Fabrication of AlGaN/GaN High Electron Mobility Transistors

Vijay Gopal Thirupakuzi Vangipuram
Electrical and Microelectronic Enginering
Rochester Institute of Technology
Rochester, NY 14623

***Abstract*— A first attempt at fabricating AlGaN/GaN High Electron Mobility Transistors (HEMTs) on a Si substrate was made at RIT. A basic process flow was developed to fabricate enhancement-mode devices. The proposed fabrication flow was attempted and completed. The single metallization step using Ni as the metal yielded Schottky contacts in source, drain and gate regions.**

I. Introduction

GaN-based high electron mobility transistors (HEMTs) are of significant interest for high-power and high-frequency applications. Due to the high mobility, wide bandgap and thermal stability of GaN, it is an ideal material system for producing high-power and high-frequency devices. [1]

AlGaN/GaN HEMTs are inherently depletion mode (D-Mode) devices. They are already being used for mainstream applications. In order to further expand the number of applications, and to enable monolithic integration of GaN-HEMTs for analog electronic circuits, a key consideration is the ability to produce enhancement mode (E-Mode) devices. [3,6,7]

GaN is not a naturally occurring material; Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Deposition (MOCVD) is required to grow GaN on a substrate. Typically, for optical applications, GaN on sapphire is used due to its transparency. GaN on sapphire however, has a very low thermal conductivity, and is not ideal for high power applications. GaN on Si provides a good alternative as a starting substrate.[2] It provides good thermal conductivity, with the added advantage of the possibility of future integration of Si technology with GaN. GaN on Si is also significantly cheaper in comparison to GaN on SiC. While GaN on SiC offers even better thermal conductivity compared to Si, the costs associated with the substrate are much higher than standard Si substrates.

Vijay Gopal Thirupakuzi Vangipuram is an undergraduate student at Rochester Institute of Tehnology in the Department of Electrical and Microelectronic Engineering.

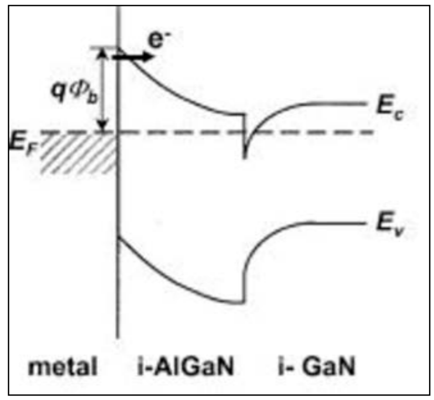

Fig. 1: AlGaN/GaN Band Structure [9]

II. Theory

A. 2-Dimensional Electron Gas

The heterojunction that forms due to the varying bandgaps of AlGaN and GaN produces a triangular quantum well. Electrons present in this quantum well are thereby confined in one dimension while they are free to move in the other two dimensions. The 2-dimensional electron gas (2-DEG) that is formed by the triangular quantum well essentially creates a channel of electrons. Fig. 1 shows the band structure of the AlGaN/GaN interface and the presence of a quantum well. [5]

The bandgap of the AlGaN layer can be varied by varying the ratio of Al to Ga present within the AlGaN layer. The bandgap varies roughly in accordance with Vegard's Law. However, experimental results have also shown that there are bowing parameters associated with the variation of the bandgap with the percentage composition of Al present.[4]

B. Techniques Towards E-Mode Devices

1) Gate Recessing

Recessing the gate region allows for barrier thinning. The thinner barrier leads to the channel under the gate being depleted. The depleted channel thereby leads to an enhancement mode device. Fig. 2 shows an exemplar gate recessing process. A key consideration that limits this method is the crystalline damage that is caused by dry etching. There is also the consideration of the selectivity of the etch between GaN and AlGaN layers that would need to be taken into account since they are both etched by Cl-based dry etching. This can lead to uncertainty in producing extremely thin AlGaN gate regions.

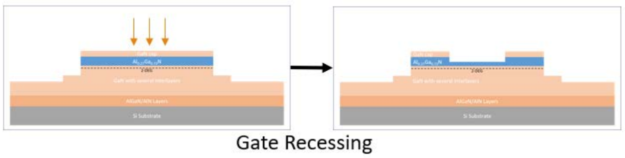

Fig. 2: Gate Recessing by Cl_2-based plasma

2) Fluorine Ions

Significant amount of work has also shown the effects of adding fluorine ions into the gate regions of HEMTs and MISHEMT structures.[7] Typically, the fluorine ions are incorporated by exposing the substrates to a fluorine plasma, leading to the fluorine ions being "implanted" within the gate regions. While the incorporation of fluorine ions have been reported to successfully further shift the threshold voltage in a positive direction, towards an E-mode HEMT, there has been a significant amount of concern as to its reliability and the long term performance of such a device.[8] Fig. 3 shows a typical HEMT structure and the area just below the gate metal where the fluorine ions are implanted.

