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Sanyam Bajaj, Fatih Akyol, Sriram Krishnamoorthy, Yuewei Zhang, and Siddharth Rajan

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AlGaN channel field effect transistors with graded heterostructure ohmic contacts

Sanyam Bajaj,a) Fatih Akyol, Sriram Krishnamoorthy, Yuewei Zhang, and Siddharth Rajan
Department of Electrical and Computer Engineering, The Ohio State University, Columbus, Ohio 43210, USA
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We report on ultra-wide bandgap (UWBG) Al0.75Ga0.25N channel metal-insulator-semiconductor field-effect transistors (MISFETs) with heterostructure engineered low-resistance ohmic contacts. The low intrinsic electron affinity of AlN (0.6 eV) leads to large Schottky barriers at the metal-AlGaN interface, resulting in highly resistive ohmic contacts. In this work, we use a reverse compositional graded n++ AlGaN contact layer to achieve upward electron affinity grading, leading to a low specific contact resistance ($\rho_{sp}$) of $1.9 \times 10^{-6}$ $\Omega$ cm$^2$ to n-Al0.75Ga0.25N channels (bandgap $\sim$5.3 eV) with non-alloyed contacts. We also demonstrate UWBG Al0.75Ga0.25N channel MISFET device operation employing the compositional graded n++ ohmic contact layer and 20 nm atomic layer deposited Al2O3 as the gate-dielectric. Published by AIP Publishing.

III-Nitrides offer a broad spectrum of bandgaps from 0.6 eV (InN) to 6.2 eV (AlN) and have various device applications ranging from optoelectronics to RF amplification and power switching applications. Due to the superior intrinsic material properties of AlN, wide bandgap AlGaN with high Al composition could enable next-generation RF power amplifiers and switches. The large bandgap of AlN results in a theoretical breakdown field of 12–16 MV/cm, which is almost 4–5 times higher than that of GaN.1 Furthermore, Monte-Carlo calculations have estimated electron saturation velocity in AlGaN channels to be comparable to that in GaN channels,2,3 making AlGaN a promising material for high power and high frequency applications. For power switching application, previous analytical calculations suggested that replacing conventional GaN channels with high Al composition AlGaN channels in high electron mobility transistors (HEMTs) could result in reduced switching losses and enhanced normally-off operation.4 Although previous experimental reports on AlGaN channel HEMTs have shown encouraging on-state and off-state device characteristics,5–9 a critical challenge preventing further advancement in ultra-wide bandgap (UWBG) AlGaN-based devices was high-resistance ohmic contacts. Several studies have investigated alloyed ohmic contacts to n-AlGaN channels. While alloys using metals such as Titanium, Vanadium, and Zirconium10–15 were reported with low specific contact resistance values below $10^{-5}$ $\Omega$ cm$^2$ on n-AlGaN channels with Al alloy compositions up to 66%, they are challenging to reproduce reliably due to extremely high temperature processes and typically show non-uniformity in current-voltage characteristics. Alternate heterostructure engineering approaches are therefore needed to realize low contact resistance to large bandgap AlGaN.

A low-resistance ohmic contact is formed by reducing the potential barrier between a metal and semiconductor. The ideal n-type ohmic contact would have a zero or low Schottky barrier height at the metal-semiconductor interface, which can be achieved by matching the semiconductor electron affinity and metal work function. However, the intrinsic low electron affinity of AlN (0.6 eV) leads to larger metal-AlGaN Schottky barriers, resulting in a poor tunneling probability for electrons (probability $\sim e^{-\sqrt{\varphi_bW}}$, where $\varphi_b$ is the barrier height and $W$ is the tunneling width), and therefore highly resistive ohmics. In this work, we take the

![Diagram](http://dx.doi.org/10.1063/1.4963860)

