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Thermal Stability of Plasma-enhanced chemical vapor deposition Silicon Nitride Passivation on AlGaN/GaN High-electron-mobility transistors

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A thesis submitted in partial satisfaction
of the requirements for the degree Master of Science
in Materials Science and Engineering

by

Minh-Trang Teresa Ha

2016
ABSTRACT OF THE THESIS

Thermal Stability of Plasma-enhanced chemical vapor deposition Silicon Nitride Passivation on AlGaN/GaN High-electron-mobility transistors

by

Minh-Trang Teresa Ha

Master of Science in Materials Science and Engineering

University of California, Los Angeles, 2016

Professor Dwight Christopher Streit, Chair

AlGaN/GaN HEMTs are the most promising high power switching devices. The material properties of III-nitrides are exceptionally better than that of Si and GaAs. GaN-based devices have been recorded to have higher operating temperatures and higher breakdown field due to the wide bandgap. AlGaN/GaN heterostructures forms 2DEG without doping due to the spontaneous polarization. The performance and reliability of AlGaN/GaN HEMTs are dependent on the structure of the AlGaN/GaN heterostructures.

Surface passivation has been proven to improve the 2DEG conductivity and device performance. 20 nm of plasma-enhanced chemical vapor deposition (PECVD) SiN was deposited on AlGaN/GaN HEMTs, and the PECVD SiN passivated sample demonstrated higher carrier concentration of $9.88 \times 10^{12} \text{ cm}^{-2}$ compared to the un-passivated sample, $8.08 \times 10^{12} \text{ cm}^{-2}$. 


High temperature annealing is an important processing step in the fabrication of the devices, and the effects have shown to improve the DC and RF performance. High temperature annealing may affect the structure and the 2DEG conductivity. The annealing effects modifies the AlGaN layer and the AlGaN/GaN interface. Herein, we present the study on the thermal stability of the PECVD SiN passivation layer on AlGaN/GaN HEMT structures at high temperature anneals. High-resolution x-ray diffraction (HRXRD) measurements were used to investigate the strain of AlGaN layer, and Hall measurements were used to investigate the 2DEG conductivity.

PECVD SiN passivated and un-passivated AlGaN/GaN HEMTs structure underwent high temperature thermal anneals for 30 minutes in N₂. The starting temperature of the annealing is 400°C with step of 50°C until degradation. Degradation was determined through Hall sheet resistivity and mobility measurements. The ending annealed temperature is 1000 °C and 700 °C for passivated and control samples, respectively. From no anneal to degradation temperature, the 2DEG conductivity dropped by 15% and 34% for passivated and un-passivated samples, respectively. The HRXRD measurements found the change in-plane strain of the AlGaN layer after high temperature anneals. Higher in-plane strain showed higher 2DEG conductivity. In-plane strain from no anneal to degradation temperature dropped from 2% and 7% for passivated and un-passivated samples, respectively. Therefore, the passivated sample demonstrated to be more stable at high temperatures. The SiN passivation layer adds tensile stress to the AlGaN layer thus increased the piezoelectric effect and 2DEG conductivity.
The thesis of Minh-Trang Teresa Ha is approved.

Ya-Hong Xie

Mark S. Goorsky

Dwight Christopher Streit, Chair

University of California, Los Angeles

2016
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<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRXRD</td>
<td>High Resolution X-Ray Diffraction</td>
</tr>
<tr>
<td>HEMTs</td>
<td>High-electron-mobility transistors</td>
</tr>
<tr>
<td>MBE</td>
<td>Molecular Beam Epitaxy</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma-enhanced chemical vapor deposition</td>
</tr>
<tr>
<td>TAD</td>
<td>Triple axis diffractometer</td>
</tr>
</tbody>
</table>


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1. Introduction

1.1 Motivation

Modern transistors need to meet the demands of high power, high speed, and high efficiency electronic. Power switching devices play a vital role in managing and controlling of electric energy networks; thus, modern transistors need to meet the demands of high power, high speed, and high efficiency communications. III-nitrides semiconductors have a direct and wide band gap, high melting temperature, high electron mobility, and high breakdown field making them ideal candidates for high power and high temperature applications. [1-4]

