MBE-Regrown Ohmics in InAlN HEMTs With a Regrowth Interface Resistance of 0.05 $\Omega \cdot$ mm

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***Abstract*—Nonalloyed ohmic contacts regrown by molecular beam epitaxy were made on InAlN/AlN/GaN/SiC high-electron-mobility transistors (HEMTs). Transmission-line-method measurements were carried out from 4 K to 350 K. Although the total contact resistance is dominated by the metal/n^+-GaN resistance ($\sim$0.16 $\Omega \cdot$ mm), the resistance induced by the interface between the regrown n^+ GaN and HEMT channel is found to be 0.05–0.075 $\Omega \cdot$ mm over the entire temperature window, indicating a minimal barrier for electron flow at the as-regrown interface. The quantum contact resistance theory suggests that the interface resistance can be further reduced to be < 0.02 $\Omega \cdot$ mm in GaN HEMTs.**

***Index Terms*—AlN, contact resistance, GaN, high-electron-mobility transistor (HEMT), InAlN, metal–organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE), regrowth, transistor.**

I. Introduction

GaN-BASED high-electron-mobility transistors (HEMTs) have attracted immense attention for high-speed and power electronics due to their wide bandgap, high electron velocity, and large 2-D electron gases (2DEGs) [1]–[5]. To further improve the device performance with ultrascaled device geometries, e.g., operating at higher frequencies and higher efficiency, it is highly desirable to minimize contact resistance since it generally dominates the total parasitic resistance. It has been challenging to achieve low contact resistances on GaN-based HEMTs due to their wide bandgap and large barrier height between metal and semiconductor. Numerous approaches have been studied with various degrees of success on GaN-based HEMTs (see [6]–[9] and references therein), among which the lowest contact resistances were reported in regrown contacts by molecular beam epitaxy (MBE) [6], [7]. In one report on N-face GaN HEMTs with MBE-regrown ohmics, an interface resistance of 0.09 $\Omega \cdot$ mm was extracted between the 2DEG and the regrown ohmics [10]. However, the temperature dependence and physical mechanisms associated with the regrowth interface resistance have not been reported yet to date.

In this letter, we investigated the MBE-regrown nonalloyed ohmic contact characteristics in lattice-matched InAlN/GaN HEMT heterostructures over a wide range of temperatures from 4 K to 350 K. Measurements show that the as-regrown interface-induced contact resistance is about 0.05 $\Omega \cdot$ mm over the entire temperature window, indicating a rather favorable energy band alignment for electron flow between the regrown n^+ GaN and the 2DEG channel. We show that this low interface resistance in GaN HEMTs is expected based on the quantum contact resistance analysis, and it can be further improved.

II. Experiments

The InAlN/AlN/GaN HEMT structure was grown by metal–organic chemical vapor deposition (MOCVD) on a SiC substrate at IQE RF LLC. It consists of a 2-μm semi-insulating GaN, 1-nm AlN spacer, and 5.6-nm $In_{0.17}AlN$ barrier. A 2DEG charge of $2 \times 10^{13}/cm^2$, electron mobility of 1210 $cm^2/V \cdot s$, and sheet resistance of 257 Ω/sq were determined by the Hall effect measurement at room temperature on the as-grown wafer. Device processing and regrowth were performed at TriQuint. A SiO_2/SiN_x mask was first deposited using plasma-enhanced chemical vapor deposition (PECVD) and patterned by reactive ion etching. InAlN/AlN/GaN was then etched down for 12 nm in the ohmic region, followed by an undercut etch of SiO_2 regrowth mask. A GaN:Si ($> 1 \times 10^{19}$ cm^{-3}) of 40 nm was regrown by MBE, and the detailed growth condition has been reported by Guo *et al.* [9]. After ohmic regrowth, the polycrystalline GaN deposited on top of the mask was lifted off by buffered HF. To investigate the properties of the as-regrown interface, nonalloyed ohmic contacts were formed by the deposition of a Mo/Au-based stack. The sample was finally passivated by a 20-nm PECVD SiN. HEMTs fabricated using the MBE-regrown contacts show comparable characteristics with the ones reported by Wang *et al.* [3], [4] since their total contact resistances and source–drain distances ($\sim$1 μm) are similar, thus not shown in this letter. Overall, the yield of this regrown-contact process is better than 99%, and the resultant total contact resistance has a standard deviation to the average value ratio of 0.25, which was measured using transmission-line-method (TLM) patterns on 4-in wafers.

