Silicon Nitride Shadowed Selective Area Growth as a Device Processing Method for Heteroepitaxy of GaN on β-Ga_2O_3

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Abstract

Silicon nitride shadowed selective area growth (SNS-SAG) for homoepitaxy of GaN via RF plasma-assisted molecular beam epitaxy (PAMBE) has been shown to avoid the defects that arise from conventional selective area processing methods such as inductively coupled plasma reactive ion etching (ICP-RIE) and ion implantation. This work investigates the extension of this method to improve the heteroepitaxy of GaN on β-Ga_2O_3 by modifying the makeup of the SNS-SAG mask. Gallium rich and nitrogen rich GaN films are grown with SNS-SAG masks on β-Ga_2O_3 substrates. While current device performance has yet to be optimized, the adapted SNS-SAG mask retains both function and structural integrity as shown by scanning electron microscopy (SEM).

INTRODUCTION

Large critical electric fields and high electron mobilities, along with other attractive material properties, give ultra-wide band gap (UWBG) semiconductors the potential to improve the capabilities and efficiencies of modern power devices. With bandgaps greater than those of conventional semiconductors, these materials can enable devices to operate under higher voltages and temperatures [1]. Of the UWBG materials garnering interest, one of the most prominent is β-Ga_2O_3, which has a bandgap of 4.85 eV [2]. Compared with other UWBG semiconductors such as AlGaN and diamond, gallium oxide's controllable n-type doping concentration and low-cost substrate availability make it one of the most promising materials for the future of power electronics [2]. β-Ga_2O_3's inability to be p-doped, however, remains a challenge when structuring devices [1]. An approach to dealing with this difficulty is to form a heterojunction with a robust p-type semiconductor [3].

GaN is a wide bandgap semiconductor with a bandgap of 3.4 eV. Because of its low lattice mismatch with the (-201) plane of β-Ga_2O_3, p-doped GaN is a potential option for forming heterojunctions with β-Ga_2O_3 [4]. Previous work has shown encouraging results for growing epitaxial p-GaN on β-Ga_2O_3 substrates via PAMBE [5,6]. Preceded by a step of nitridation to convert the (-201) β-Ga_2O_3 surface into GaN, growing an epitaxial GaN layer with PAMBE results in highly crystalline thin films with FWHM of (0002) X-ray diffraction rocking curves as low as 136 arc sec [5].

One drawback of GaN, however, is the defects that are likely to arise when performing conventional device processing methods. After planar growth of GaN via PAMBE or metalorganic chemical vapor deposition (MOCVD), dry etching with inductively coupled plasma reactive ion etching (ICP-RIE) is typically done to selectively etch the device architectures. ICP-RIE has been shown to introduce defects such as nitrogen vacancies to the remaining GaN crystal, which limits gallium nitride's full potential in devices [7,8,9].

Silicon nitride shadowed selective area growth (SNS-SAG) is a method that has been shown to evade this issue for homoepitaxial GaN. By depositing a pre-growth mask on a substrate that only exposes selected areas, the growth will only interact with desired parts of the substrate. Subsequently removing the mask will result in a structure similar to the one achieved conventionally; the difference, however, is that SNS-SAG does not require the ion bombardment of the GaN film and therefore eliminates defect induced damage from the processing [10].

In order to retain the benefits of selective area growth on a foreign substrate, this work investigates the expansion of the SNS-SAG method to the heteroepitaxy of GaN on β-Ga_2O_3 using PAMBE. By modifying the SNS-SAG mask deposition process to complement β-Ga_2O_3 substrates and by performing nitridation before film growth, the full potential of GaN on β-Ga_2O_3 epitaxy can be realized. Characterization of films are done using scanning electron microscopy (SEM) and X-ray Diffraction (XRD).

Figure 1a depicts the cross-sectional schematic of the SNS-SAG mask. The masks were deposited on (-201)-oriented β-Ga_2O_3 substrates using a PECVD. For the mask material, a bilayer of SiO_2 and SiN was chosen. The ordering of the layers was inverted from the original process for homoepitaxial GaN to reduce the difference in the thermal expansion coefficient between primary mask layer and the substrate. Selective etching to achieve the undercut is done with 10:1 buffered oxide etch (BOE) to provide suitable selectivity between growth mask layers and substrate.