Table 1.1: Comparison of electronic properties for different semiconductors. [1,4]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Si</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band-Gap (eV)</td>
<td>1.12</td>
<td>1.43</td>
<td>3.26</td>
<td>3.4</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>11.4</td>
<td>13.1</td>
<td>9.7</td>
<td>9.5</td>
</tr>
<tr>
<td>Electron Mobility (cm²/Vs)</td>
<td>1350</td>
<td>8500</td>
<td>700</td>
<td>900</td>
</tr>
<tr>
<td>Saturated Electron Velocity (10⁷ cm/s)</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Breakdown Field (MV/cm)</td>
<td>0.4</td>
<td>0.5</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Maximum Temperature (°C)</td>
<td>300</td>
<td>300</td>
<td>600</td>
<td>700</td>
</tr>
</tbody>
</table>

Table 1.1 compares the electronic properties of GaN with other semiconductors [1,4]. GaN demonstrated larger band gap, high saturated electron velocity, and better thermal stability compared to Si and GaAs [4]. Current research has focused on AlGaN/GaN high-electron mobility transistors (HEMTs) for low loss and high voltage switching devices because of the
formation of the two-dimensional electron gas (2DEG) in AlGaN/GaN heterojunction interface from strong polarization effects. However, AlGaN/GaN HEMTs suffers from unstable performance affecting its reliability. The main concern is current collapse, in which the drain current decreases and ON-resistance increases. This phenomena is not fully understood, but possible causes could be due to trapping. Surface passivation with dielectrics is a method to minimize the trapping effects. [2]

High temperature annealing is an important processing step in the fabrication of the devices and affect the structure and the 2DEG behavior. [1-5] Chen et al. reported that annealing resulted nonreversible lattice relaxation in the AlGaN layer and decreased in 2DEG mobility. [23] Gatabi et al. reported an improved 2DEG density from post-annealing after PECVD SiN deposition. [9] Jeon et al. studied the effects of the tensile stress induced by the SiN passivation layer increased the 2DEG density. [12] Feng et al. found that SiN passivation layer enhanced the thermal stability of the AlGaN/GaN HEMTs structure at long annealing time. [10]

1.2 Objective

The aim of this thesis is to investigate the plasma-enhanced chemical vapor deposition (PECVD) SiN passivated and un-passivated AlGaN/GaN HEMTs after annealing at high temperatures. High Resolution X-Ray Diffraction (HRXRD) and hall measurements were used to characterized and study the annealing effects on PECVD SiN passivated and un-passivated AlGaN/GaN HEMTs. These results were used to identify and understand how the PECVD SiN layer affects the stability and 2DEG behavior of the AlGaN/GaN HEMTs structures at high thermal anneals.
2. Background

2.1 AlGaN/GaN Heterostructures

Both GaN and the alloy AlGaN are III-nitrides semiconductors and wide bandgap material. III-nitrides can be grown into two crystal structures: zinc blende structure with cubic shaped lattice and wurtzite with hexagonal shaped lattice. The only differs in their stacking sequence of nitrogen and the metal atom. Both crystal structures are non-centrosymmetric, hence, they are both piezoelectric materials. Wurtzite exhibits spontaneous polarization due the lack of inversion symmetry and the bond along [0001] direction has different iconicity than other bonds. [14-16]

GaN growth is difficult due to the lack of native substrate, which results in large n-type carrier background concentration. III-nitrides semiconductors are grown by epitaxial growth. The process is highly controlled as the crystal film is deposited one atomic layer at a time. There are two most common methods of growing large scale III-nitrides: metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). Due to the mismatch lattice and thermal between substrate and epitaxial layer, the epitaxial layer is prone to strain, stacking faults, dislocations, and defects. [14-16]

III-nitrides growth is heavily influenced by the substrate during epitaxial growth. Sapphire is the most commonly used substrate for III-nitrides growth. Sapphire has been predominantly used in both research and commercially III-nitride growth due to low cost, stable at high temperature, and developed growth technology. The lattice mismatch between GaN and sapphire is approximately 15%. The quality of the III-nitride film is better if grown on the \( a \) plane sapphire than \( c \) plane sapphire. [17]
2.1.1 Biaxial Stress

The lack of native substrate results in biaxial strain between the epilayer and substrate due to the lattice mismatch. In the case of III-nitrides, biaxial stress is assumed to be present in the grown film, in which the crystal is stressed in the (0001) plane and relaxed in the [0001] direction. Biaxial strain causes the lattice parameters to change and the hexagonal symmetry is preserved (figure 2.1). [8, 18]

![Figure 2.1: Illustration of biaxially stressed unit cell of GaN](image)