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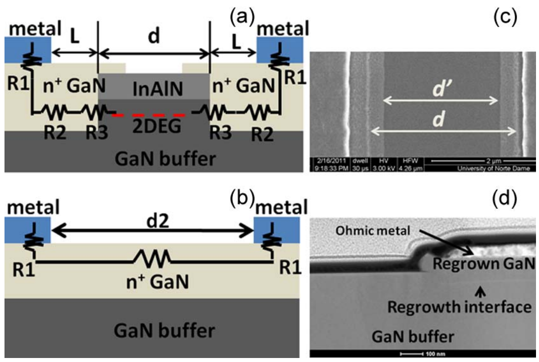

Fig. 1. Schematics of the MBE-regrown contact TLM pattern (a) on InAlN HEMT heterostructure and (b) MBE-regrown n$^+$ GaN (control). (c) SEM top view of the TLM pattern on the HEMT. (d) STEM image of the regrowth cross section in the HEMT (another sample with thicker regrown n$^+$ GaN).

III. Results and Discussion

Shown in Fig. 1 are the schematics of the contacts fabricated on MBE-regrown n$^+$ GaN and the regrown contacts in InAlN/GaN HEMTs. TLM gaps between regrown n$^+$-GaN wells (d) and gaps between regrowth lips (d') were measured by scanning electron microscopy (SEM) [Fig. 1(c)]. As it will be shown hereinafter, the 2DEG transport properties under the regrowth lip were found to be the same with that in the HEMT between the regrowth lips. Therefore, TLM gaps between regrowth wells (d) are used in the following discussions. The total contact resistance R_c can be divided into three components: $R1$, resistance between the ohmic metal and regrown n$^+$ GaN; $R2$, resistance of the n$^+$-GaN access region; and $R3$, resistance between regrown n$^+$ GaN and the 2DEG channel. To extract each component resistance, TLMs were made on the same wafer where the InAlN barrier was etched away and the n$^+$ GaN was regrown, referred as the control TLMs. It is assumed that the metal/n$^+$-GaN resistance $R1$ is equal to the contact resistance extracted from the control TLMs; twice of $R2$ is equal to the $R_{\rm sh}$ extracted from the control TLMs times the distance 2L [Fig. 1(a)], where 2L is constant for all TLM patterns as confirmed by SEM, taking into account the pattern misalignment [Fig. 1(c)]; and $R3$ can be obtained by subtracting $R1$ and $R2$ from the total resistance. The scanning transmission electron microscopy (STEM) image, taken on another sample processed in a similar fashion but with a thicker n$^+$ GaN, shows a nearly invisible regrowth interface [Fig. 1(d)].

In Fig. 2(a), two TLM fittings at 300 K are shown using the regrowth well distance (d) and the regrowth lip distance (d'), respectively. First, it is noted that the slopes of the two fittings are the same, corresponding to a 2DEG sheet resistance of 254 Ω/sq., very close to 257 Ω/sq. determined by the Hall effect measurement. Second, the 2DEG sheet resistance under the regrowth lip can be calculated using the intercept resistance difference of 1.34 Ω, TLM width of 100 μm, and $d - d' = 525 \pm 35$ nm, which is 255 ± 24 Ω/sq. Third, band diagram simulations show that a negligible change in the 2DEG density is expected under the regrowth lip region for the conditions used in this study. Hence, it is justified to conclude that the 2DEG sheet resistance under the regrowth lip is the same with that between the lips. TLM measurements were carried out from 4 K to 350 K, and the results are shown in Fig. 2(b)–(d). These nonalloyed regrown contacts are ohmic over the entire temperature range. From 4 K to 350 K, the total contact resistance (R_c) is largely constant, in the range of 0.26–0.28 $\Omega \cdot$mm; the sheet resistance increases slowly from 59 Ω/sq. at 4 K to 115 Ω/sq. at 200 K then quickly to 375 Ω/sq. at 350 K. The same trend of sheet resistance dependence on temperature in InAlN HEMTs was also observed by Tulek *et al.* [11], similar to that in AlN HEMTs [12], since InAlN HEMTs contain an AlN interlayer between InAlN and GaN. Below 200 K, temperature-independent interface roughness is the dominant scattering mechanism. Above 200 K, optical phonon scattering increases, therefore, leading to a decrease in mobility with an increase in temperature. The carrier concentration is constant in the entire temperature range. R_c and $R_{\rm sh}$ obtained on the control TLMs are shown in Fig. 2(c). Different from the InAlN HEMT TLMs, the sheet resistance of n$^+$ GaN is nearly independent of temperature because of the high doping level $> 1 \times 10^{19}$ cm^{-3}, with impurity scattering dominating the carrier mobility. The specific contact resistance on the n$^+$-GaN sample is in the range of $1.1{-}1.45 \times 10^{-8}$ $\Omega \cdot \mathrm{cm}^2$, which is also independent of temperature within the experimental errors. This indicates that the dominant current transport mechanism between ohmic metal and regrown n$^+$ GaN is tunnelling or field emission [13] since thermionic emission would have a significant temperature dependence and thermionic field emission is applicable at lower doping ranges (10^{16}–10^{18} cm^{-3}).

