. The result

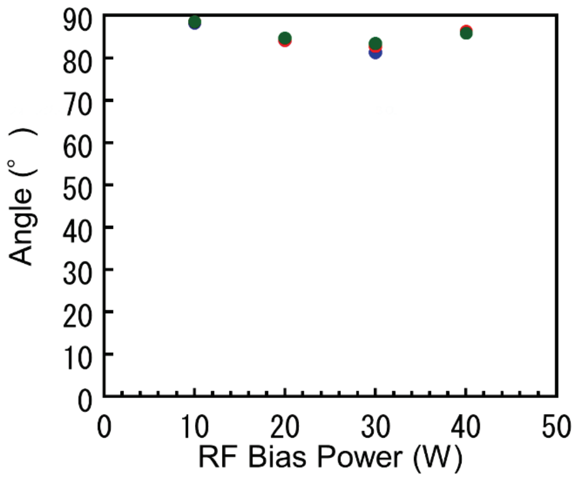

Fig. 4 RF bias power dependence of the slope angle.

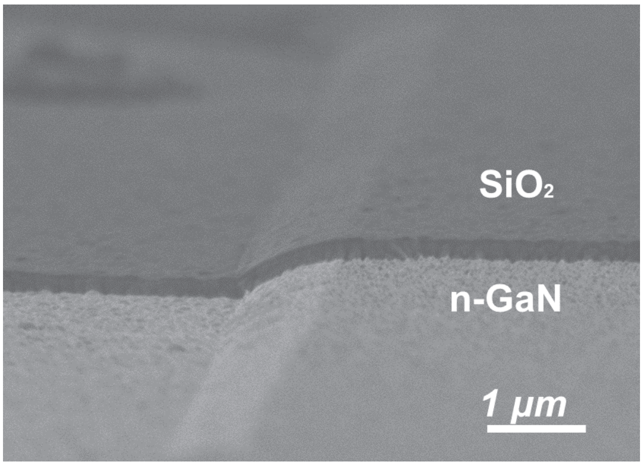

Fig. 5 Bird's-eye view SEM image (×5,000) of the micro-LED pixel after forming the SiO2 isolation layer.

indicates that present optimized condition is also suitable to form smooth surface for the LED sidewall.

5 Conclusions

We investigated dry etching conditions to form a gentle slope for the side surface of GaN mesa structure. Chemical etching dominantly occurs when the gas mixture of BCl_3 and Cl_2 is used. Formation of the gentle slope for the mesa structure was attributed to the isotopic etching. The dry etching process was also successful in forming a smooth side surface. The technique enables us to prevent the electrode disconnection when the top-down monolithic integration method is employed to fabricate the micro-LED displays.

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