The strain is defined using the in-plane lattice parameter $a$ and the out-of-plane lattice parameter $c$:

$$\varepsilon_a = \frac{a_{\text{meas}} - a_0}{a_0} \quad (2.1)$$

and

$$\varepsilon_c = \frac{c_{\text{meas}} - c_0}{c_0} \quad (2.2)$$

where $a_{\text{meas}}$ and $c_{\text{meas}}$ are measured strain parameters, $a_0$ and $c_0$ are relaxed parameters. For simple biaxial strain, the out-of-plane strain and in-plane strain is related to Poisson's ratio $\nu$:  

4
\[ \varepsilon_c = -2\frac{C_{13}}{C_{33}} = -\frac{2\nu}{1-\nu}\varepsilon_a \]  

(2.3)

where \( C_{13} \) and \( C_{33} \) are the elastic coefficients. The theoretical Poisson's ratio value is chosen to be 0.193 for AlGaN. This value was calculate from the chosen Poisson ratio of 0.183 and 0.203, for GaN and AlN, respectively. [22] The formation of misfit dislocations alleviates the epitaxial strain [20,21], and this affects the piezoelectric polarization in AlGaN and 2DEG concentration.

### 2.1.2 Polarization Effects

AlGaN/GaN heterostructure have a unique characteristic, which forms 2DEG without doping. This characteristic is primarily due to the spontaneous polarization and the piezoelectric properties found in III-nitrides. These properties are based on the crystal structures of III-nitrides. Due to the high electronegativity difference between the III elements (Al, Ga, and In) and N, the atoms are tetrahedrally bonded, in which each atoms are bonded to four different atoms. [14-17]

The crystal structure of III-nitrides results in spontaneous polarization (\( P_{SP} \)). This is due to the strong electronegativity difference from the nitrogen and metal, which affects the spontaneous polarization. [16] GaN layer is epitaxially grown normal to the (0001) plane and has lack of inversion symmetry. This results spontaneous polarization in exist in the \langle 0001 \rangle direction (figure 2.2).
Figure 2.2: Spontaneous polarization and piezoelectric polarization AlGaN/GaN

Heterostructures

The second polarization field is piezoelectric polarization ($P_{PE}$) from strain in the epitaxial layers. Piezoelectric polarization originates from mechanical deformation and lack of symmetry. In AlGaN/GaN HEMTs, the GaN layer is several orders of magnitude thicker than the AlGaN layer, and the GaN layer can be assumed to be fully relaxed and no piezoelectric polarization. The stress is applied to the AlGaN layer because when AlGaN is grown on top of GaN, the lattice constant of ALGaN has to match the lattice constant of GaN. The stress causes strain in both the basal plane and growth directions, and the strain results in piezoelectric polarization. The piezoelectric polarization field can be expressed:

$$P_{PE} = 2\varepsilon_d \left( e_{31} - \frac{e_{33} c_{33}}{c_{33}} \right)$$

where $e_{31}$ and $e_{33}$ are the piezoelectric coefficients. [10]

A heterointerface between the AlGaN and GaN layer will induce a discontinuity in the polarization. The polarization induced charge density can be expressed:

$$\sigma = (P_{SP,AlGaN} + P_{PE,AlGaN}) - P_{SP,GaN}$$ (2.5)
This indicates that there will be a permanent fixed polarization sheet charge at the AlGaN/GaN interface. Since the spontaneous polarization in AlGaN is larger than GaN, there will be positive bound charges at the AlGaN/GaN interface. [20]

### 2.1.3 Two Dimensional Electron Gas (2DEG) Formation

The polarization fields form a conductive channel at the heterointerface. The polarization difference results in positive bound charges at the interface and the conduction band at the interface is pulled downward. The highly positive sheet charge density attracts the electrons and become confined into the a triangular shaped potential well (figure 2.3)

![Band Diagram of AlGaN/GaN heterostructure](image)

**Figure 2.3:** Band Diagram of AlGaN/GaN heterostructure

The polarization induces a negative bound charges at the surface and the conduction band the surface is pulled upwards. These electrons are confined in the two dimension, which forms the 2DEG at the GaN channel. The 2DEG sheet concentration \(n_s\) can be described: [10]

\[
n_s = \left( \frac{a_{\text{int}}}{q} \right) - \left( \frac{e_0 \epsilon_r}{q^2 \ell_{\text{AlGaN}}} \right) \left( q \phi_b + E_F - \Delta E_C \right) \tag{2.6}
\]
where $\sigma_{\text{int}}$ is the net positive fixed sheet charge at the AlGaN/GaN heterostructure interface from polarization difference (equation 2.5), $q$ is elementary charge ($1.602 \times 10^{-19}$ C), $\varepsilon_r$ is the dielectric constant of AlGaN, $t_{\text{AlGaN}}$ is the thickness of the AlGaN layer, $q\phi_b$ is the Schottky-Barrier height of the gate contact, $E_F$ is the Fermi level with respect to the GaN conduction band, and $\Delta E_C$ is the conduction band offset between AlGaN and GaN. [20] For HEMTs, it utilizes a heterostructure to create a potential well for electrons to move freely in two dimension, forming a 2DEG. [10, 20]

