Development of GaN Vertical High-Power Devices Enabled by Plasma-Assisted Molecular Beam Epitaxy

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Abstract

Selective Area Growth using GaN PAMBE is used to develop vertical device structures suitable for high power electronics. P-doping levels and crystallinity of grown films are confirmed, and a comparison is made between ICP-RIE etched GaN and selectively regrown regions. Imaging of each step of the process is shown and discussed, and future plans are outlined,

Introduction

Gallium nitride power devices have garnered a great deal of interest in recent years due to GaN's high band gap, high breakdown field, and high mobility which give it the highest BFOM of commercially available materials [1]. MOCVD is widely used to grow GaN films, however this method suffers in various areas such as high growth temperatures, use of hydrogen-containing precursors, and the need for etching/ion implantation. Plasma-assisted molecular beam epitaxy (PAMBE) offers a means of avoiding all of these issues. Via PAMBE, our group has repeatedly demonstrated high p-doping (Figure 1), high-crystallinity films (Figure 2), in addition to low background doping (~10^{16} cm^{-3} determined by C-V of SBDs) all of which are necessary in the area of power devices. In conjunction with our selective area growth (SAG) technique this enables the design of many different device architectures. In our sister paper, device architectures and simulated characteristics are discussed to drive experimental progress. Currently, p-islet merged-PIN-Schottky diodes are being produced and studied with the goal of moving towards more complex devices in the near future.

Experimental Results

Figure 1 shows common doping levels and resulting activation percentages. The SIMS data in Figure 1 not only gives us the incorporation levels, the decay of the peaks gives insight into the growth kinetics. The effects of this are explored in a sister paper. By making MOS capacitors, doping levels were obtained. Low 10^{18} cm^{-3} hole concentrations were observed, corresponding to activation levels slightly above

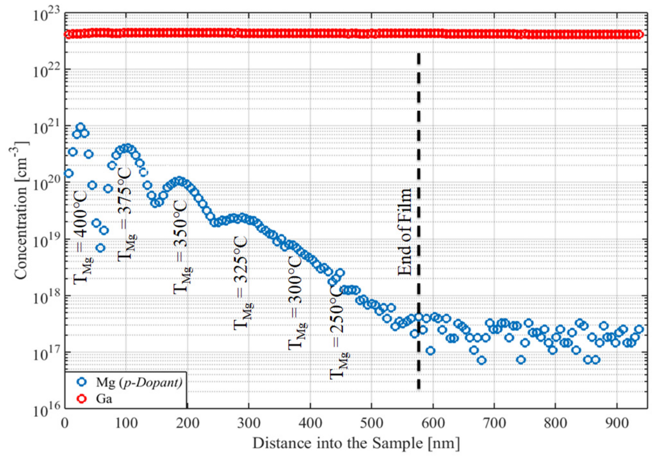

Fig 1. SIMS measurement demonstrating Mg incorporation. In the above, T_{Mg} indicates Mg effusion cell temperature in the PAMBE system. Undoped regions are used as spacers during a continuous growth. The activation rates range from 3-5% for moderate incorporation levels. A more detailed breakdown is given in our MPS-focused sister paper.

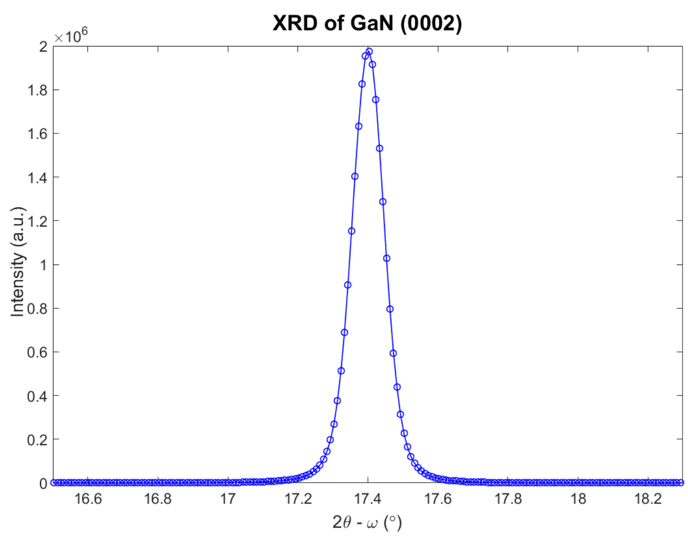

Fig 2. XRD of a typical PAMBE grown GaN film. In this example, the FWHM is 405 arcsec.

