RF High Electron Mobility Transistor Research Project

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***Abstract*—This paper provides an overview of prior research of RF High-Electron Mobility Transistor device processing, with an emphasis of AlGaN/GaN devices and using Si substrates.**

Keywords—RF, HEMT, AlGaN/GaN, process

I. Introduction

With the desire to produce signals that reach the Terahertz range, the current standard that is the silicon transistor falls short. One answer is the High Electron Mobility Transistor (HEMT), a transistor based on high electron mobility materials, such as gallium nitride (GaN), in conjunction with a structure that produces a 2-dimensional electron gas (2DEG) when in the on-state. [1]

Understanding the processes involved in constructing these devices is of utmost importance, as they often affect performance directly. Depending on the specific materials, feature sizes, layer depths, and physical constraints processes of chemical vapor deposition (CVD), molecular beam epitaxy (MBE), or etching may be used, purely or in conjunction with one another [2, 3, 4]. Additionally, the choice of substrate also has a deep impact on the performance, process, and price of the device [5].

II. MOCVD

One of the primary methods for fabricating HEMTs is through metal-organic chemical vapor deposition (MOCVD). The process is similar to preexisting chemical vapor deposition (CVD) methods, such as LPCVD, but has a distinction where the metallic element used is carried by an organic gas such as trimethylgallium (TMGa) and trimethylindium (TMIn) alongside hydride gasses like arsine (AsH_3) or phosphine (PH_3) [9]. The gases are then able to decompose at high temperatures and produce the desired film. MOCVD has continued to be one of the most popular methods for growing epitaxial films since its inception in the 1960s due to its many advantages, ability to maintain uniform thickness, and high-quality material growth. However, the method still has disadvantages that may not be seen in other methods, such as the need for a high and precise temperature and release of toxic gasses. The advantages and disadvantages of MOCVD will be further investigated in this section.

MOCVD has distinct advantages over the competing method of MBE, or molecular-beam epitaxy. Perhaps most notable is the high scalability and throughput of the method, meaning that growth of epitaxial layers can be performed on larger 200 mm wafers quickly and with good uniformity. This is mostly from the design of a standard MOCVD reactor that has a gas inlet similar to a shower head, allowing for the gasses to cover most if not all the substrates. Assisting in this process is a rotating susceptor where the wafer sits during manufacturing. This plate is also heated uniformly, contributing to the uniform layer thickness. This entire system can be seen below in Fig. 1.

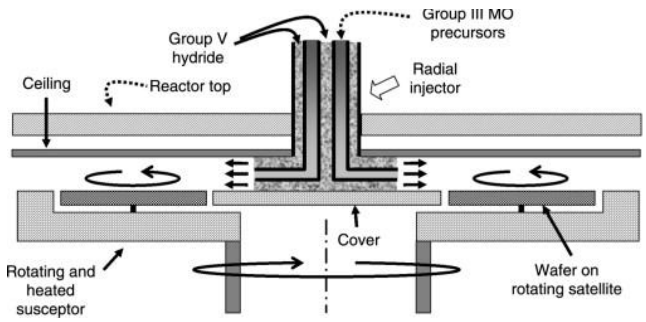

Figure 1. Diagram of a typical MOCVD reactor [10].

The result of this coverage leads to excellent thickness uniformity across the wafer, with variations across the wafer of less than 2% being typical in most applications [6]. Resulting material quality can also be excellent in a well optimized system, which is most crucial for achieving low-noise HEMTs. This material quality depends on the way the wafers are manufactured, as seen below in Table 1.

Table I. 2DEG performance of samples with different C and O concentrations and different structures [7].

	Structure	Mobility (cm^2/Vs)	Sheet Carrier Density (cm^{-2})	Sheet Resistance (ohm/cm^2)
A	Square	1740.3	9.3368E+12	384.13
B	Square	1224.6	1.2902E+13	395.04
C	Cross	2161.4	7.1593E+12	403.38

In these scenarios a 100 mm wafer was used, and samples A and B had the same structure, while A and C had the same C and O concentration. As seen in the table, the two-dimensional electron gas (2DEG) mobility can be as high as 2161.4 $cm^2/V·s$ given a wafer is produced with a cross contact structure [7]. This mobility, enabled by MOCVD, is the primary advantage for using the process in manufacturing GaN HEMTs, since it allows for the high frequencies needed for RF applications where these devices are used.