2.2 Surface Passivation

Crystal defects, dislocations, and impurities are present due to the high lattice and thermal mismatch during III-nitrides crystal growth and create traps, which are energy states in the band gap of the semiconductor. Traps at the interface or surface affect the device operation and performance. When a large negative gate voltage is applied, this will induce an electric field close the gate and the electrons from the gate leak to the surface trap states, creating a "virtual gate" and depleting the channel. During pulsed operation, the gate voltage changes abruptly. The trapped electrons are unable to respond quickly and the channel remains partially depleted. This results in reduction of drain current and output power, which is current collapse. Defects in the buffer layer trap excited electrons from channel due to the high drain voltage. This results in the depletion region expanding and drain current is significant reduced. [1,2]

The AlGaN surface is passivated to resolve the surface states because there is a high density of positive charges of AlGaN surface, which is a response to the negative polarization charge in AlGaN/GaN heterostructures. The most widely used method is surface passivation by dielectrics, such as SiN film. A thin dielectric film is deposited on the surface, usually between
the source-gate and drain-gate contacts. Various sources has shown that surface passivation has been recorded that passivated AlGaN/GaN heterostructures have higher 2DEG density. [9] The mechanism of passivation is not fully understood, but the most accepted explanation is that passivation reduces surface trap density. The passivation layer buries traps prevent electrons from the gate to access it. Therefore, this prevents "virtual gate" for forming and depletion region narrowing, allowing carrier to move more easily. SiN passivation causes Si to be incorporated as shallow donor at the AlGaN surface. [5]
3. Experimental Methods

3.1 Hall Measurements

Hall effect measurements are used to characterized semiconductors and provides information on the majority type concentration, mobility, and resistivity. These measurements are commonly used to measure the channel conductivity in HEMT structure. [6]

The Hall effect measurements are based on the measurements of induced voltage of a samples in magnetic field oriented perpendicular to samples surface. The electrons moving in the magnetic field are influenced by the Lorentz Force: [6]

\[ F = q \cdot (v_d \times B) \]  

(3.1)

where \( q \) is elementary charge \( (1.602 \times 10^{-19} \text{ C}) \), \( v_d \) is drift velocity, and \( B \) is the inductance of the magnetic field. Using current density \( (J = env_d) \) for electrons and electric field \( (E) \):

\[ \frac{J}{en} B_z = -E_y \]  

(3.2)

And the Hall factor \( (R_H) \):

\[ R_H = \frac{1}{en} \]  

(3.3)

Conductivity \( (\sigma_n) \) is measured and the Hall mobility \( (\mu_n) \) for electrons can be determined: [6]

\[ \mu_n = \frac{\sigma_n}{en} \]  

(3.4)

Mobility of the 2DEG is important for functionality and performance in devices. [10]
3.2 High Resolution X-Ray Diffraction (HRXRD)

X-ray diffraction is used to characterize semiconductor epitaxial layers used in optical and electronic devices. X-rays are produced when electrons decelerate. From the deceleration of the electrons at the target, a continuous radiation spectrum is observed along with sharp intensity peaks. This is due to K electrons being “knocked” out of their shell causing a cascade of other electrons to fill in the shell causing a release in energy. This results in the characteristic wavelength, $K\alpha$, to have the higher intensity.

From the diffraction peaks, an angular position is recorded from each peak. Taking half of the given angle gives the Bragg’s angle. Using Bragg’s Law:

$$2dsin\theta = n\lambda$$  \hspace{1cm} (3.5)

Where $n$ is the order of diffraction, $\lambda$ is the x-ray wavelength which in this case is the Cu $K\alpha_1$ wavelength (1.5406 Å), $d$ is the interplanar spacing, and $\Theta$ is the Bragg angle for the material. This formula will then give the theoretical d-spacing used to find the correct hkl indices for each diffraction peak. In this experiment, the (002) plane will be observed.