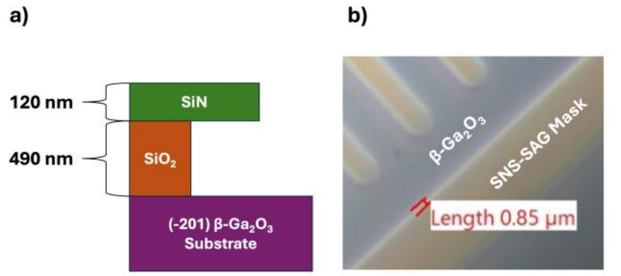

Fig. 1. a) Structure for the SNS-SAG mask. b) Optical microscopy of mask. Exposed β-Ga_2O_3 substrate (blue) and SiN surface of mask (tan). 0.85 µm undercut (white) is visible.

The mask thicknesses were selected to accommodate GaN growth of up to 490 nm thick, which is typical for p-GaN device layer thickness. The risk of parasitic polycrystalline GaN interacting with the regrowth is eliminated by depositing 490 nm of SiO_2 for the primary layer. The SiN layer was chosen to be thick enough such that even after about 100 nm are etched during the BOE etch, there is still enough to support the polycrystalline GaN that will form on top of it without collapsing. Once the bilayer was deposited, photolithography was performed to protect selected areas from the following ICP-RIE step. During the ICP-RIE etch, care was taken to not etch fully through the SiO_2 layer so that the Ga_2O_3 surface is not exposed to ion damage. This was followed by a BOE etch to obtain the intended schematic in Figure 1a. For the undercut length, the angle of the nitrogen source in the MBE chamber must be considered to ensure that the angle of the regrown mesa sidewall will not be coinciding with the SiO_2 layer. Calculation of the necessary length is done in a previous work, where the undercut depth is chosen to be at least the thickness of the lowermost mask layer [10]. When inspecting the growth mask on the substrate via optical microscopy, it was seen that the achieved undercut was 0.85 µm after 7 minutes of etching, which is indeed sufficient to eliminate parasitic poly-GaN growth along the sidewall.

Following the mask deposition, the substrate was loaded into the PAMBE vacuum chamber. The substrate was heated at the rate of 5 °C/min to the nitridation temperature to ensure that the mask structure remains intact. The RF-plasma assisted nitridation was done with a flow rate of 0.69 sccm and power of 400 W. The substrate was kept at 500°C for 2 hours, followed by a ramp to 700°C at 10 °C/min. Upon reaching 700°C, the nitridation continued such that the total time for nitridation was 4 hours.

Two UID GaN films, one nitrogen rich and one gallium rich, were grown with SNS-SAG masks. The nitrogen rich film had a growth rate of 234 nm/hour, while the Ga rich growth had a growth rate of 258 nm/hour. Both growths were done for 100 minutes. After the growth, gallium droplets were found on the Ga rich film, as well as a visible layer of gallium spread evenly on the mask surface. This sample was submerged in HCl to clean this deposited gallium on the surface. A concentrated HF solution was used to remove was growth mask, leaving just the GaN film and the substrate. SEM images were taken before and after mask removal using the JEOL 7000F with an accelerating voltage of 5.00kV. XRD data was collected after mask removal using a Bruker D8 Advance system with a copper (Cu) $K_{\alpha 1}$ X-ray source, monochromated with a 2-bounce Ge (004) monochromator.

Schottky barrier diodes were fabricated to test the device performance of the grown UID GaN films. 100 nm of SiO_2 is deposited as a passivation layer between the GaN mesas. When processing the growth mask, the samples are left with planar regions of Ga_2O_3 where the GaN can grow without interacting with a mask. Devices were fabricated in these regions as well. Schottky contacts were comprised of 20 nm of platinum followed by 100 nm of gold deposited on the GaN mesas. For ohmic contact to the Ga_2O_3, 20 nm of titanium was deposited followed by 100 nm of gold.