Despite the several advantages, there are considerations to be made when using MOCVD as the method for fabricating HEMTs. The precursors commonly used for this process, as well as the hydride gases, are extremely toxic and require additional safety precautions to be taken. This inherently means that extra equipment that may not be necessary for other methods, such as MBE, must be purchased, adding to the overall cost and complexity of a MOCVD system [8]. The high temperatures required for this process can also be seen as a disadvantage. While modern reactors can reach the temperatures required for developing GaN HEMT devices (nearly 900 °C), parasitic reactions between gases and other material can still occur and lead to contamination or unintentional Ga doping on the wafer [6]. The high temperatures can also lead to the wafer bowing due to thermal expansion, which can be avoided by adding AlN/GaN super lattices as buffer layers [6]. However, this would also contribute to the complexity of the system.

The challenges brought up by MOCVD can be diminished through careful optimization of the entire system. The issues are far less prevalent in modern day reactors, thanks to advances in automation found in larger systems. Knowing the advantages and disadvantages of MOCVD, as well as general steps that can be taken to avoid most issues, it would make sense for large-scale operations to keep taking advantage of this method. Although, when creating HEMTs on a smaller scale for research and development purposes, other methods that don't have such disadvantages may be worth considering.

III. Molecular Beam Epitaxy

MBE is an epitaxy process in which the epitaxy chamber is brought to a very high vacuum, and pure molecule beams of the growth material are released by digitally controlled shutters with precision enough at the high end for single molecule thick layering. This process avoids several shortcomings of MOCVD, for example it does not require the toxic metalorganic gasses, but instead pure material supply, but that is a debatable benefit when considering the acids necessary for the wet treatment applied to a wafer to remove any impurities prior to growth. A more clear cut benefit is the low growth temperatures of MBE, that prevent interdiffusion of heterojunction layers during growth, as MOCVD's high activation temperatures causes AlN layers to absorb GaN while growing, lowering the polarization of the now AlGaN barrier layer, and density of the 2DEG, compared to pure AlN [11].

As of 2013, most improvements to HEMT performance came from steady fabrication process optimization [12]. However, as the parameters that affect performance have been isolated, and accounted for with complex fabrication methods, HEMT tech has approached a point where epitaxial defects are the greatest limiters of performance. The primarily impactful defects are surface termination, point defects, impurities, and extended defects or misalignment in lattice structure, as any increase in concentration of the defects causes loss of reliability and max power due to increased thermal output [13]. Thanks to the precise control of growth, and lack of high temperature requirements when growing with MBE, layers of exact thickness and pure makeup can be grown with sub-nanometer RMS surface roughness [14], as shown in Figure 2.

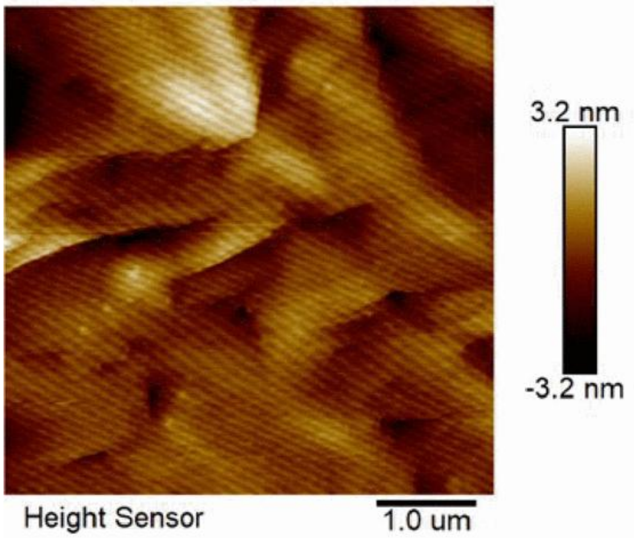

Figure 2. MBE Grown AlN/GaN Heterojuction Surface Imaged/Measured via AFM [14].