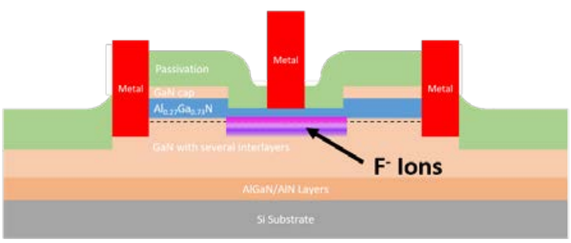

Fig. 3: Fluorine Ions within Gate Regions

III. Mask Design, Process Flow and Fabrication

A mask design with HEMTs and MISHEMTs (Metal-Insulator-Semiconductor HEMTs) with varied gate lengths, L_g, ranging between 5µm to 100µm. The gate to drain and gate to source lengths were also varied by the same amount for each device ($L_{GD}=L_{GS}=L_G$). Apart from the HEMTs and MISHEMTs, a metal resistor, Van der Pauw's structures and CBKRs for measuring sheet resistances and contact resistances were part of the mask design. Figure 4 shows a single cell of the mask layout with the different sizes of devices highlighted in different colors. The single cell was arranged into a 10x10 array for the complete mask.

Fig. 4 shows the mask layout of the single cell. The devices outlined in green have a gate length, L_G of 5µm. Devices outlined in purple have 10µm gate lengths. Devices with gate lengths of 20µm, 50µm and 100µm are outlined in red, cyan and yellow respectively in Fig. 4.

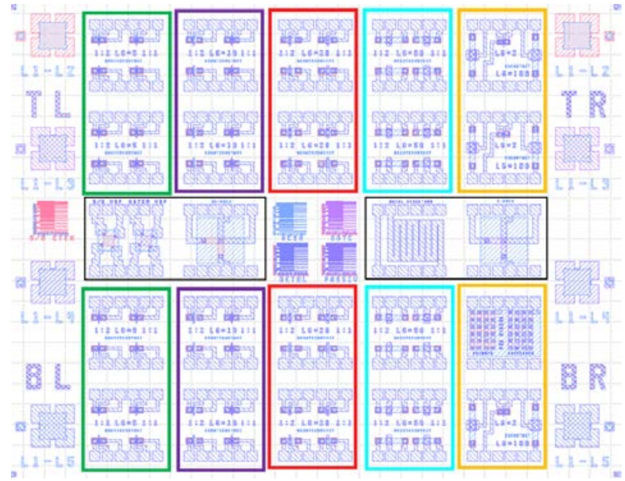

Fig. 4: Single Cell of Mask Layout.

