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Fabrication of GaN Nano Pillars using Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) Technique: A Review

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Introduction

The ICP-RIE is very popular experimental technique frequently used in the field of fabrication of semiconductor nanostructures as well as their devices[1-5]. Here, we present a short review on ICP-RIE technique to manipulate the surface morphology of semiconductor materials and to fabricate the semiconductor nanostructures with emphasis on Gallium Nitride (GaN) and their nanostructures. It is a very efficient dry etching technique for thin-film of Indium Nitride (InN), Aluminium Nitride (AlN) and Gallium Nitride (GaN) based III-V semiconductor materials etc.[2-8]. The advantage of ICP-RIE technique is used forselective dry etchingwhich yields an excellent finishing accuracy as well reproducibility for etching of the chemically hard materials namely Silicon Carbide (SiC), GaN or diamond[1-3, 5, 9, 10]. This method has been employed to fabricate the various types of non-planar microstructures and structures having a tilted sidewalls [3, 4, 9, 11-13]. The SiC has a wide applications in the field of semiconductor electronics [3, 9, 11, 13]. Although, these materials have a lot of applications but they are very hard and chemically inert. Therefore, their chemical processing is a tough task [3, 11]. For the etching of such materials the plasma etching is preferably used [3, 11]. This technique has been utilised for the processing of thematerials' surface preparation for the fabrication of schottkydiodes ofdiamond or cubic boron nitride (c-BN) also[12-14].

ICP-RIE technique has been widely used as a top down approach for the fabrication of GaN based nanostructures[1, 4-10, 15]. GaNtogether with its alloys have primarily been targeted for their numerous applications in optoelectronic devicesas well as high temperatures, high powers, and high frequencies electronic devices [5, 16]. In past few decades, GaNnanostructures have received a focused attention in nanoscale device integration. These structures are usually obtained by employing different bottom-up as well as top down approaches [17-20]. GaNnanopillars aresimplyfabricated by keeping the wafer of a GaN epitaxial layer inside the argon/chlorine plasma in ICP-RIE plasma chamber. The beauty of this etching technique is that it does not need any form of prior lithography processing for the fabrication of nanostructure [1-3, 5, 10].Kao*et al*. reported the fabrication of nano-roughened

GaN laser lift-off (LLO) light-emitting diodes (LEDs)[1, 6-8]. Here, they modified the roughness using ICP-RIE technique in controlled manner. Their study suggests that the electrical properties were almost intact without degradation. Further, they reported that the light-output power and the efficiency of LLO LED both enhanced significantly [1, 6-8]. Lee*et al*. investigated the Au/n-GaNschottky barrier diodes fabricated in an ICP-RIE system[1, 2, 10]. Their finding suggests that the electrical properties of these diodes depend strongly on various parameters of RIE gas composition[2, 3].

Fabrication of GaN Nano Pillars: A Case Study

Here, we have briefly reviewed the utilization of ICP-RIE technique to fabricate the GaN nanostructure (tapered pillar shaped structures)[9].The detailed mechanism for the formation of these nanopillarsare reported elsewhere [9]. Ghosh *et al*. reported that theinversion domains (IDs) are route cause for the formation of these pillars. In the pillar formation the reactive ion etching process plays an important role for the polarity selective etching of GaN[1, 2, 4, 5, 9, 10, 12]. Here, we focuson the sputtering process using ICP-RIE for thefabrication of tapered shaped GaN nanostructures[1, 2, 8, 9, 12]. ICP-RIE is a highly efficient technique which has the ability to etch the material with high etching rate, high selectivity and low damage processing[1, 2, 4, 5, 8-10, 12]. Since the plasma can made available at low pressures, this technique offers awell controlledprofile control of structures.

Physics of Sputtering Process

The etching of the wafers/materials via ICP-RIE utilizes the phenomenon of interaction of ions species of plasma with the material to be etched [5]. The reactive plasma is formed due to the glow discharge of etching gas[5, 9, 11]. Here,the plasma excitation is producedby an electromagnetic field of radio-frequency[5, 9, 11]. The exchange of momenta amongst the plasma ions and materials due to collision is responsible for physical sputtering.This process creates the cascading effect in the target material. As a result of this cascade event, an atom will be ejected from the surface of the material provided that such cascades recoil and reach the target surface with energy greater than the surface binding energy of the target material. The primary particle in the sputtering process can be triggered by igniting plasma inside the processing chamber.

