Engineered Tunneling Contacts with Low-Temperature Atomic Layer Deposition of AlN on GaN

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Keywords: GaN, AlN, ALD, low-temperature, 2DEG, quantum tunneling

Abstract

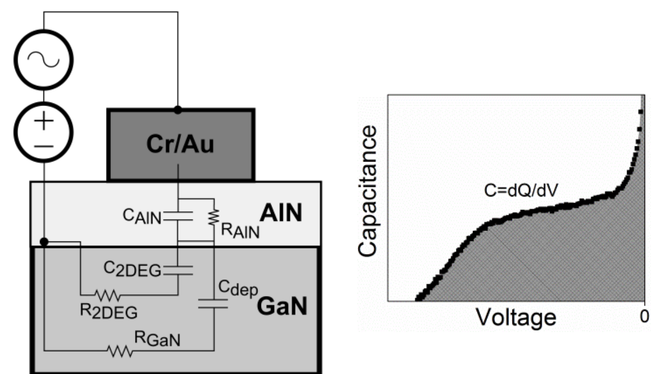
The tunneling conductivity of ultrathin AlN deposited on GaN using low-temperature ALD was observed to vary significantly with n-type GaN doping concentration. While highly-doped (~10^{18} cm^{-3}) GaN produced consistently ohmic JV plots in a 3-6 nm AlN range, undoped (~10^{14} cm^{-3}) GaN only showed such a characteristic at 3 nm. Conductivity-voltage plots show that the 2DEG concentration becomes the primary influence on quantum tunneling in this case, while the transmission coefficient through AlN influences undoped GaN.

INTRODUCTION

Ultrathin AlN deposited on GaN is promising for developing low-resistance tunneling ohmic contacts. Removing the gallium concentration from the standard AlGaN/GaN heterojunction maximizes the polarization strain and subsequently the 2DEG concentration between the two materials. [1] The high 2.4% crystal lattice mismatch between AlN and GaN creates a strong piezoelectric polarization strain between the two materials, which results in sharp conduction band bending and a deep quantum well, thus forming the 2DEG from the resulting polarization induced triangular quantum well at the interface. The tensile strain limits the AlN layer thickness to below 5 nm due to cracking, but these ultrathin layers allow significant quantum tunneling to circumvent the high energy barrier of AlN relative to the contact metal and GaN. This work describes the use of low-temperature ALD to deposit AlN on GaN and achieve ohmic contacts using quantum tunneling from the 2DEG to the metallic contact.

PROCESS AND CHARACTERIZATION

Deposition was performed at 250ºC using TMA and nitrogen plasma precursors. Dielectric AlN layers with 40-70



(a) (b)

Figure 1: (a) Schematic of the AlN/GaN MOSCAP. (b) Plot of reverse bias integration method to determine 2DEG.

deposition cycles, corresponding to 3-6 nm thicknesses, were deposited on 5 µm HPVE GaN on sapphire substrates (Kyma Inc.) with two different donor concentrations: 7x10^{17} cm^{-3} (N+) and ~10^{14} cm^{-3} (N-). Circular planar MOSCAP structures were developed in-house [2] with Cr as the contact metal. Current-voltage (JV) plots displayed contact behavior while capacitance-voltage profiling was used to extract 2DEG concentrations using the lumped-element circuit model in Figure 1.

EXPERIMENTAL RESULTS

Figure 2 compares the AlN/GaN junction for the two different doping levels. The N+ GaN samples consistently demonstrated pseudo-ohmic JV curves, with 4 nm AlN as the most linear while 5 nm AlN most resembled a double Schottky diode. For N- GaN, only 3 nm AlN was thin enough to display significant quantum tunneling effects through the barrier [3], with the JV showing pseudo-ohmic behaviour as a result. In contrast, the thicker AlN layers blocked the tunneling current and behaved as Schottky diodes.