FIG. 1. Structure schematic, energy-band diagram, and charge diagram for the reverse compositional graded n++ AlGaN contact layer on the UWBG n-AlGaN channel. Negative polarization charge in the reverse graded AlGaN layer is compensated by donors, resulting in a flat conduction-band profile under the ohmic contact.
heterostructure engineering approach in which the Al alloy composition in the AlGaN channel is graded from the wider bandgap to the narrower bandgap under the ohmic contacts, hence grading up electron affinity and presenting a higher electron affinity at the metal-semiconductor interface (GaN electron affinity, $\varepsilon_{\text{GaN}} = 4.1 \text{ eV}$). AlGaN layers with compositional grading from GaN to AlGaN have been studied extensively and shown to induce bulk three-dimensional electron distributions due to positive polarization (spontaneous + piezoelectric) charge.\textsuperscript{16–19} The polarization-induced fixed charge, $\rho_{\text{p}}, \rho_{\text{p}} = -\nabla \cdot \mathbf{P}$, where $\mathbf{P}$ is the sum of spontaneous and piezoelectric polarization in AlGaN alloys. In the case of layers with reverse Al compositional grading from wider to narrower bandgap AlGaN, a negative polarization charge is formed, causing a positive curvature in the energy band profile, thereby creating a barrier to electron flow. To ensure that the conduction band stays flat, it is necessary to compensate for the negative polarization charge using donors. This is shown in the charge diagram in Figure\textsuperscript{1}, where donors in the graded region compensate for the negative charges, leading to an effective n-type region. The entire energy band gap offset is supported in the valence band, as shown in the energy band diagram, and there are no heterojunction or electrostatic barriers to transport between the channel and the surface of the semiconductor.

AlGaN structures were grown on Al-face AlN on Sapphire templates\textsuperscript{20} using plasma-assisted molecular beam epitaxy (PAMBE) as shown in Fig. 2(a). The 100 nm n-Al$_{0.75}$Ga$_{0.25}$N channel (Si = $3 \times 10^{19} \text{ cm}^{-3}$) was grown at 720 °C on a 30 nm undoped Al$_{0.75}$Ga$_{0.25}$N buffer layer, followed by a 50 nm n$^+\text{+}$ contact layer formed by linearly grading down the Al content from 75% to 0% (actual 6%). Figure 3(a) shows the X-ray diffraction scan measured with AlN as the reference to confirm the Al composition and thickness of the epi layers. Atomic force microscopy (AFM) on the as-grown surface, as shown in Fig. 3(b), indicated a fairly smooth surface morphology with a rms roughness of 1.1 nm and a step-flow growth mechanism. Non-alloyed Ti/Al/Ni/Au ohmics were evaporated on the as grown structures, followed by device mesa isolation of 200 nm using Cl$_2$-based inductive plasma etching. To achieve an active Al$_{0.75}$Ga$_{0.25}$N channel and characterize the ohmic contact, the compositional graded contact layer was recessed between the source and the drain of the device using low-power (6 Watts) Cl$_2$-based inductive plasma etching.

