Fabrication of pyramid array nanostructure on gallium nitride

Cheng-Che Hsieh[*], Wen-Cheng Ke[**], Nien-Po Chen[*1], Wen-Jen Lin[***], Yi-Cheng Cheng[***], Ta-Ching Li[***], and Jia-Ching Lin[***]

[*]Dept. of Photonics Engr., Yuan Ze University, 135 Yuan-Tung Road, Tao-Yuan, 32003, Taiwan
[**]Dept. of Mechanical Engr., Yuan Ze University, 135 Yuan-Tung Road, Tao-Yuan, 32003, Taiwan
[***]Chung-Shan Inst. of Science & Technology, 481 Chung-Cheng Road, Tao-Yuan 32546, Taiwan

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 refraction 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_3PO_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

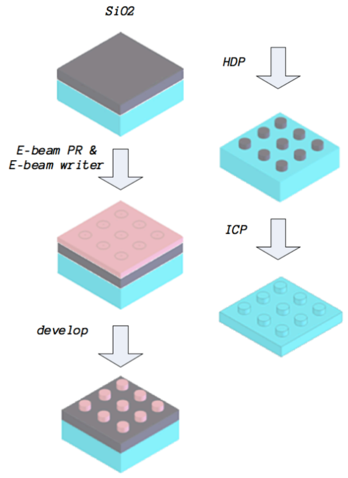

Figure 1: the schematic showing the fabrication process.

---

[1] Phone: +886-3-4638800 x7519 FAX: +886-3-4514281
e-mail: npchen@saturn.yzu.edu.tw

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. 2*b*. 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. 2*a*. On the other hand, an etching duration longer than the critical time yields pyramids with tips damaged by the etching, as shown in Fig. 2*c*.

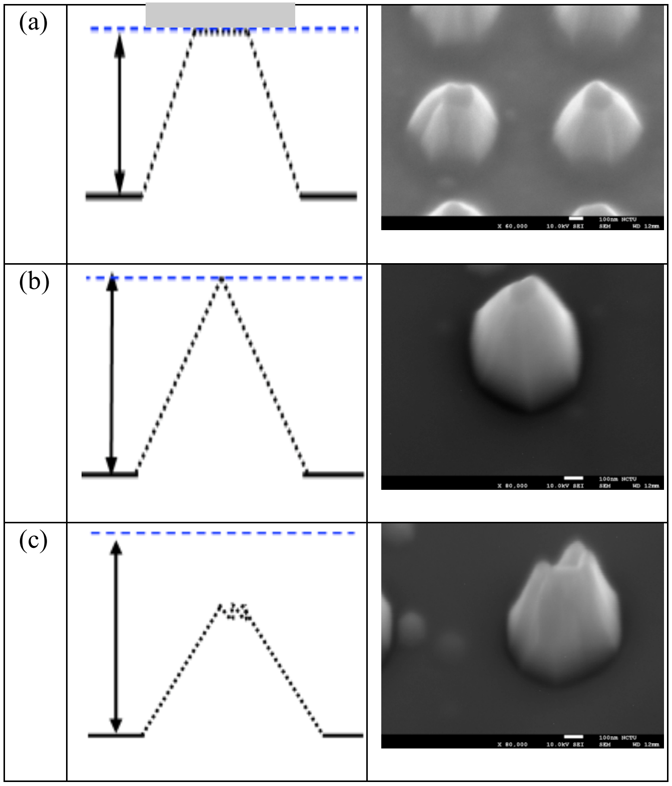

Figure 2: The effect of various ICP etching time: (a) shorter than, (b) equal to, and (c) longer than the critical time.

3.2 Reactant Gas Ratio

Changing the reactant gas (BCl_3, Cl_2, Ar) ratio can make different shapes of pyramids. Figure 3*a* shows a rounded pyramid, or a cone; Fig. 3*b* shows a desired pyramid; Fig. 3c shows a pyramid with an unwanted tip facet.