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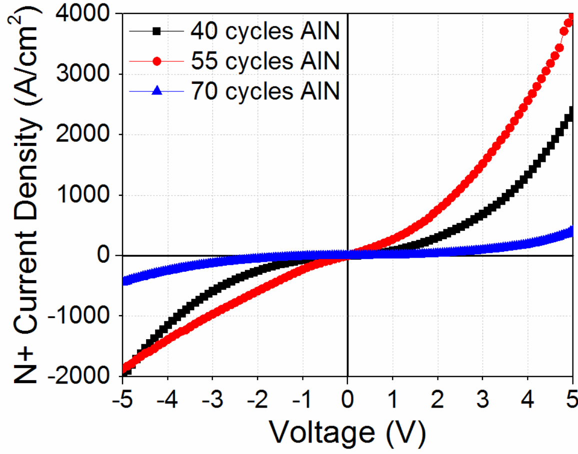
Doping type	N+			N-		
ALD Cycles	40	55	70	40	55	70
AlN Thickness	3.2 nm	4.5 nm	5.7 nm	3.2 nm	4.5 nm	5.7 nm
Q_{2DEG} ($\times 10^{12}$ cm^{-2})	18	22	7	5.9	6.2	19
Trans. Coeff. T_{Cr}	1.64E-11	4.62E-16	2.04E-18	1.64E-11	4.62E-16	2.04E-18
T_{Cr}*Q_{2DEG} (cm^{-2})	2.9E+02	1.2E-02	1.4E-05	9.7E+01	2.9E-03	4.1E-05

Table I: Summary of MOSCAP CV and simulation results for the AlN/GaN junctions. The AlN thicknesses were determined through ellipsometry. T*Q represents the average number of electrons passing through the AlN barrier.



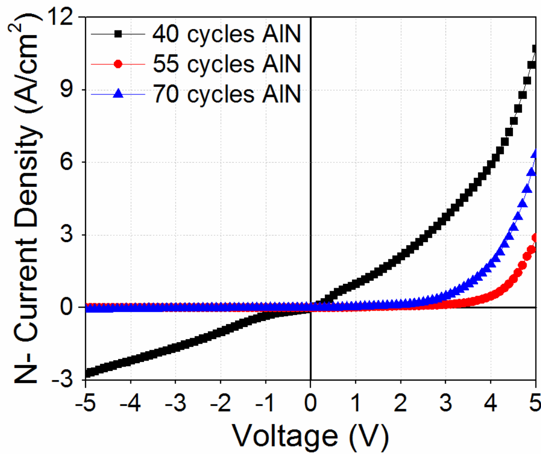
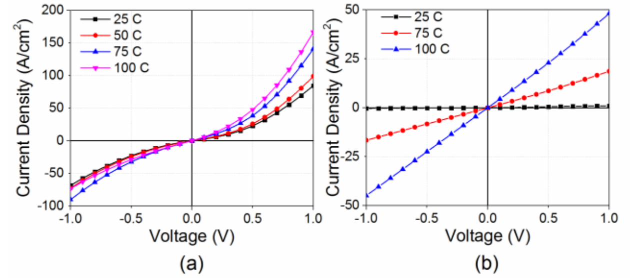


Figure 2: JV plots of AlN on (a) N+ GaN and (b) N- GaN.

Figure 3's temperature-variant JV plots further confirm the influence of quantum tunneling. For N+ GaN with 40 cycles of AlN, the curve minimally changes with temperature, but with 55 cycles, its JV characteristic steadily becomes more linear, with particularly ohmic behaviour demonstrated at 100 C. The JVs for 40 cycles of AlN on N- GaN transition more drastically, as a virtually



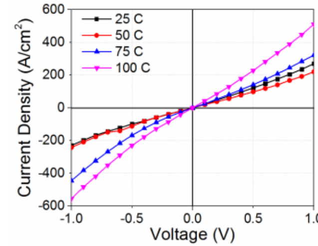
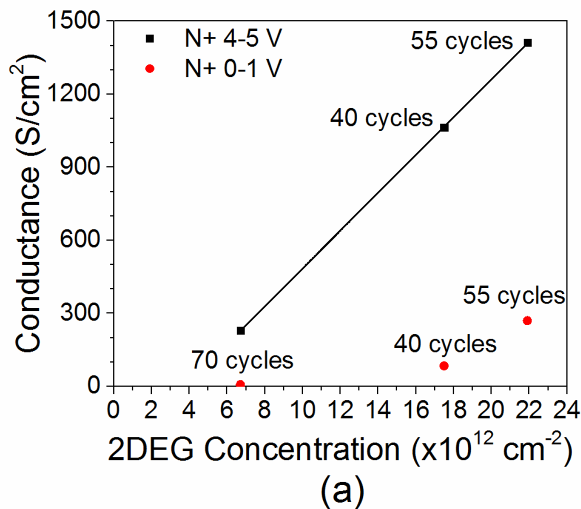
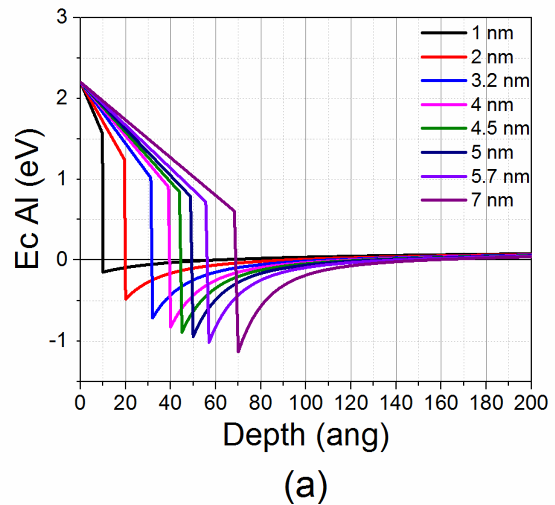