As gate length is reduced for the purpose of improved frequency characteristics, the thickness of the barrier layer must be reduced proportionally, to maintain the aspect ratio, or a short channel effect will emerge, causing loss of 2DEG density [14]. With MOCVD, the AlGaN barrier layer thickness must be increased to achieve a smoother surface [13], as well as to produce equivalent polarity to pure AlN [14]. Reversed, this means that a thinner barrier layer will result in a greater surface roughness, increasing lattice mismatch and propagating structural defects, reducing reliability and power characteristics due to increased thermal output.

With all the above issues avoided by MBE through more pure and precise growth, and lack of temperature requirements causing interdiffusion, simple device designs as pictured in Figure 3 have tracked the high-frequency performance of MOCVD grown HEMTs [12], despite lacking equivalent design optimizations to those found in both the device structure, and even the growth reactors [13], that have been engineered as a result of MOCVD's wider adoption.

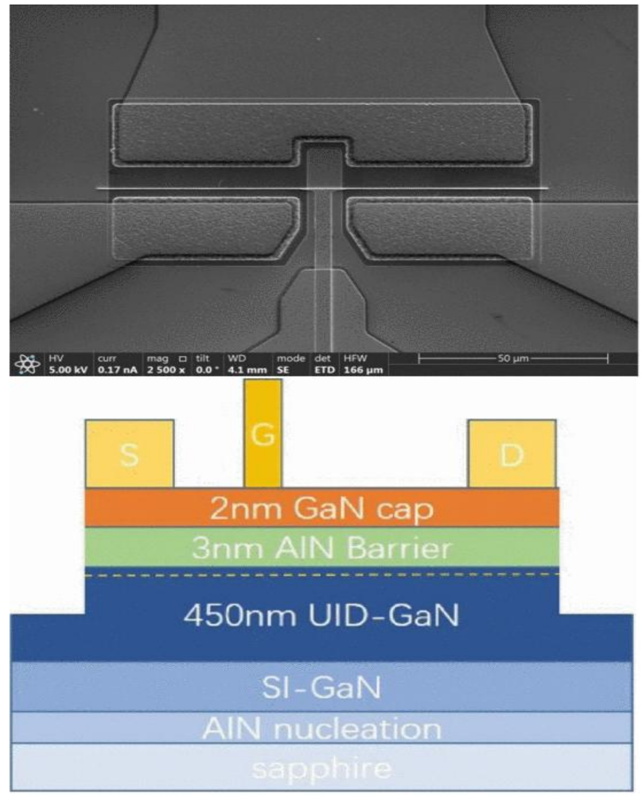

Figure 3. SEM Image and 2D-Crosssection, of AlN/GaN HEMT Device [14].

Figure 3 demonstrates the simplicity of MBE grown HEMT devices, but not a design exclusively functional when fabricated via MBE. Section 2 discussed the various architectural complexities necessary to avoid the performance loss otherwise induced by the challenges posed by MOCVD growth. The relatively simple device of Figure 3 achieves a mobility of 832 $cm^2/V\cdot s$, carrier density of 1.9E13, and sheet resistance of 386 Ω/cm^2 [14].

Although the MBE grown HEMT's electron mobility leaves some to be desired when compared to the MOCVD examples in section 2 at less than half that of examples A and C in Table 1, that is likely the result of experimental differences. Specifically, the device of Figure 3 is not passivated, leaving dangling bonds on the surface of the lattice at the AlN/GaN junction that capture electrons while in use, decreasing 2DEG density, and decreasing maximum output current. SiN passivation, further reduction in device size, and use of the more advanced T-gate structure, should all result in significant performance improvement for only minor increase in complexity, and all should be easily implemented for follow-up research [14].

The downsides of slower growth (5 nm/min [14]), worse industrial scaling, and overall lower output volume per cost in machinery and space for MBE fabrication, maintain the popularity of MOCVD. Until industrial scaling is made cheaper and more efficient, MBE is unlikely to see widespread adoption as a result. However, with the performance found to be comparable between the HEMT designs discussed so far, and the MBE design leaving significant improvements on the table for the sake of experimental control, it is possible that the benefits will outweigh the increased costs and production time, and MBE will see far more common use in the fabrication of HEMTs.