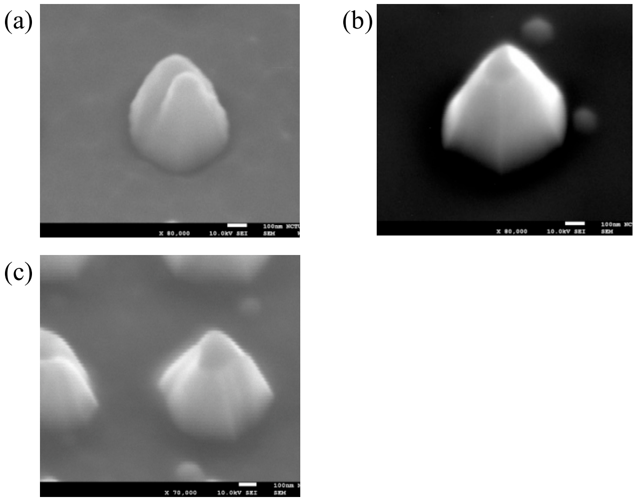

Figure 3: The effect of different ratios of reactant gases: (a) a cone, (b) a desired pyramid, and (c) a pyramid with an unwanted tip facet.

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

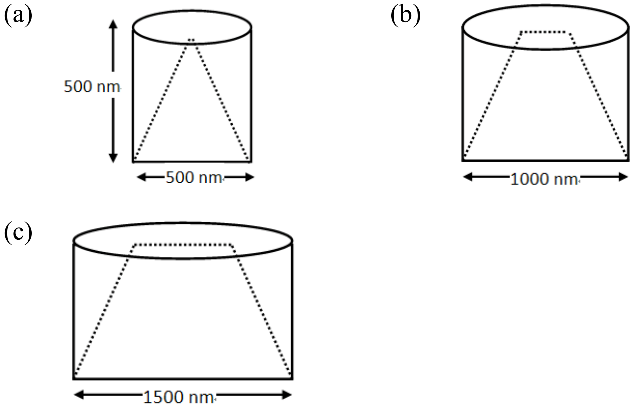

Figure 4: The schematics showing the expected shapes of pyramids with different diameters and pitches.

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 5*a* 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. 5*b* and 5*c*. 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 obtained by using the etch rate of configuration *a* (diameter of 500 nm,) configures *b* and *c* with greater etch windows experience faster etch rate and result in over-etch and craters.

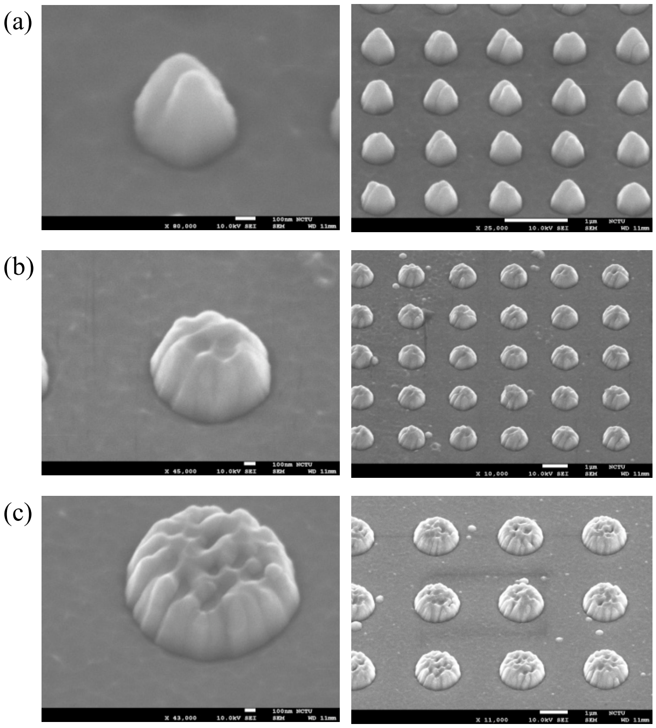

Figure 5: SEM pictures of three different pyramid diameters: (a) 500 nm, (b) 1000 nm, and (c) 1500 nm. For each type of pyramid, individual and array SEM pictures are shown.

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.

ACKNOWLEDGMENT

The authors would like to thank the support by the grant XV98G27P251PE.