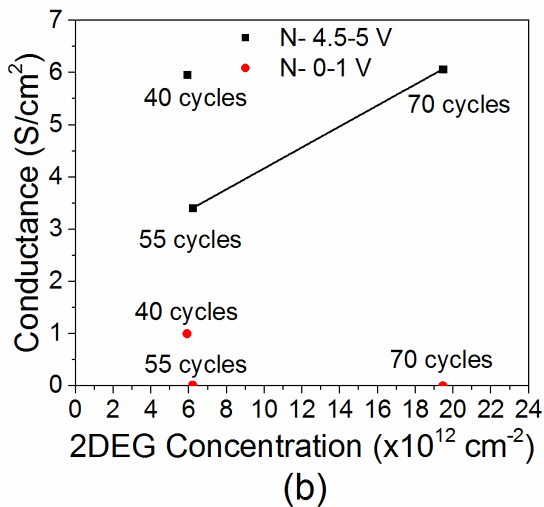
Figure 3: Temperature-dependent JV plots of (a) 40 cycles of AlN on N+ GaN, (b) 40 cycles of AlN on N- GaN, and (c) 55 cycles of AlN on N+ GaN

perfect ohmic relation appears starting from 75 C. Due to the minimal temperature dependence displayed, these parameters are the most conducive to quantum tunneling and are thus preferred for contacts.

Since current is proportional to the product of the transmission probability and the charge concentration, the AlN/GaN junction conductivity values calculated from the JV slopes in Figure 2 were plotted against the 2DEG concentration derived in Table I, taken at high and low voltages to analyze quantum tunneling effects with varying thicknesses and doping. Figure 4a shows that N+ GaN promotes minimal transmission probability variation through the AlN barrier. In fact, the conductivity becomes wholly dependent on the 2DEG concentration at higher voltages as indicated by their linear relation. As a result, 55 cycles of AlN results in the most ohmic JV relationship due to its high amount of polarization charge. Figure 4b indicates that the tunneling probability is highly dependent







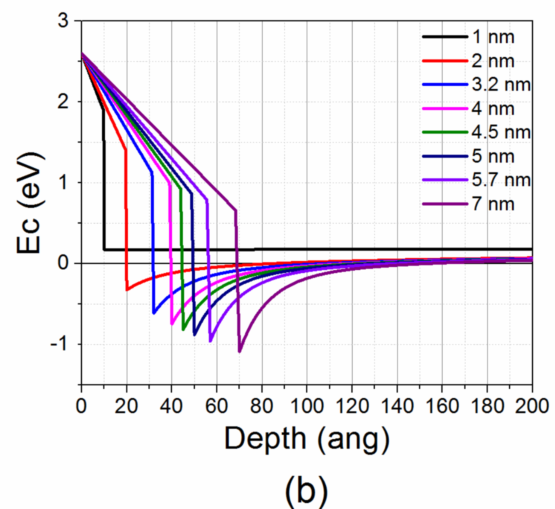


Figure 4: Linear fit of conductance plotted against 2DEG concentration for (a) N+ and (b) N- GaN.

Figure 5: Conduction band diagrams of the AlN / N- GaN heterojunction varying by AlN thickness. The contact metal simulated was (a) Cr and (b) Al. The Fermi level was set at $E_c = 0$ eV.

on AlN thickness for N- GaN, which favours the thin 40 cycles AlN barrier layer.