Since GaN is a wurtzite (hexagonal), the following equation can be used to find the d-spacing:

$$\frac{1}{d} = \frac{4}{3} \frac{h^2+k^2+hl}{a^2} + \frac{l^2}{c^2}$$  \hspace{1cm} (3.6)

Where $d$ is the interplanar spacing, $a$ is the lattice parameter, and $hkl$ are the plane indices.

Coupled scan or 2theta-omega (20-\omega) scan have the source is fixed, and the samples and detector rotates. The coupled scan is used to study the lattice mismatch, composition, and
relaxation, which affects the position of the Bragg peak. Rocking curves or omega (ω) scan have the samples tilted while the detector is set at an angle in which omega changes. The rocking curve is primarily used to study the defects and dislocations, which are related to the full width half maximum (FWHM). [11]

Then using Vegard’s Law, the composition can be determined using the following formulas:

\[
d_{Al_{x}Ga_{1-x}N} = d_{AlN}x + d_{GaN}(1 - x)
\]  \hspace{1cm} (3.7)

The composition \( x \) can be used to find the relaxed parameter for the relaxed lattice parameter: [8]

\[
c_{Al_{x}Ga_{1-x}N,relaxed} = c_{AlN}x + c_{GaN}(1 - x)
\]  \hspace{1cm} (3.8)

For good 2DEG concentration and mobility, the Al composition should be between 0.20 and 0.30. [9]
4. Study of PECVD SiN passivated AlGaN/GaN HEMTs at High Annealing Temperatures

4.1 Experimental Procedure

AlGaN/GaN HEMT structure were grown using by molecular beam epitaxy (MBE) at Northrop Grumman Aerospace System (NGAS) on sapphire substrates. The structure consisted of a thin AlN nucleation layer, GaN buffer layer, 1560 Å of GaN Channel, and 230 Å AlGaN Barrier (figure 4.1a). Hall measurements were done on LEI 1600 mobility measurement system and LEI process resistivity mapper in room temperature. The LEI 1600 instrument allows for non-destructive and non-contact mobility and resistivity. The on-wafer Hall measurements show the sheet carrier concentration of $8.40 \times 10^{12} \text{ cm}^{-2}$, mobility of 768 cm$^2$/V s, and sheet resistivity of 919 $\Omega$/sq.
Figure 4.1: (a) AlGaN/GaN HEMTs structure and (b) PECVD SiN AlGaN/GaN HEMTs structure

20 nm SiN layer were deposited with Plasma-Therm SLR series (figure 4.1b). The SiH₄, NH₃, and N₂ flow rates were 16 sccm, 605 sccm, and 2600 sccm, respectively, with pressure of 900 torr, temperature of 250 °C for 2 minutes. The on-wafer Hall measurements showed the sheet carrier concentration of $9.88 \times 10^{12}$ cm$^{-2}$, mobility of 749 cm$^2$/V s, and sheet resistivity of 792 $\Omega$/sq. An un-passivated samples was used for control, and the on-wafer Hall measurements showed the sheet carrier concentration of $8.08 \times 10^{12}$ cm$^{-2}$, mobility of 806 cm$^2$/V s, and sheet resistivity of 884 $\Omega$/sq.

The control and passivated samples were annealed in furnace in N₂ for 30 minutes. The starting temperature of the annealing is 400°C with step of 50°C until degradation. Degradation was determined through Hall sheet resistivity and mobility measurements. The ending annealed temperature is 1000 °C and 700 °C for passivated and control samples, respectively.
High-resolution x-ray diffraction (HRXRD) was used to analyze the applied stress and crystalline quality in the AlGaN. The X-ray measurements were taken by high-resolution triple axis diffractometer (TAD) by using Cu $K\alpha_1$ (1.5406 Å). The $c$ lattice parameters and full width half maximum (FWHM) were determined from symmetrical (002) 2θ-ω scan diffraction peaks and the symmetric (002) ω scan (rocking curve), respectively.

4.2 Characterization Measurements

4.2.1 Hall Measurements

Hall measurements were done on LEI 1600 mobility measurement system and LEI process resistivity mapper. The LEI 1600 instrument allows for non-destructive measurements for mobility and resistivity. Hall measurements were done at room temperature (figure 4.2).
Figure 4.2: Hall measurements (resistivity, mobility, and concentration) for (a) un-passivated and (b) PECVD SiN passivated AlGaN/GaN HEMTs at different annealing temperatures. (c) 2DEG conductivity for un-passivated and PECVD SiN passivated AlGaN/GaN HEMTs.
Figure 4.2 shows the comparison of the 2DEG behavior and degradation of the un-passivated and passivated AlGaN/GaN HEMTs structure at different annealing temperatures. At 700°C, the resistivity of the un-passivated samples significantly increased to 1188 Ω/sq from 884 Ω/sq indicating 26% degradation. In comparison, passivated sample degraded at 1000 °C as indicated from the resistivity increased to 863 Ω/sq from no anneal resistivity 792 Ω/sq showing 9% increase. Both samples showed drop of 1% for passivated and 6% for un-passivated in concentration from no anneal to annealing temperature 400 °C. The un-passivated sample showed improvement in the 2DEG conductivity at 500°C as observed in highest mobility of 884 cm²/V s and lowest resistivity of 874 Ω/sq.

