Selective Area Growth for Gallium Nitride Devices

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I. Introduction

Just last week it was the anniversary of Moores law. However, we all know that silicon is about to reach its physical limit as transistor sizes keep decreasing. Gallium nitride, along with other 3-5 materials, have promising characteristics that can eventually replace silicon all together.

Currently, GaN is typically used for niche applications, such as Radar systems, missile defense systems and high power applications. Size and cost are not a concern for these applications, performance and robustness are metrics that matter. The wide band gap characteristic of the material leads to a higher electric field tolerance, improved mobility, and ability to operate at higher temperatures.

While promising characteristics for device design, there is a lack of a suitable substrate for gallium nitride to grow a high crystalline quality material. A Sapphire substrate is typically used due to availability, low cost, surface morphology and high temperature stability when compared to other substrates, such as silicon carbide, or silicon. However, a 13% lattice mismatch introduces multiple structural defects. Understanding electrical properties because complicated. With Silicon based devices, doping determines electrical characteristics of a device, however with GaN, Defect density is a major factor when determining electrical characteristics.

Selective area growth(SAG) is introduced as a possible alternative to improve fabrication issues with GaN devices and structures. 3-5 devices in general stand to benefit from SAG technique. Substrates, SAG, High electron mobility transistors, and nanostructures are explored and compared from traditional growth techniques to SAG techniques.

II. Substrates

Several substrate solutions have been researched to reduce the lattice mismatch. Silicon Carbide is used today due to its 3.4% lattice mismatch. While a promising substrate for the low mismatch, the substrate is relatively expensive when compared to sapphire. Diamond Substrates demonstrate a lattice mismatch closer to that of sapphire. However, the promising thermal properties of the substrate, allow for fabrication flexibility. Thermal conductivity is nearly 5 times higher than that of SiC, allowing for thinner GaN active layers[7]. Lithium Gallate is another promising substrate due to its .19% lattice mismatch. The use of this substrate would reduce dislocation densities by several orders of magnitude.[8] Dislocation densities would surely decrease. However, the substrate shows poor thermal stability in a MOVPE growth environment. The substrate can be removed by a simple wet etch and could consequently be used to grow high quality GaN substrates.

III. Selective Area Growth

Selective Area Growth (SAG) has the ability to reduce several of the issues that plague a GaN device fabrication process. The technique is a combination of a lithography and MOVPE growth process. A dielectric mask is deposited on the GaN surface, and then etched to expose regions for growth. To reduce defect densities, SAG can be used to implement an epitaxial lateral overgrowth (ELO) by etching and exposing strips of GaN surface. The mask remains while the growth rate is restarted to block original threading dislocations from propagating on the new epitaxial layer. GaN device performance can be improved by selectively growing active layer region of a GaN High Electron Mobility Transistor (HEMT). Finally, SAG can be utilized to grow high quality nanostructures, such as nanowires or nanodots. Each topic will be discussed in the following section.

A. *Epitaxial Lateral Overgrowth*

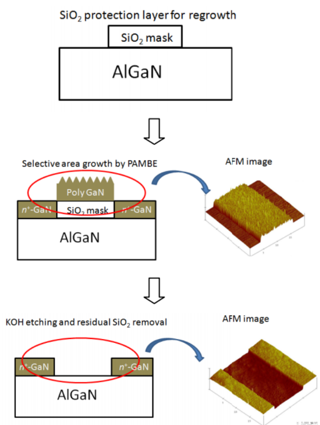
Epitaxial Lateral Overgrowth utilizes this selective area epitaxy to reduce defect densities. This technique relies on the principle of restarting the growth process. First a dielectric mask is depositing on the GaN surface, next narrow slits are etched to expose GaN surface. A MOVPE growth technique is then used to grow the epitaxial layer within the openings. The dielectric layer remains for the next restart of the growth process. The epitaxial layer will grow laterally to fill the trenches created by the SAG process. The dielectric layer prevents threading dislocations from penetrating the new epitaxial layer that was grown. Several variations to this technique have been implemented, such as 2 step ELO or multi-step ELO[6]. This technique has been proven to reduce defect densities by several orders of magnitude.