SIMULATION RESULTS

The theoretical energy band diagrams for the AlN/GaN heterojunction were modeled using a self-consistent Schrodinger-Poisson solver (Fig. 5) [5], from which the theoretical 2DEG for the fully strained junction could be obtained (Fig. 6). The measured 2DEG values in Table I are significantly lower than simulated on N- GaN while the N+ GaN samples are relatively close except for the drastic concentration drop at 70 cycles of AlN. The concentration peaks at 55 cycles of AlN on N+ GaN and 70 cycles of AlN on N- GaN, which are attributed to the onset of strain relaxation. [4] These concentrations compare favourably with the higher values found in AlGaN/GaN junctions. [1]

A multistep potential approximation model for quantum tunneling [6] was used to obtain the transmission probability through the AlN layer, which decreased by a factor of approximately 10^3 for each nanometre increase in thickness (Fig. 7). The average number of electrons transmitted through the barrier is approximated by multiplying the probability by the 2DEG concentration at the interface. For AlN thicknesses higher than 3.2 nm, this value is much lower than 1 cm^{-2}, indicating that electron transmission is highly improbable for these layers, but it improves to about 10^2 cm^{-2} at 3.2 nm. This correlates with the ohmic quality of the N- GaN JV plots since significant

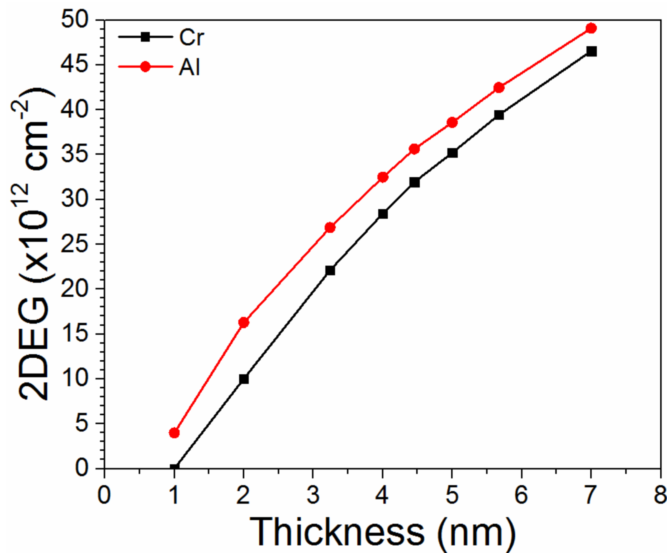


Figure 6: Theoretical 2DEG for the fully strained AlN/GaN heterojunction.

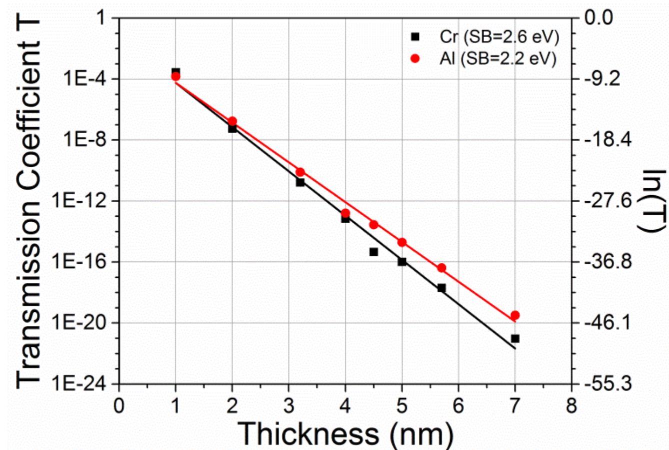


Figure 7: Transmission probability by thickness for the AlN/GaN heterojunction. SB stands for Schottky barrier.

quantum tunneling occurs only for 40 cycles of AlN. For N+ GaN, the JV plot linearity is not related to this product since the higher donor electron concentration compensates the 2DEG concentration in the quantum well and results in more consistent tunneling.

By replacing Cr, with a work function of 4.5 eV, with Al at 4.1 eV, the transmission probability improves due to the lower Schottky barrier height. This also lowers the triangular quantum well relative to the Fermi level, which should result in higher 2DEG concentrations (Fig. 6).

CONCLUSIONS

This work has shown that for low-temperature ALD of AlN on GaN, the ohmic contact quality can be modelled by the transmission coefficient for N- GaN and the 2DEG concentration for N+ GaN. The ideal parameters for developing ohmic contacts are 4.5 nm AlN on N+ GaN and 3.2 nm AlN on N- GaN using a low work function contact metal such as Al.

ACKNOWLEDGEMENTS

Special thanks to NSERC Discovery, Canadian Foundation for Innovation, and Alberta Innovates Technology Futures for supporting this research.

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ACRONYMS

2DEG: Two-Dimensional Electron Gas
ALD: Atomic Layer Deposition
CV: capacitance-voltage
HPVE: high pressure vapor epitaxy
JV: current-voltage (density)
TMA: trimethylaluminum