IV. GaN-on-Si

Though the performance and reliability of a silicon carbide (SiC) substrate is the industry's standard due to its relatively high thermal performance and low cost (compared to a GaN substrate) [5], the ideal for mass manufacturing would be to develop AlGaN/GaN HEMTs on Si substrates. The two main issues with placing AlGaN/GaN HEMTs directly on Si are in thermal dissipation and structural stress. In the case of RF applications, the first issue may not pose much trouble as the main goal there is to produce high-efficiency switches [2], which shouldn't face high power. However, the high structural stresses will often cause cracks [4], with the effect of degraded performance [3]. The reasons for these stresses are due to the lattice mismatch between Si and GaN (17%) and the difference in thermal expansion coefficients (5.6E-6 K^{-1} for GaN vs. 3.6E-6 K^{-1} for Si) [2, 4, 5]. These mismatches cause strain on the structure from the moment of production and will continue to cause issues through use.

A solution to these crack-forming mismatches has been to add an interlayer between the nucleation layer (typically AlN) and the substrate. Two promising materials to act as interlayers are 3C-SiC [3] and AlN [2, 4]. All of the discussed experiments use Si(111) substrates.

Additionally, by using a Si substrate, heterogenous integration can be used for situations where a purely HEMT chip would not be appropriate, such as needing the capabilities of Si-based CMOS with the amplification and switching speed characteristics of GaN HEMTs [15].

A. AlN Interlayer

The method of adding an AlN interlayer typically uses the MBE process (much as the rest of the HEMT structure) to achieve sharp interfaces [2]. In essence, a very thin SiN crystalline layer is grown on the Si substrate by applying NH_3 in a very low dose before applying a monolayer of Al. This is done because simply exposing Si to Al creates the Al-Si alloy at the surface, which would cause excess strain on the layers to follow. Further just a monolayer of Al converts the SiN layer to an AlN layer, causing a clean AlN/Si interface. Once this process is complete, shutters to both NH_3 and Al are opened, allowing for an AlN layer to grow at 0.1 micrometer per hour. Once a desired depth is grown (in this experiment's case, 40 nm), Ga is added into the chamber. Both experiments are vague [2, 4] on this part of the process, however one can deduct from Figure 4 that the process involves applying Ga and NH_3 into the chamber without sterilizing it first of Al, since the third layer from the top indicates some unintentional amount of Al in the layer. After this point, an AlGaN/GaN transistor is processed as usual using MBE, including the typical AlN nucleation layer (e.g. the 250 nm AlN layer in Fig. 4).

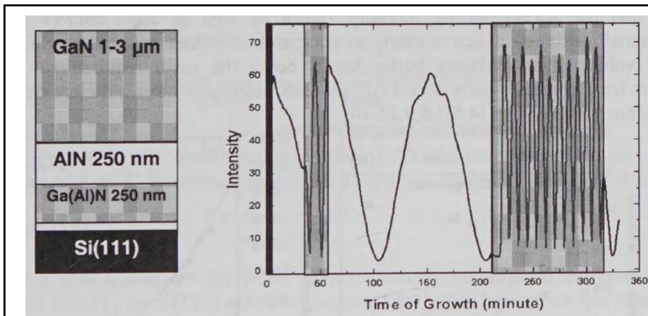

Figure 4. Left- Schematic diagram of the layer structure developed. Right- In-situ reflectometry recorded along the growth showing the different growth sequences (λ=640 nm) [2].

Both experiments report no cracking in the GaN layer after a micrometer has been grown. As the GaN layer becomes thicker, the less it experiences compression and dislocation densities, as shown in Fig. 5.