3%. P-doping is explored further in the paper mentioned previously in the hopes of achieving even higher activation rates.

SAG allows for intricate, high-aspect-ratio patterns to be created while completely avoiding ion-implantation and the etching of crystalline GaN. The regrown layers exhibit extremely low surface roughness to which non-alloyed ohmic contacts have been demonstrated [2]. Other work has shown that even the state of the art ICP-RIE and ion implantation techniques exhibit some extent of irreversible lattice damage [3]. While there has been effort to repair this damage via novel annealing techniques, it obviously does not result in complete healing [4]. This work demonstrates a direct comparison of device performance of SAG and etching based devices. The absence of this sidewall and surface damage is one key aspect that sets SAG apart from other techniques. SAG features are entirely epitaxially grown and are shown to depend directly on the geometry and quality of the masking material. This greatly limits interfacial leakage pathways that would arise from damaged surfaces, increasing device performance, reliability, and lifetime. It also means that interface quality is limited by conventional mask processing which is not related to GaN material growth. Past work in our group has demonstrated the high quality and reliability of SAG to produce smooth and well-defined features [2]. At present, work towards multilevel SAG is being performed in order to produce MPS devices and buried structures. Since SAG produces fully crystalline features, it is a completely repeatable and stackable process, allowing for lateral and vertical freedom in device architecture. The result of this is that by demonstrating a single SAG layer, the only difficulties in moving towards multiple layers would lie in device processing. Past SAG work has focused predominantly on ohmic contact for lateral device structures, so vertical multilevel SAG is an exciting area of exploration. Examples of SAG regrowth are shown in Figures 3, 4, and 5 outlining the process involved.

SAG, like all doping techniques, can only provide a specific dopant concentration for each growth step, i.e. there is no lateral variation in doping without redefining the SAG mask. Based on novel device architectures being developed in our group, it is of interest to be able to vary ohmic and Schottky contact type laterally on the same p-GaN layer. Since it is obviously desirable to do this while only using a single growth step, it is necessary to change the contact metal while maintaining the same p-doping level. Ohmic contact metals to p-GaN include Ni, Pt, Pd, and others [5]. Recently however, it has been observed that oxidation of Ni/Au bilayer contacts causes a dramatic increase in work function, significantly decreasing the metal-semiconductor contact resistance. This occurs due to the out-diffusion of Ni to the surface, where it reacts to form the high work function NiO. This process also removes interfacial impurities and greatly increases the local carrier concentration [6]. Having observed the rectifying to ohmic transition for Ni contacts to p-GaN of different carrier concentrations, we here investigate an efficient method of selectively oxidizing Ni/Au bilayers during annealing, thereby forming ohmic contacts in the oxidized region and rectifying contacts in the unoxidized region. PAMBE especially enables this via the use of SAG and the ability to precicely control doping and activation levels. As mentioned before, SAG creates excellent ohmic contact regions due to the high crystallinity and smooth surface of the regrown layers. This is even more important for p-type films where compensating defects such as hydrogen and surface states can dramatically reduce conductivity and increase leakage. SAG makes island definition straightforward which is important for contact structures. Apart from SAG, PAMBE itself often allows for the highest activation levels, providing more carriers with lower defect scattering resulting in superior conductivity.