REFERENCES

[1] H.-W. Huang, C.-C. Kao, T.-H. Hsueh, C.-C. Yu, C.-F. Lin, J.-T. Chu, H.-C. Kuo, and S.-C. Wang, “Fabrication of GaN-based nanorod light emitting diodes using self-assemble nickel nano-mask and inductively coupled plasma reactive ion etching,” *Mater. Sci. Engi. B*, vol. 113, pp. 125–129, 2004.

[2] C. H. Chiu, T. C. Lu, H. W. Huang, C. F. Lai, C. C. Kao, J. T. Chu, C. C. Yu, H. C. Kuo, S. Wang, C. F. Lin, and T. H. Hsueh, “Fabrication of InGaN/GaN nanorod light-emitting diodes with self-assembled Ni metal islands,” *Nanotech.*, vol. 18, p. 445201, 2007.

[3] H. W. Huang, J. T. Chu, T. H. Hsueh, M. C. Ou-Yang, H. C. Kuo, and S. C. Wang, “Fabrication and photoluminescence of InGaN-based nanorods fabricated by plasma etching with nanoscale nickel metal islands,” *J. Vac. Sci. Technol. B*, vol. 24, pp. 1909–1912, 2006.

[4] Y.-R. Wu, C. Chiu, C.-Y. Chang, P. Yu, and H.-C. Kuo, “Size-dependent strain relaxation and optical characteristics of InGaN/GaN nanorod LEDs,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, pp. 1226–1233, 2009.

[5] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, “Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening,” *Appl. Phys. Lett.*, vol. 84, pp. 855–857, 2004.

[6] W. C. Peng and Y. C. S. Wu, “Improved luminance intensity of InGaN–GaN light-emitting diode by roughening both the p-GaN surface and the undoped-GaN surface,” *Appl. Phys. Lett.*, vol. 89, p. 041116, 2006.

[7] R.-H. Horng, X. Zheng, C.-Y. Hsieh, and D.-S. Wuu, “Light extraction enhancement of InGaN light-emitting diode by roughening both undoped micropillar-structure GaN and p-GaN as well as employing an omnidirectional reflector,” *Appl. Phys. Lett.*, vol. 93, p. 021125, 2008.

[8] X. Guo, T. Williamson, and P. Bohn, “Enhanced ultraviolet photoconductivity in porous GaN prepared by metal-assisted electroless etching,” *Solid State Commun.*, vol. 140, pp. 159–162, 2006.

[9] N. Kouklin and J. Liang, “Ultradense GaN nanopillar and nanopore arrays by self-assembly nanopatterning,” *J. Electron. Mater.*, vol. 35, pp. 1133–1137, 2006.

[10] Y. D. Wang, S. J. Chua, S. Tripathy, M. S. Sander, P. Chen, and C. G. Fonstad, "High optical quality GaN nanopillar arrays," *Appl. Phys. Lett.*, vol. 86, p. 071917, 2005.

[11] D. Kim, H. Lee, N. Cho, Y. Sung, and G. Yeom, "Effect of GaN microlens array on efficiency of GaN-based blue-light-emitting diodes," *Jpn. J. Appl. Phys.*, vol. 44, pp. L18–L20, 2005.

[12] M.-L. Wu, Y.-C. Lee, S.-P. Yang, P.-S. Lee, and J.-Y. Chang, "Azimuthally isotropic irradiance of GaN-based light-emitting diodes with GaN microlens arrays," *Opt. Express*, vol. 17, pp. 6148–6155, 2009.

[13] H. W. Huang, C. H. Lin, C. C. Yu, K. Y. Lee, B. D. Lee, H. C. Kuo, S. Y. Kuo, K. M. Leung, and S. C. Wang, "Investigation of Gan-based vertical-injection light-emitting diodes with GaN nano-cone structure by ICP etching," *Mater. Sci. Engi. B*, vol. 151, pp. 205–209, 2008.

[14] K. H. Baik and S. J. Pearton, "Dry etching characteristics of GaN for blue/green light-emitting diode fabrication," *Appl. Surface Sci.*, vol. 225, pp. 5948–5951, 2009.

[15] H. M. Ng, N. G. Weimann, and A. Chowdhury, "GaN nanotip pyramids formed by anisotropic etching," *J. Appl. Phys.*, vol. 94, pp. 650–653, 2003.