Fabrication of pyramid array nanostructure on gallium nitride

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ABSTRACT

GaN is employed in more and more blue-violet/bright light emitting diode (LED) applications. However, its relatively high refractive index is responsible for trapping light inside and lowering the external quantum efficiency of the device. A novel way to combine the various methods to solve the problem is to construct a pyramid array on the GaN surface. Not only does it have the periodic structure, it also has an effective index of refractive index with gradient value along the height of the pyramid. An n-type GaN wafer of (0001) plane is used as the substrate. With the SiO$_2$ mask defined by an e-beam writer, it undergoes inductively coupled plasma (ICP) etching. By varying the etching rate and the mask layer thickness, we can obtain different shapes of pyramids. The study investigates various factors affecting the outcomes of arrays, with several array sizes and pitches. The technique can be deployed to GaN layers in photonics devices to have arrays with desired pitch and size for optimal performance in different applications.

Keywords: plasma enhanced chemical vapor deposition, high density plasma, inductively coupled plasma, e-beam writer, GaN pyramid array

1 INTRODUCTION

Gallium nitride (GaN) is employed in more and more blue-violet/bright light emitting diode (LED) applications. However, its relatively high refractive index (~2.5) results in small critical angle (~23°) at the interface with air, which is responsible for trapping light inside and lowers the external quantum efficiency of the device.

Many researches have been devoted to solve the problem. One way is to make texture on the surface of GaN. Irregular nano rods as surface texture can be made by rapid annealing to form Ni metal spheres and dry etching [1–4]. Alternatively, rough surface texture can be made by wet etching with KOH and H$_3$PO$_4$ [5–7]. However, it is more challenging to do wet etching on GaN. Also, metal-assistant etching can be applied on p-GaN [8].

Second way is to make a periodic nano structure on GaN surface to form photonic crystal such as nano rods [9,10] and micro lens [11,12]. Another way is to deposit thin film layer(s) with gradient refractive index to minimize the great mismatch of refractive index between GaN and air.

A novel way to combine the various methods is to construct a pyramid array on the GaN surface. Not only does it have the periodic structure, it also has an effective index of refraction with gradient value along the height of the pyramid. In this study, we present the process and the result of making pyramid of array of GaN.

2 FABRICATION PROCESS

An n-type GaN wafer of (0001) plane is used as the substrate. A SiO$_2$ layer with 200 nm thickness is grown on the substrate by the plasma enhanced chemical vapor deposition (PECVD) with the temperature at 270°C, the pressure at 0.1 mTorr, the RF-power at 50 W. Next, a 500-nm layer of negative photoresist is spin-coated on the SiO$_2$ layer. After the soft bake, the mask pattern is transferred to the wafer by an e-beam writer. Then, the wafer undergoes develop and hard bake before the high density plasma (HDP) etching to form the SiO$_2$ mask. The HDP etching has the RF-power at 100 W, the etch time of 240 s, and the gases of Ar, O$_2$, SF$_6$, He with the flow rates of 25, 5, 50, 10 sccm, respectively. Finally, the wafer with SiO$_2$ mask is etched by the inductively coupled plasma (ICP) system

Figure 1: the schematic showing the fabrication process.
having the RF-power at 600 W, the chamber pressure below 10 mTorr, the gases of BCl$_3$, Cl$_2$, Ar with the flow rates of 19, 49.9, 5 sccm, respectively, to have the etch rate of 40 Å/s and the etch time of 150 s. The process is summarized in Figure 1.

3 RESULTS

There are three important factors affecting the resultant shape of the pyramid. They are the ICP etching time, the ICP reactant gas ratio, and the array pitch. The detail description is in the following.

3.1 ICP Etching Time

The time duration in ICP etching process can be used to control the etching depth of GaN for the desired shape. With a particular set of values for the parameters of the RF-power, the reactant gas ratio, and the gas flow rate, the critical etching time is found as 150 s at 40 Å/s etching rate with which the SiO$_2$ layer is barely etched away and a pyramid tip is formed, as shown in Fig. 2b. For comparison, an etching duration shorter than the critical time results in pyramids with truncated tips because of some SiO$_2$ remains on top of GaN, as shown in Fig. 2a. On the other hand, an etching duration longer than the critical time yields pyramids with tips damaged by the etching, as shown in Fig. 2c.

3.2 Reactant Gas Ratio

Changing the reactant gas (BCl$_3$, Cl$_2$, Ar) ratio can make different shapes of pyramids. Figure 3a shows a rounded pyramid, or a cone; Fig. 3b shows a desired pyramid; Fig. 3c shows a pyramid with an unwanted tip facet.

3.3 Array Pitch

The pitch of pyramid array also affects the outcome of the pyramid etching. The following demonstrates the effect. We make three arrays with different sizes and pitches. Three mask patterns are defined with array of circles whose diameters are 500 nm, 1000 nm, 1500 nm, respectively. The space between adjacent circles is set to equal to the diameter. Therefore, the pitches of the three arrays are 1000 nm, 2000 nm, and 3000 nm. With the identical process condition (e-beam photoresist thickness, SiO$_2$ layer thickness, e-beam exposure time, HDP etching time, ICP...
etching time), we expect the etching depth to be identical and yield pyramid with identical incline angle but different base width, as shown in Fig. 4.

The result is observed with SEM, as shown in Fig. 5. Figure 5a shows the pyramid (a rounded pyramid, or a cone) with a well defined tip. This is an expected result. Processes with greater diameters also yield expected shapes with truncated tips, except that the truncated facet has numerous craters, as shown in Fig. 5b and 5c. The formation of craters is due to the micro loading effect in ICP etch. Specifically, the etch rate can affected by the mask pattern; greater etch window on the mask results in faster etch rate. Because the critical time for ICP etch is formation of craters is (diameter of 500 nm,) configures b and c with greater etch windows experience faster etch rate and result in over-etch and craters.

(a)

(b)

(c)

Figure 5: SEM pictures of three different pyramid diameters: (a) 500 nm, (b) 1000 nm, and (c) 1500 nm. For each type of pyramid, individual and array SEM pictures are shown.

4 CONCLUSION

By varying the etching rate and the mask layer thickness, we can obtain different shapes of pyramids. Figure 6 shows some of them: rounded pyramids, pyramids with acute tops, and pyramids with blunt tops. The study investigates various factors affecting the outcomes of arrays, with several array sizes and pitches. The technique can be employed to GaN layers in photonics devices to have arrays with desired pitch and size for optimal performance in different applications.

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