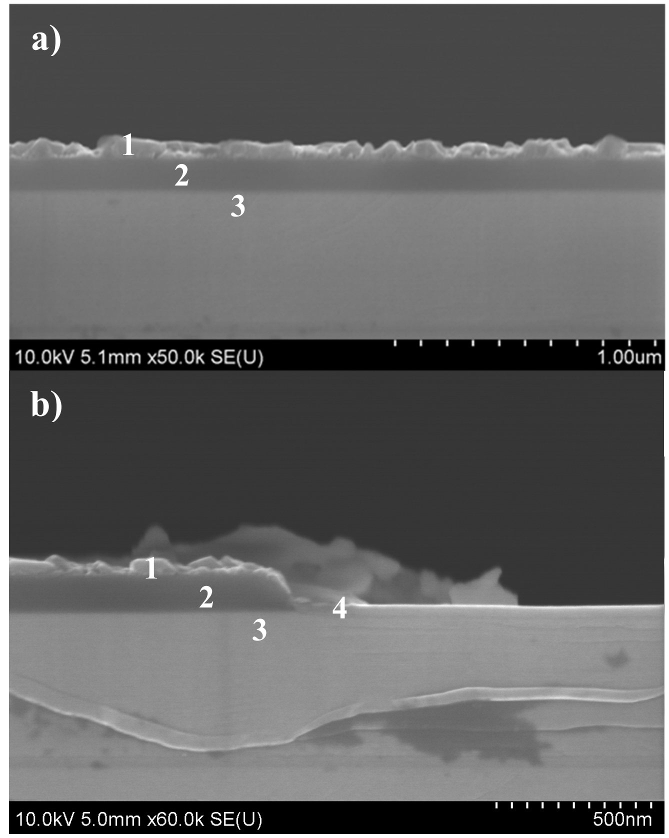

Fig. 3. In 3a and 3b, a cross sectional view is shown of a thin regrowth. Region 1 corresponds to polycrystalline GaN which can be easily etched away chemically. Region 2 is the masking layer which defines the region that no regrowth will occur on. Region 3 is the primary growth. This layer is also done by PAMBE to ensure a smooth template for the SAG process. The XRD data in Figure 2 corresponds to region 3. Region 4 is the regrown area. In this example, the film is quite thin, though by thickening the masking layer thicker films can be similarly achieved.

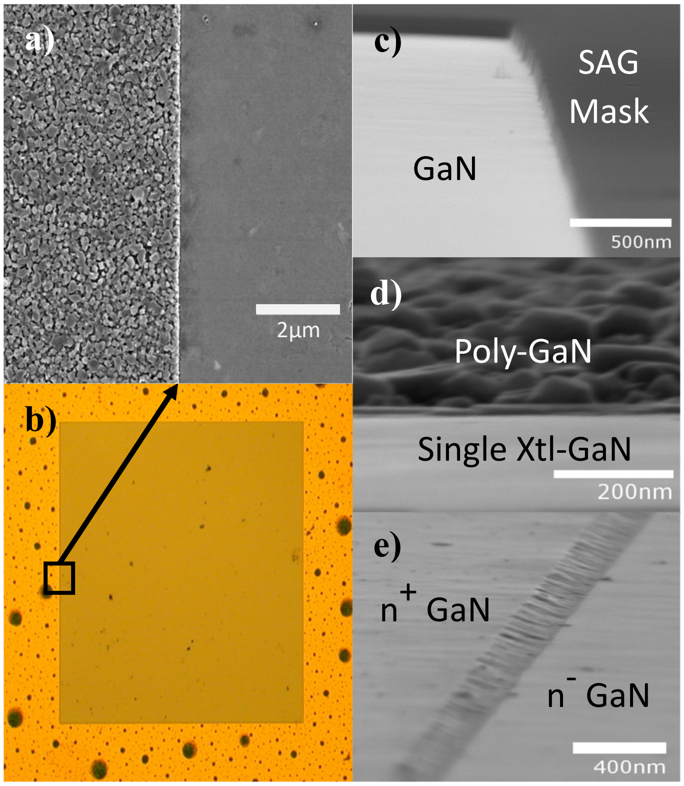

Fig 4. 4a and 4b show a top down view of a SAG island post MBE regrowth and before the removal of the polycrystalline GaN and mask layers. The demarcation of the polycrystalline and crystalline regions is shown both under an optical microscope (4a) and under an electron microscope (4b). 4c, 4d, and 4e show the 3 main steps involved in SAG via SEM: the mask definition on top of the initial GaN growth (4c), post regrowth with polycrystalline GaN grown on the mask and homoepitaxial GaN grown on the unmasked region (4d), and post removal of mask/poly-GaN (4e).