Figure 2(b) shows the energy-band diagram in the contact region (as-grown), simulated using a 1D Schrodinger-Poisson simulator.\textsuperscript{21} It can be seen that the conduction band ($E_c$) profile under the contacts does not have any abrupt or electrostatic barriers to block the flow of electrons. The Hall measurement on the as-grown structures with both channel and contact layers gave a sheet resistance ($R_{\text{SH}}$) of 160 $\Omega/\square$ and a net effective mobility of 35 cm$^2$/Vs. Figure 4(a) illustrates the transport and resistance components in the as-grown structures. The transfer length measurement (TLM), shown in Fig. 4(b), gave an $R_{\text{C1}}$ of 0.15 $\Omega$ mm, which is the
contact resistance at the metal-n$^{++}$ Al$_{0.06}$Ga$_{0.94}$N junction. To test the contact to the Al$_{0.75}$Ga$_{0.25}$N channel, measurements were repeated after recessing the graded contact layer and leaving the 90 nm thick channel. The Hall measurement on the recessed structure gave a sheet resistance ($R_{SH1}$) of 725 $\Omega/\square$ and a low channel mobility of 16 cm$^2$/Vs, feasibly limited by the impurity scattering effect due to the high Si donor concentration and native defects in the channel layer. A high Si concentration was used in the channels since high Si donor concentration and native defects in the channel grown for better recess control and to achieve a lower channel charge suitable for transistor operation, mainly device pinch-off and high breakdown voltage. The graded contact layer was recessed between source/drain pads to form an active channel with thickness $\leq 12$ nm confirmed using AFM. The device process was concluded with a 20 nm ALD Al$_2$O$_3$ gate-dielectric deposited at a substrate temperature of 300 °C, followed by post-deposition annealing at 700 °C to minimize the Al$_2$O$_3$/AlGaN interface defect states or hysteresis and deposition of the Ni/Au/Ni gate metal. Figure 6 shows the final MISFET device structure and experimental characteristics for gate-length, $L_G = 0.7$ μm, and gate-drain spacing, $L_{GD} = 1.1$ μm. The reverse compositional graded n-Al$_{0.75}$Ga$_{0.25}$N channel MISFET device exhibits a low specific contact resistance ($\rho_{sp}$) of 1.9 x 10$^{-6}$ $\Omega \cdot$cm$^2$, which is the lowest value reported for AlGaN with such a high bandgap of 5.3 eV using non-alloyed ohmic contacts, and is comparable to typical values achieved on lower band gap GaN channels.

To demonstrate metal-insulator-semiconductor field-effect transistor (MISFET) device operation, identical structures with thinner (20 nm) n-Al$_{0.75}$Ga$_{0.25}$N channels were grown for better recess control and to achieve a lower channel charge suitable for transistor operation, mainly device pinch-off and high breakdown voltage. The recessed contact layer was formed by source/drain pads to form an active channel with thickness $\leq 12$ nm confirmed using AFM. The device process was concluded with a 20 nm ALD Al$_2$O$_3$ gate-dielectric deposited at a substrate temperature of 300 °C, followed by post-deposition annealing at 700 °C to minimize the Al$_2$O$_3$/AlGaN interface defect states or hysteresis and deposition of the Ni/Au/Ni gate metal. Figure 6 shows the final MISFET device structure and experimental characteristics for gate-length, $L_G = 0.7$ μm, and gate-drain spacing, $L_{GD} = 1.1$ μm. The reverse compositional graded n-Al$_{0.75}$Ga$_{0.25}$N channel MISFET device exhibits a low specific contact resistance ($\rho_{sp}$) of 1.9 x 10$^{-6}$ $\Omega \cdot$cm$^2$, which is the lowest value reported for AlGaN with such a high bandgap of 5.3 eV using non-alloyed ohmic contacts, and is comparable to typical values achieved on lower band gap GaN channels.

In summary, a low specific contact resistance ($\rho_{sp}$) of 1.9 x 10$^{-6}$ $\Omega \cdot$cm$^2$ was achieved on UWB Ga$_{0.75}$Al$_{0.25}$N channels using heterostructure engineered non-alloyed ohmics. The reverse compositional graded n$^{++}$ AlGaN layer eliminated the Schottky barrier at the metal-semiconductor interface and resulted in a flat conduction-band profile posing no energy barriers to the electron carriers. This approach employed non-alloyed ohmic contacts which have enormous
advantages of enabling self-aligned and Au-free device processes. This result could also have applications in a large range of AlGaN-based electronic and photonic devices, and advance the research in the area of high Al composition AlGaN materials and devices. We also demonstrated UWBG Al$_{0.75}$Ga$_{0.25}$N channel MIS transistors with heterostructure engineered ohmic contacts and 20 nm Al$_2$O$_3$ gate-dielectric, with an $I_{DS_{\text{MAX}}}$ of 60 mA/mm, $g_m_{\text{peak}}$ of 14 mS/mm, and $V_{br}$ of 200 V/µm.

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20The substrates were purchased from DOWA Electronics Materials Co. Ltd., Tokyo, Japan, http://www.dowa-electronics.co.jp/en/.