The passivated sample displays higher concentration in comparison to the un-passivated sample and remains high even at increasing annealing temperatures. SiN passivation layer provides stability to the 2DEG concentration as it did not fluctuate more than 5%. In comparison, the unpassivated sample degraded concentration decreased 20% from no anneal to 700 °C anneal. The mobility of the passivated sample was reduced from no anneal 749 cm²/V s to 1000°C anneal 621 cm²/V s, representing a 20% drop. While the mobility of un-passivated sample had a decrease of 11% from no anneal to 700°C anneal. At 750°C, the passivated sample had the lowest resistivity of 749 Ω/sq indicating improved 2DEG conductivity.

From no anneal to degradation temperature, the 2DEG conductivity dropped by 15% and 34% for passivated and un-passivated samples, respectively (figure 4.2c). PECVD SiN passivation increases the 2DEG concentration due to the reduction of trap density. [9] SiN passivation layer adds additional strain to the AlGaN layer, which increases the piezoelectric polarization and increases the sheet concentration. [12]
4.2.2 XRD Measurements

**Figure 4.3**: 2\(\Theta\)-\(\omega\) scans for (a) un-passivated and (b) PECVD SiN passivated AlGaN/GaN HEMTs.
Symmetric (002) 2Θ-ω diffraction measurements were taken (figure 4.3). The out-of-plane lattice constant \( c \) of GaN and Al\(_x\)Ga\(_{1-x}\)N was determined from the position of the Bragg angle (table 4.1 and table 4.2). The composition could be determined using determined using equation 3.7 and relaxed lattice parameter \( c \) of Al\(_x\)Ga\(_{1-x}\)N could be determined using 3.8. Assuming biaxial stress, the in-plane strain can be determined from the out-of-plane strain (equation 2.2) using equation 2.3.

Table 4.1: Un-passivated symmetric (0002) AlGaN/GaN HEMTs 2Θ-ω scan measurements

<table>
<thead>
<tr>
<th>Temperature</th>
<th>GaN Bragg Angle</th>
<th>GaN Lattice Parameter</th>
<th>Al(<em>x)Ga(</em>{1-x})N Bragg Angle</th>
<th>Al(<em>x)Ga(</em>{1-x})N Lattice Parameter</th>
<th>( x )</th>
<th>Relaxed Lattice Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 °C</td>
<td>17.091 °</td>
<td>5.242 Å</td>
<td>17.336 °</td>
<td>5.170 Å</td>
<td>0.237</td>
<td>5.193 Å</td>
</tr>
<tr>
<td>400 °C</td>
<td>17.087 °</td>
<td>5.243 Å</td>
<td>17.329 °</td>
<td>5.172 Å</td>
<td>0.233</td>
<td>5.195 Å</td>
</tr>
<tr>
<td>500 °C</td>
<td>17.092 °</td>
<td>5.242 Å</td>
<td>17.335 °</td>
<td>5.170 Å</td>
<td>0.234</td>
<td>5.193 Å</td>
</tr>
<tr>
<td>700 °C</td>
<td>17.074 °</td>
<td>5.247 Å</td>
<td>17.303 °</td>
<td>5.180 Å</td>
<td>0.220</td>
<td>5.202 Å</td>
</tr>
</tbody>
</table>
**Table 4.2:** PECVD SiN Passivated symmetric (002) AlGaN/GaN HEMTs 2Θ-ω scan measurements