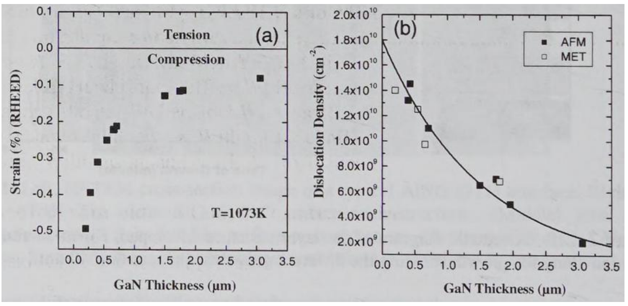

Figure 5. Left- Residual strain vs. GaN thickness measured at the growth temperature. Right- Total threading dislocation density vs. GaN thickness measured by Atomic Force Microscopy (AFM) and Transmission Electron Microscopy (TEM) [2].

It is to be noted that experiment [4] differs from that of [2] by the fact that they used RFMBE as opposed to simple NH_3-MBE. This allowed them to grow the structures at reduced temperatures (maximum temperature of 800 °C). This in turn allows for less thermally induced tensile stress [4]. Additionally, the depths of their layers differ from one another, though the general proportions are still similar.

B. 3C-SiC Interlayer

Per Reference [3], since Cubic SiC has just a 3% lattice mismatch to GaN and a 4.5E-6 K^{-1} thermal expansion coefficient (which is almost exactly between that of Si and GaN), this interlayer is a promising candidate to reducing the aforementioned second issue with Si substrates for AlGaN/GaN HEMTs, since it aims to closely model the SiC substrates most AlGaN/GaN HEMTs usually sit upon.

The process of applying the 3C-SiC interlayer involves a carbonization phase followed by a growth phase using CVD. Using hydrogen as a vector gas, applying propane at 1100 °C carbonizes the substrate then adding silane and increasing the temperature to 1350 °C develops the 3C-SiC layer up to 2.2 μm thick. After the newly formed 3C-SiC/Si substrate is complete, it is out-gassed in the MBE chamber in which the rest of the device will be processed in a typical manner using MBE [3].

Fig. 6 shows that as the 3C-SiC layer becomes thicker, a device will experience less diffraction, therefore it can be concluded less cracks form. However, the structure still exhibits wafer bowing and some number of cracks due to the mismatches. Thankfully, the GaN growth does not add to these deformities [3].

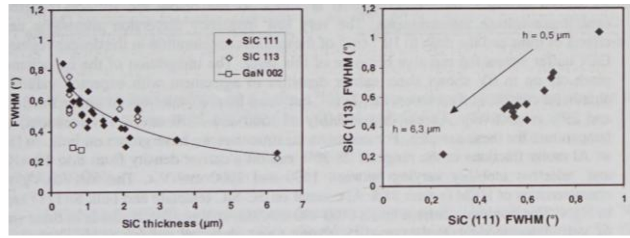

Figure 6. Dependence of the full width at half of maximum (FWHM) of the 3C-SiC(111), (113), and GaN (002) X-ray reflection line with the thickness of the film deposited on Si(111) [3].

Even with the 3C-SiC deformities, the performance of the HEMTs is better than if they were produced directly on Si. Fig. 7 shows nearly matching current-voltage characteristics, however it is to be noted that the gate length of the HEMT on 3C-SiC/Si was double that of the one on bulk Si [3]. Therefore, per the drain current equation where drain current proportionally increases with a decreasing gate length, we can figure that the HEMT on 3C-SiC may exhibit up to double the drain current if reduced to the same gate length as the on-bulk-Si sample.

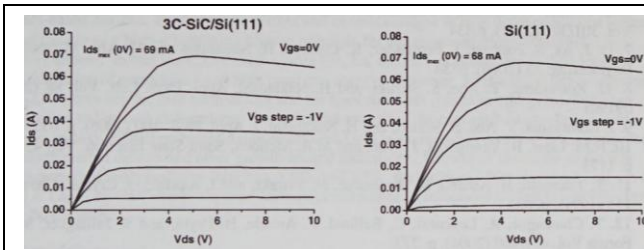

Figure 7. I-V output characteristics of a 3μm x 150 μm nominal gate transistor realized on the GaN based HEMT grown on 3C-SiC/Si(111) (left) and on bulk Si(111) (right) [3].

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