Figure 2 shows the Ga rich sample after the growth and HCl cleaning. The GaN mesa is present where the substrate was exposed prior to growth, and the surface morphology appears smooth and uniform. The texture of the sidewall shows roughly 10 nm wide steps descending from the surface to below the undercut of the mask. The polycrystalline GaN was deposited on the surface of the bilayer mask. Poly GaN features form about 100 nm in diameter, and 10 nm wide crystallites appear to be hanging down from the edge of the mask. The dark shadow present under the SNS-SAG mask indicates that the GaN mesa is not contacting the polycrystalline GaN or the mask.

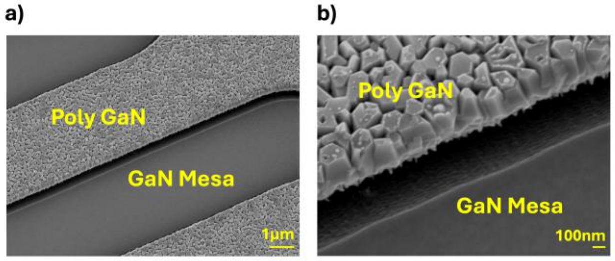

Fig. 2. a) SEM image of the UID Ga rich GaN film grown with bilayer SAG mask. Taken at a 30° tilt. b) SEM image of GaN mesa sidewall and polycrystalline GaN. Taken at a 30° tilt. The mesa sidewall appears smooth, and the sidewall is not in contact with the polycrystalline GaN.

SEM of the Ga rich film after mask removal is done to inspect the remaining GaN mesa. As shown in Figure 3, remnants of the mask or polycrystalline GaN are not present, indicating that the mask architecture effectively allows the film to grow with near vertical sidewalls without direct contact. At the base of the GaN mesa, the Ga_2O_3 substrate appears to have been etched. The GaN sidewall extends down to where the etching occurs, indicating that the growth occurred inside the crater, rather than the etching being formed around the film. This means that the etching likely occurred before the growth, either during the growth mask fabrication process or the nitridation, rather than during the removal of the mask. This effect on the substrate is potentially inhibiting the device performance by causing damage to the interface.

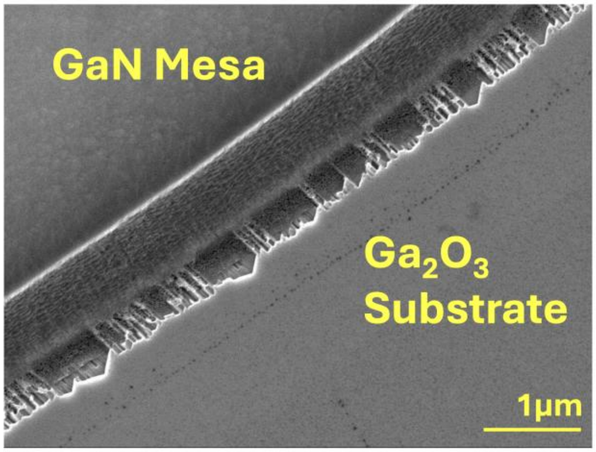

Fig. 3. 20kx plan-view SEM image of the UID Ga rich GaN film after mask removal. Sidewall of GaN mesa appears smooth and uniform, while the Ga_2O_3 substrate at the base of the mesa appears to be etched.

Causes for this etching are being explored. Etching of this nature was not observed during mask processing on a native GaN substrate. In contrast to homoepitaxy, heteroepitaxy on β-Ga_2O_3 requires a nitridated GaN buffer region. A possible explanation is that nitridation is moving laterally near the edge of the film into areas of the substrate the are covered by the mask. The desorption of the GaN in this region may be causing this effect. Further work using AFM is to be conducted to further investigate this substrate etching.