<table>
<thead>
<tr>
<th>Temperature</th>
<th>GaN Bragg Angle</th>
<th>Lattice Parameter</th>
<th>AlGaN Bragg Angle</th>
<th>Lattice Parameter</th>
<th>x</th>
<th>Relaxed lattice parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 °C</td>
<td>17.098 °</td>
<td>5.240 Å</td>
<td>17.351 °</td>
<td>5.166 Å</td>
<td>0.242</td>
<td>5.190 Å</td>
</tr>
<tr>
<td>400 °C</td>
<td>17.090 °</td>
<td>5.242 Å</td>
<td>17.341 °</td>
<td>5.169 Å</td>
<td>0.242</td>
<td>5.193 Å</td>
</tr>
<tr>
<td>750 °C</td>
<td>17.097 °</td>
<td>5.240 Å</td>
<td>17.356 °</td>
<td>5.164 Å</td>
<td>0.249</td>
<td>5.189 Å</td>
</tr>
<tr>
<td>1000 °C</td>
<td>17.097 °</td>
<td>5.240 Å</td>
<td>17.344 °</td>
<td>5.168 Å</td>
<td>0.237</td>
<td>5.191 Å</td>
</tr>
</tbody>
</table>

Rocking curves scans were done to look at the crystal quality of the GaN and Al$_x$Ga$_{1-x}$N layer. Symmetric (002)-plane is related to screw and mixed dislocations. The FWHM is an indicator of crystal quality. [11]
Figure 4.4: FWHM of ω scans vs. Temperature for (a) GaN layer and (b) AlGaN layer

Figure 4.4 shows the FWHM of the rocking curve of the symmetric (002) for the AlGaN and GaN layer. Annealing changes the AlGaN/GaN interface structure. The FWHM is related to
the crystalline quality and dislocation densities of the film. The FWHM of the GaN and AlGaN layer increases at higher annealing temperature. The FWHM of the GaN and AlGaN layer showed 7% and 8% increase, respectively, from no anneal to 700°C. In comparison, the passivated sample display decrease in the FWHM of the GaN and AlGaN layer. The change of the FWHM of the GaN and AlGaN layer from no anneal to 1000°C anneal is 94% and 75%, respectively.

Misfit dislocation and threading dislocations can be formed at the AlGaN/GaN interface and create strain relaxation. Based on the FWHM, the crystalline quality is best at 1000°C anneal in the passivated sample and at 400°C anneal for the un-passivated sample because the FWHM is the smallest in the AlGaN layer. The crystalline quality is poor at no anneal in the passivated sample and at 700°C anneal for the passivated sample.

4.3 Effects of Passivation and Annealing

High temperature annealing effects have shown to improve the DC and RF performance. [1-5] High temperature annealing may affect the structure and the 2DEG conductivity. PECVD SiN passivation has been documented to significantly improve the performance of AlGaN/GaN HEMTs specifically increases the 2DEG concentration. This is observed in figure 4.2 in which the PECVD SiN passivated samples has significant higher 2DEG concentration compared to the un-passivated samples.

The 2DEG concentration is related to the piezoelectric and spontaneous polarization (equation 2.4). Piezoelectric polarization is proportional to in-plane strain. The in-plane strain also affects the 2DEG mobility from the formation of dislocations. Dislocation scattering reduces
the 2DEG mobility. As a result, the 2DEG conductivity \((n_s \times \mu \times q)\) reduces with decreasing in-plane strain.

Figure 4.5 shows the in-plane strain and the 2DEG conductivity are proportional. In-plane strain from no anneal to degradation temperature dropped from 2\% and 7\% for passivated and un-passivated samples, respectively. At no anneal, the in-plane strain is \(9.38 \times 10^{-3}\) and \(9.63 \times 10^{-3}\) for un-passivated and passivated samples, respectively. In general, the passivated sample exhibits higher in-plane strain compared to the un-passivated sample. Thus, the 2DEG conductivity is higher in the passivated samples. The higher 2DEG conductivity in passivated samples is from the SiN passivation layer adding strain to the AlGaN layer, increasing the 2DEG conductivity. The SiN passivation layer keeps the 2DEG conductivity and piezoelectric polarization stable from high temperature anneals.
Figure 4.5: 2DEG conductivity and in-plane strain vs. temperature for (a) un-passivated and (b) PECVD SiN passivated AlGaN/GaN HEMTs