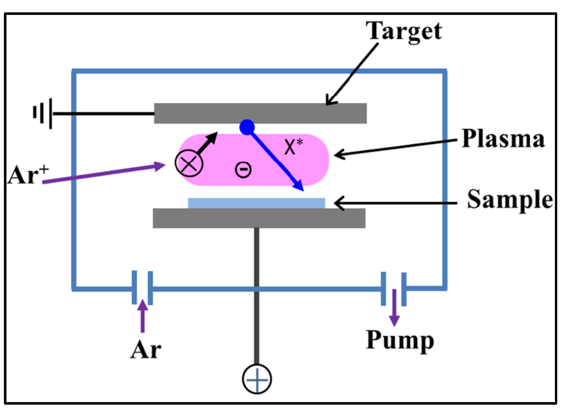

Figure 1:*The schematic diagram of metal sputtering process chamber and their integral parts of the Metal Sputtering System NORDIKO, CEN - Centre of Excellence in Nano electronics, Indian Institute of Technology Bombay, Powai, Mumbai.*

Figure 1 shows the schematic of Nordiko Metal sputtering system. This machine essentially consists of vacuum chamber, target, Plasma sources, RF frequency generators, Impedance matching network and pressure gauges for measuring pressure inside the processing chamber. Metal sputter system has 2 inch sample/wafer holder attached with a substrate heater which can heat the substrate upto~400°C. The base pressure and sputtering pressure was kept at 1.3×10^{-3} and 2.6×10^{-3} mbar, respectively. In the process of sputtering Argon (Ar) gas was used while nitrogen gas was used for venting of the growth chamber.

Experimental Details

The tapered shaped nanopillars were fabricated by ICP-RIE technique [1]. A commercially available hydride vapor phase epitaxy (HVPE) grownc-plane GaNwith layer grown on c-plane sapphire substratehaving thickness 3μm was procured from Technologies and Devices International, Inc. The details are reported elsewhere[9].

Table1: The parameters of ICP-RIE process for the fabrication of GaNnanopillars.Reprinted from "Polarity selective etching: A self-assisted route for fabricating high density of c-axis oriented tapered GaNnanopillars", A. Ghosh, H. P. Bhasker, A. Mukherjee, et al, Journal of Applied Physics 110, 033528 (2011), with the permission of AIP Publishing with License Number 5516571426719.

ICP Power (Watt)	RF Power (Watt)	Cl_2 flow rate (sccm)	Ar flow rate (sccm)	Chamber Pressure (mTorr)	Electrode Temperature (°C)
300-500	325	25	5	2-15	25

Results and Discussions

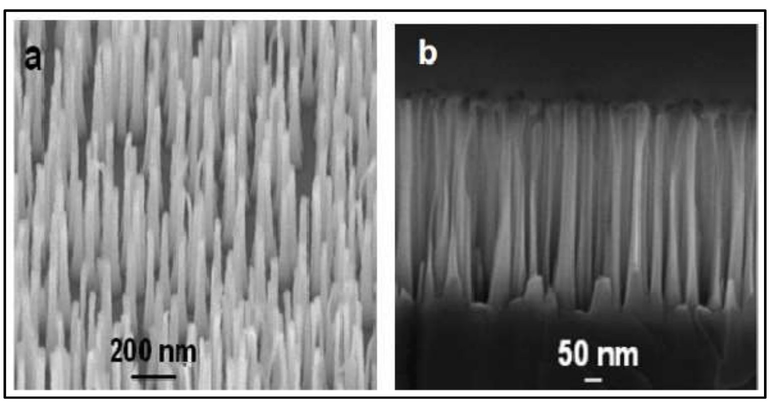

Figure 2: *SEM images for the HVPE sample after the RIE process; (a) surface image with 45° surface orientation. (b) Cross-sectional SEM scan. Reprinted from "Polarity selective etching: A self-assisted route for fabricating high density of c-axis oriented tapered GaNnanopillars", A. Ghosh, H. P. Bhasker, A. Mukherjee, et al, Journal of Applied Physics 110, 033528 (2011), with the permission of AIP publishing with License Number 5516571426719.*