Conclusions

Extensive work has been carried out to develop GaN based vertical power devices. To accomplish this, PAMBE is being used to perform selective area growth that allows for vertical high quality GaN structures without etching or ion implantation. This work has demonstrated high p-doping levels with excellent crystallinity of films as well as the feasibility and benefit of using SAG as opposed to etching. In addition, ohmic contact formation is discussed and plans are outlined for selective contact type variation across single metal sheets. Moving forward, vertical devices will continue to be fabricated and their performance compared to other state of the art work.

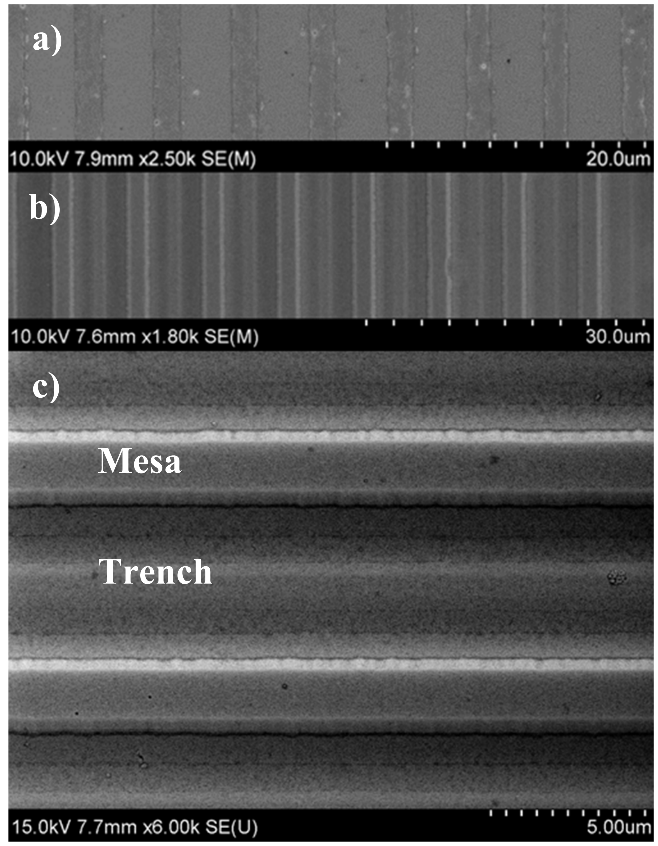

Fig 5. SEM images comparing SAG to ICP-RIE. 5a and 5b show SAG and etched lines within an MPS diode design, respectively. The SAG image shows very little contrast between the base layer and regrown areas in comparison with the etched sample, showing that SAG produces much more vertical sidewalls and no damage at the bottom of the trench. 5c is a closeup of the etched sample, showing angled sidewalls and high contrast regions at their base. These regions indicate surface damage as well as nonuniformity of the trench base.

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ACRONYMS

PAMBE: Plasma-Assisted Molecular Beam Epitaxy
ICP-RIE: Inductively Couple Plasma Reactive Ion Etching
BFOM: Baliga Figure of Merit
MOCVD: Metal-Organic Chemical Vapor Deposition
C-V: Capacitance-Voltage
SBD: Schottky Barrier Diode
SAG: Selective Area Growth
PIN: p-type, intrinsic, n-type
SIMS: Secondary-Ion Mass Spectroscopy
MOS: Metal-Oxide-Semiconductor
MPS: Merged PIN-Schottky
XRD: X-ray Diffraction
FWHM: Full-Width at Half-Max