Misfit dislocation can be formed at the ALGaN/GaN interface and create strain relaxation causing decrease in piezoelectric polarization and 2DEG conductivity. The rocking curve of the symmetric (002) for the AlGaN layer can reveal the misfit dislocation and threading dislocation densities based on the FWHM (figure 4.6 and figure 4.7). [22]
Figure 4.6: Un-passivated AlGaN/GaN HEMTs for (a) 2DEG concentration and AlGaN (002) FWHM of vs. temperature and (b) mobility and AlGaN (002) FWHM of vs. temperature
The 2DEG conductivity and AlGaN (002) FWHM of un-passivated samples are proportional except at the annealing temperature 700 °C. Figure 4.4 shows increasing FWHM at increasing annealing temperature indicating poorer crystalline quality at higher annealing temperatures. The poorer crystalline quality can be due to higher dislocation density, which can result in more dislocation scattering and lowered mobility (figure 4.6b). The dislocation scattering and lowered mobility do not affect the 2DEG conductivity until at annealing temperature 700 °C. At 500 °C anneal, the crystalline quality is best as indicated from by the smaller FWHM and possibly entails lower dislocation density; hence, 2DEG conductivity is the highest.
Figure 4.7: PECVD SiN passivated AlGaN/GaN HEMTs

for (a) 2DEG concentration and AlGaN (002) FWHM of vs. temperature and (b) mobility and AlGaN (002) FWHM of vs. temperature

The 2DEG conductivity and AlGaN (002) FWHM of PECVD SiN passivated samples are inversely proportional except at annealing temperature 1000 °C. The improved crystal quality could possibly indicate lower dislocation density and no strain relaxation. In figure 4.7b, the mobility and FWHM have no correlation. The 2DEG conductivity is affected by the in-plane strain. The SiN passivation layer contributes to the strain of the AlGaN layer, which improves the stability of the 2DEG conductivity at higher temperatures. The increasing annealing temperatures reconstruct the SiN/AlGaN interface and reduces the interface traps, in which oxygen vacancies. The improved crystal quality observed in the lowered FWHM indicates the reduction of traps. [5]
5. Conclusions

5.1 Conclusions

Surface passivation is known to improve the 2DEG behaviors in AlGaN/GaN HEMTs. High temperature annealing may affect the structure and the DC and RF performance. The thermal stability of the surface passivation on AlGaN/GaN HEMTs is studied at high annealing temperatures. Hall measurements and high resolution X-ray diffraction (HRXRD) are used to characterized the 2DEG behavior and AlGaN layer structure and strain.

At high annealing temperatures, un-passivated AlGaN/GaN HEMTs degraded faster at 700 °C while PECVD SiN passivated AlGaN/GaN HEMTs degraded at 1000 °C. From no anneal to degradation temperature, the 2DEG conductivity dropped by 15% and 34% for passivated and un-passivated samples, respectively. PECVD SiN passivated AlGaN/GaN HEMTs have significantly higher carrier concentration compared to un-passivated AlGaN/GaN HEMTs.

The HRXRD measurements found the strain and crystalline quality in the AlGaN layer. From the rocking curve, the FWHM of un-passivated AlGaN layer increased whereas the FWHM of the passivated AlGaN layer decreased at higher annealing temperatures. The increasing FWHM is an indicator of formation of dislocation and strain relaxation. The in-plane strain of the AlGaN layer was affected by the high temperature anneals. Higher in-plane strain showed higher 2DEG conductivity. In-plane strain from no anneal to degradation temperature dropped from 2% and 7% for passivated and un-passivated samples, respectively.

The PECVD SiN passivation layer adds tensile stress to the AlGaN layer to minimize strain relaxation from high thermal anneals. At no anneal, the in-plane strain is $9.38 \times 10^{-3}$ and $9.63 \times 10^{-3}$ for un-passivated and passivated samples, respectively. In general, the passivated
sample exhibits higher in-plane strain compared to the un-passivated sample. Thus, the 2DEG conductivity is higher in the passivated samples. The PECVD SiN passivation layer adds stability to the AlGaN/GaN HEMTs structure at high annealing temperatures, and improves the 2DEG conductivity.

5.2 Future Directions

This work presented in this thesis is the starting point in understanding the thermal stability of PECVD SiN passivation layer on AlGaN/GaN HEMTs structures. HRXRD and Hall measurements were used to characterized the crystal quality, in-plane strain, and 2DEG conductivity. The in-plane strain was found using the out-of-plane strain and Poisson's ratio. HRXRD measurements on in-plane (102) could be conducted to find the percentage relaxation of the AlGaN layer and the reciprocal space map (RSM) can be made to analyzed both the out-of-plane and in-plane measurements. A study of the thermal stability of PECVD SiN at the different annealing times. Kim et al. found that at higher annealing times, the post-annealing created traps with long capturing time constants. [13] The SiN passivation layer has shown to add tensile stress to increase the piezoelectric effects and 2DEG conductivity. Many studies have confirm that PECVD SiN passivation reduces the surface traps. [9-13] Surface traps and the effects of annealing and the surface passivation should be further investigated.
References