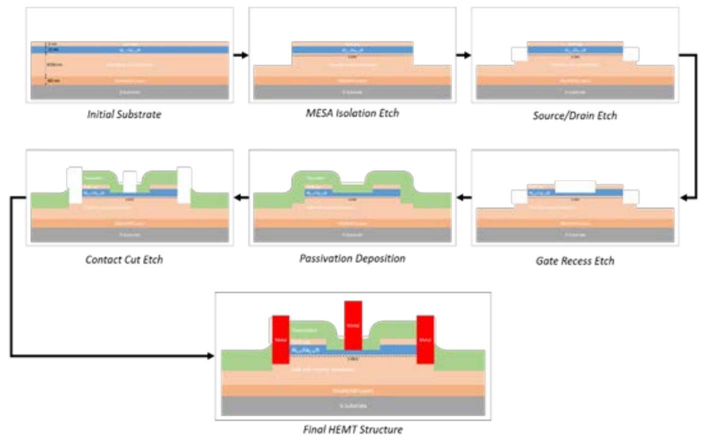

Fig. 5: HEMT Fabrication Process Flow

As a first attempt at fabricating AlGaN/GaN HEMTs at RIT, a basic process flow was developed. Fig. 5 shows the process flow in terms of the cross sections. The initial substrate supplied had a 2nm UID-GaN cap, with 25nm of $Al_{0.27}Ga_{0.73}N$ below, followed by 6700nm of UID-GaN with several buffer layers. The first step in the process flow designed was the mesa isolation. This was done to increase the series resistance between devices, thereby isolating the devices electrically from one another. This step was followed by source-drain etching. In order to compare the effect and quantify the shift in threshold voltage, gate-recessing for certain samples were carried out, followed by a further split of samples to compare the effect of fluorine ions with samples that were only recessed. All the etch steps utilized a Reactive Ion Etcher (RIE) dry etch with Cl_2 and Ar. A separate RIE etcher was used to expose the samples to a fluorine plasma. Since it is only possible to etch GaN using a Cl-based plasma, there is no effect when exposing the GaN/AlGaN regions to a F-based plasma. After gate recessing, 25nm of Al_2O_3 was deposited by Atomic Layer Deposition (ALD). The Al_2O_3 acts as a passivation layer in the HEMTs while also acting as the insulating layer within the MISHEMT structures. Contact cuts were formed by etching through the Al_2O_3 using HF. Lift-off, in conjunction with E-beam evaporation, was used to deposit and pattern the metal. For the devices fabricated, only a single metal step was used. Ni was deposited in source, drain and gate regions. All samples fabricated were pieces from a single GaN-on-Si substrate. Patterning for all layers was done using contact lithography.

IV. Results and Discussion

Fig. 6 shows the family of curves obtained for a HEMT structure with a gate length of 20µm. The curves show minimal gate control while also showing very resistive characteristics. Fig. 7 shows an I_D-V_D curve for a MISHEMT structure while keeping the gate voltage at 0V. The curve shows a diode-like characteristic as the drain voltage is swept. If it is considered that a Schottky metal-semiconductor contact has been formed in the source, drain and gate regions, and keeping the gate voltage at 0V, it is possible to conclude that one of the contacts would behave as a forward biased diode, while the other would behave as a reverse biased diode. Using this assumption, and the similarity in the plot obtained for the MISHEMT structure, it is possible to deduce that the metal-semiconductor contacts obtained were Schottky and not Ohmic. Both graphs discussed represent samples that do not have a gate recess and do not have fluorine ions present.

A key component in realizing HEMTs is the ability to form Ohmic contacts in the source and drain regions while maintaining a Schottky contact in the gate regions.

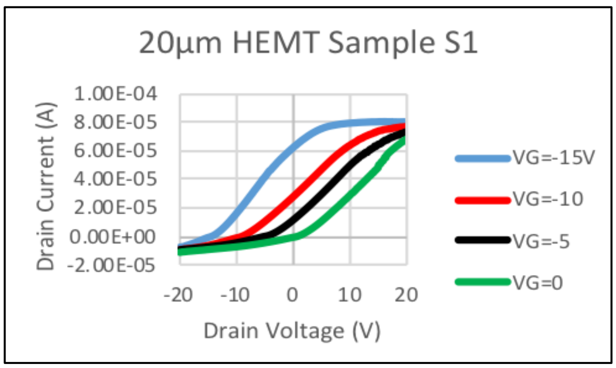

Fig. 6: Family of Curves (I_D-V_D) for L_G=20µm HEMT

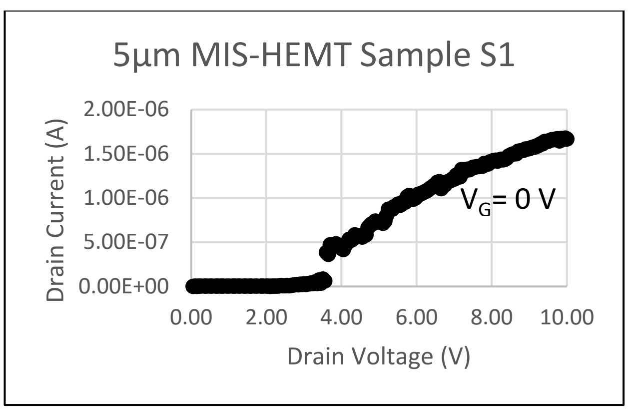

Fig. 7: I_D-V_D sweep for V_G=0V for L_G=5µm MIS-HEMT

V. Conclusion

The first fabrication run to produce AlGaN/GaN HEMTs was completed. It was found that multiple metallization steps are necessary to produce Ohmic sources and drains while producing Schottky gates. More work would need to be done to successfully fabricate enhancement mode AlGaN/GaN HEMTs.

Further work would need to be done to obtain Ohmic contacts for the source and drain regions. Different metal stacks in combination with different RTA conditions would need to be investigated. Future work would also require better etch characterization with a focus on effective etching while creating minimal surface damage in the gate regions. Utilizing an ICP-tool with Cl-based chemistries would help towards this goal. Continuing work would also require further test structures to be designed and incorporated. Designing and adding TLM structures to the mask layout would help a great deal towards characterization.

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