Figure 2(a) *shows the Scanning Electron Microscopy (SEM) surface image ofGaN which was grown using HVPE techniqueobtained after itsexposure in ICP-RIE chamber. The SEM image reveals that the large densities of c-axis oriented pillars areformed on the surface[9].*

The SEM cross-sectional images of the samplefurther confirm that these pillars are highly orientated as shown in Fig. 2(b).These pillars are found to be of similar shape as well as size and, are also homogenous in nature[9]. Interestingly, pillars were reported to be approximately equal height. The fabrication of pillars of same height could be the consequence of selective etching process. In selective etching process, the certain region of the GaNremain unaffected during the RIE process while rest of the regions is etched [9].The average tip diameter and the density of the pillars was reported to be ~ 22 nm and 3×10^{10} cm^{-2}, respectively.

Mechanism of formation of tapered shape GaNnanopillars

Ghosh et al. investigated the route cause for the fabrication of tapered shaped GaNnanopillars and proposed the following model. Since, GaN is polar material exhibiting spontaneous polarization (P = 0.29 C/cm^2) along the c-axis [9]. It is important to mention that polarization (P) is positive for the N-polar GaNwhile it is negative for the Ga-polar GaN. Therefore, the certain amount of negative charges generatesspontaneously on the Ga-polar regions while positive charges is also gets generatedspontaneously in the region of N-polar surfaces[9]. They reported that the IDs in GaN films were associated with nitrogen polar domains running from top surface to the bottom of the film connecting to the substrate [21, 22].

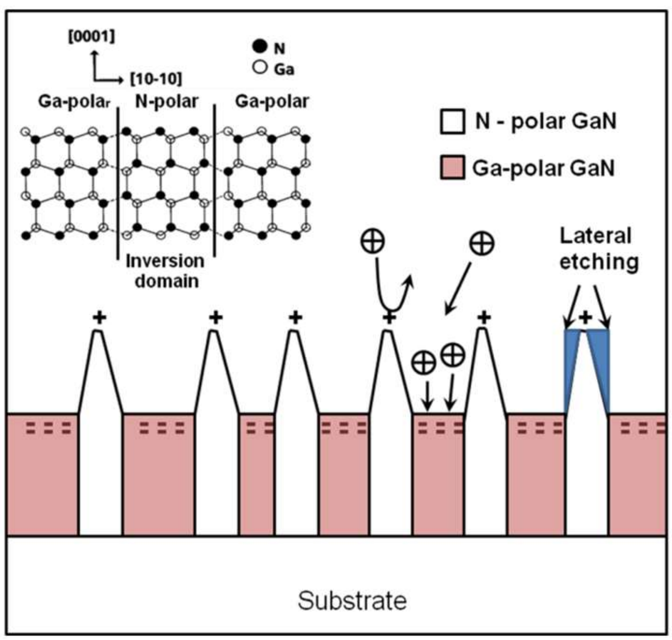

__Figure 3:__The schematic picture of the etching process. The inset schematically represents the arrangements of the atoms in the Ga and N-polar (inversion domains) regions. Positions of the atoms are projected onto the (1-210) plane.Reprinted from "Polarity selective etching: A self-assisted route for fabricating high density of c-axis oriented tapered GaNnanopillars", A. Ghosh et al., Journal of Applied Physics 110, 033528 (2011), with the permission of AIP publishing with License Number 5516571426719.

Figure 3 dipicts the selective reactive ion etching of epitaxial film for taperd shape pillar formation [9]. Details about the pillars formation can be found in ref. [9]. The columnar structure of the tapered pillars is a consequence of their lateral etching (also depicted in Fig. 3). The upper portion of the pillars are exposed for longer period while the bottom part is shorter time duration to the plasma ions. And, therefore, the upper part of the pillars is more laterally etched as compared to the lower part of the pillars [9].

They reported that thenanopillarsdensity is strongly connected with the ICP power[9]. The tapered nature could be explained in terms of two types of etching namely vertical as well as lateral [9]. The gases present in RIE laterally etch the nanopillarswhile the Ga Polar Regions are vertically etched. The nanopillars' density and diameter both are governed by the compition between the lateral and vertical etching [9].

Conclusions

Here, we present a review on fabrication of GaNbased nanostructure and related Materials using ICP-RIE technique. This technique could be very helpful for the fabrication of tapered nanopillars with high density,c-axis oriented fine tip GaN.

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