The crystallinity of the two different film growth regimes is studied via XRD rocking curves shown in Figure 4. A profilometer measured the thicknesses for the gallium rich film and nitrogen rich film to be 430 nm and 390 nm, respectively. This thickness difference should be considered when analyzing variations in intensities between the rocking curves. The full width at half maximum (FWHM) of the rocking curves for the gallium rich film and nitrogen rich film are calculated to be 363 arc sec and 385 arc sec, respectively. While the FWHM of the Ga rich film is less than that of the N rich film, a more apparent asymmetry can be observed for the Ga rich film. This indicates that while there may be a higher order of crystallinity for the Ga rich film, there are more considerable strain effects present.

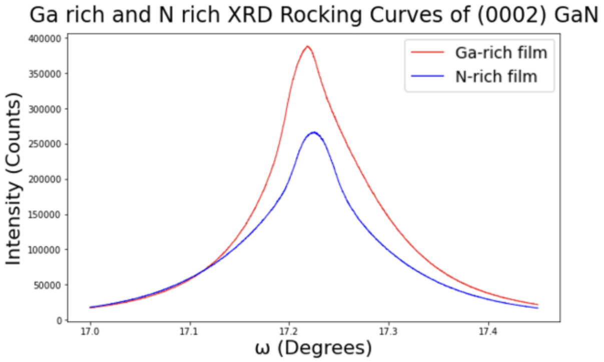

Fig. 4. Rocking curves of the (0002) GaN peak for growth done in a gallium rich regime and a nitrogen rich regime. Thickness of Ga rich film: 430nm. Thickness of N rich film: 390 nm.

The device made with the N rich grown film revealed a Schottky barrier height of 0.36 eV, an ideality of 11.5, and a current on/off ratio of 55. Current on/off ratio was calculated with voltage at 3V and -3V. Device results for the Ga rich growth showed significant current leakage, making it impossible to apply these metrics. When comparing the differences in device results between the two growth regimes to the XRD results, it can be deduced that a strong strain effect negatively impacts device performance. Additionally, a high dislocation density would result in a high leakage current like what is observed for Ga rich sample. Devices in the planar regions for the respective devices yielded similar results.

These preliminary results are promising for the future for SNS-SAG on β-Ga_2O_3. Although efforts to improve device performance are still underway, noting that the devices made in the SNS-SAG regions of the sample are performing in a similar fashion as the ones in the planar regions is indicative that presence of the SNS-SAG mask does not negatively impact epitaxy. Future work will involve investigation as to whether the growth and device performance are impacted by mask processing conditions, such as the mask deposition conditions or the BOE etching. The depositing of the bilayer mask could potentially be straining the substrate as well, which may have an effect on the growth. Additionally, the nitridation having lateral restrictions could results in differences such as the etching of the substrate observed after mask removal.

CONCLUSION

SNS-SAG is a promising approach for avoiding the conventional selective area processing methods used during the development of GaN and β-Ga_2O_3 heterojunctions. SEM data indicates that mask structures can be fabricated to allow epitaxy to occur in selected areas of a substrate without direct interaction with the film. Current device data suggests that the SNS-SAG mask enables quality epitaxy of GaN on Ga_2O_3, which is encouraging for the future applications of this method. While a nitrogen rich film has resulted in a higher-performing device, both Ga and N rich growth regimes are to be explored in future study and optimization. Following improvement of growth conditions, p-doping will be incorporated to fulfill the purpose of p-GaN on β-Ga_2O_3 vertical devices.

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ACRONYMS

SNS-SAG: Silicon Nitride Shadowed Selective Area Growth
PAMBE: Plasma-Assisted Molecular Beam Epitaxy
SEM: Scanning Electron Microscopy
XRD: X-Ray Diffraction
UWBG: Ultra-Wide Bandgap
MOCVD: Metalorganic Chemical Vapor Deposition
ICP-RIE: Inductively Coupled Plasma Reactive Ion Etching
PECVD: Plasma-Enhanced Chemical Vapor Deposition
BOE: Buffered Oxide Etch
UID: Unintentionally Doped
FWHM: Full Width at Half Maximum