B. *GaN HEMT Improvements*

GaN HEMTs, and other 3-5 devices, operate in a different principle than that of silicon based devices. Silicon devices utilize junction and substrate doping to operate, while GaN HEMTS utilize 2 dimensional electron gas or 2DEG to operate. By controlling the 2DEG density, high performance devices can be obtained. Particularly, increasing the 2DEG density in the access region and lowering the 2DEG density in the gate region will allow high current density. One such structure that attempts to utilize this SAG is a recessed gate structure. The gate is simply etched into the active region to reduce access resistance. This process is typically carried out by electron cyclotron resonance reactive ion beam etching (ECR-RIBE). This plasma treatment unavoidably introduces damage to the active region of the device, reducing reliability and stability of the device.

SAG is introduced to grow high quality active layers and to create a recessed gate structure, without introducing plasma treatment. Fabrication steps simply selective grow the active layer of the device, AlGaN in most HEMTs. Device properties greatly improved over recessed gate structures that were etched using a plasma treatment. The higher quality active layer allowed for a lower on resistance and improved drain current, due to better ohmic contacts[3]

Fig. 1: SAG process for growing active layer with recessed gate structure



C. Nanostructures

One of the breakthroughs of GaN was through optical devices, specifically the blue LED. Optical nanostructures are possible with 3-5 devices such as GaN. GaN nanocolumns have been grown using MBE or a MOVPE process. These structures have been shown to increase the internal quantum efficiency of the optical device. These nanostructures require high quality material due to quantum effects that negatively affect the operation of the structure. Thin layers of 3-5 materials experience a change in optical absorption spectrum due to quantum confinement of carriers, reducing the internal quantum efficiency.

InGaN LEDs are capable of emitting in the ultraviolet region, also visible in the blue-red range. InGaN nanostructures suffer from spontaneous and random crystal nucleations that change the optical spectrum of the optical device. SAG technique is used to etch nanodots in the mask. Nanocolumns with a smoother morphology and homogenous structure can be grown from the openings. Little variation is observed in these structures. Internal quantum efficiency is subsequently increased[2].

The University of Michigan has investigated InGan nanocolumns, or nanowires as they are termed, fabrication methods. Their method utilized a MOCVD process and a vapor-solid-solid principle (VSS)[1]. VSS is similar to a vapor-liquid-solid mechanism that is used to grow silicon or germanium nanowires. However, 3-5 devices do not require a liquid catalyst and can directly form from a solid

D. Growth Parameters for Nanostructures

Growth temperature is critical in both processes to achieve the best results. SAG process for nanocolumn formation requires a temperature range from 880 C to 900 C for critical nanocolumn formation. Temperatures below 880 C yielded insufficient selective epitaxy, while temperatures above 900 C yielded a decreased nanocolumn growth rate. This is due to the acceleration of desorption of Ga atoms from the surface. For the VSS mechanism, the best results were achieved 715 C. Pressure of the system also is key to producing good results. Temperature at 715 C and pressure at 100 torr, yielded the best results. Temperatures beyond 735 C resulted in severely reduced nanocolumn formation; the surface reverted to a thin film.

Density of the nanocolumns is dependent on growth pressure for the VSS mechanism; the Sekiguchi et al paper has no mention of pressure as a growth parameter. It is shown that the greatest density achieved by Kuo et al, is 100 torr. Higher growth pressures resulted in a steady fraction of vertical facing nanocolumns, however density decreased dramatically.

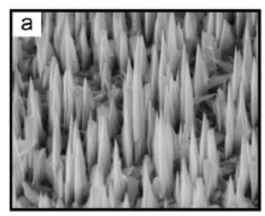


Fig. 2: Nanocolumns fabricated by MOCVD/VSS technique

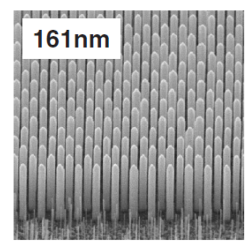


Fig. 3: Nanocolumns fabricated using SAG technique

It is then observed that utilizing SAG is the best technique for growing high quality nanostructures. Less dependence on growth parameters, while achieving smooth surface morphology and homogenous structures are observed through SAG technique.

IV. Conclusions

While SAG is a promising technique to improve various performance metrics of GaN devices, it does not completely eliminate the defect density issue of the devices. ELO proves to reduce defect densities by several orders of magnitude, through a growth restart principle. GaN based HEMTs benefit from a better quality active layer for high current density and high power devices. Plasma treatment is eliminated from the gate-recessed structure, thereby reducing lattice damage to the active layer. On resistance and ohmic contacts are also improved. Nanostructures stand to benefit from the smooth morphology and homogenous structures that can be realized using SAG technique. Optical structures can have increased internal quantum efficiencies.

References

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