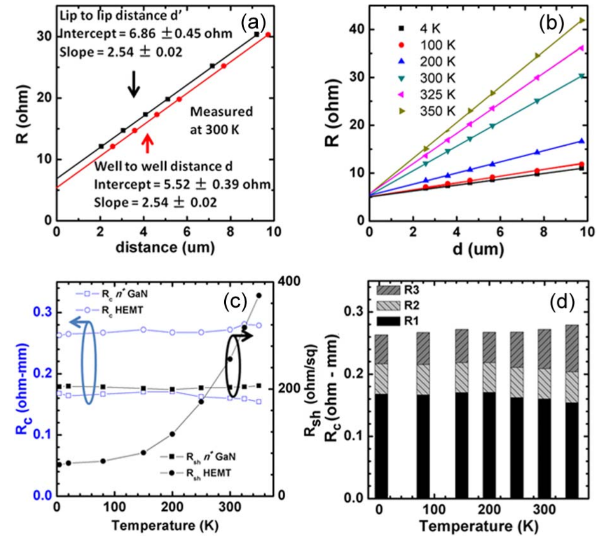

Fig. 2. (a) TLM fitting for the InAlN HEMT structure with regrown contacts using distance d and d' at 300 K. (b) TLM fitting for the HEMT structure from 4 K to 350 K. (c) R_c and $R_{\rm sh}$ extracted from the HEMT and n$^+$-GaN TLMs. (d) Extracted contact-resistance components.

Shown in Fig. 2(d), the interface resistance $R3$ between the regrown n$^+$ GaN and the 2DEG is in the range of 0.05–0.075 $\Omega \cdot$mm over the entire temperature window, which is indicative of a minimal barrier for electron flow at the regrowth interface. Adopting the TLM error analysis method in [14], the extracted $R3$ values were found to have an error of 10%. It was discussed by Solomon *et al.* [15] and Datta *et al.* [16] that the quantum limit of the minimum interface resistance between a large contact and a 2DEG depends on the 2DEG concentration (n_s) near the interface.

$$R_c = \frac{\pi\hbar}{q^2}\sqrt{\frac{\pi}{2n_s}} = (0.026\ \Omega \cdot \mathrm{mm})\sqrt{\frac{10^{13}/\mathrm{cm}^2}{n_s}} \qquad (1)$$

where $\hbar$ is the Planck's constant and q is the elementary charge. The minimum interface contact resistance of 0.019 $\Omega \cdot$mm

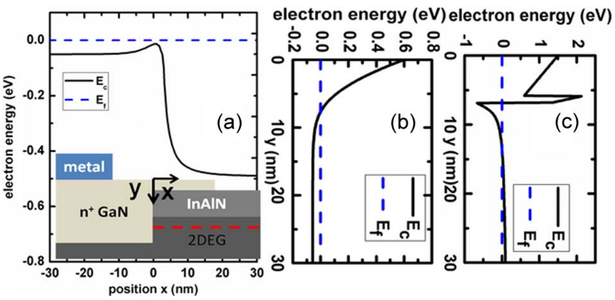

Fig. 3. Simulated electron energy band diagrams (a) along the n^+ GaN–2DEG channel (x) directions, (b) along the y-direction in the regrown-n^+-GaN region, and (c) along the y-direction in the 2DEG region.

is thus expected for $n_s = 2 \times 10^{13}/\text{cm}^2$, the 2DEG concentration in the InAlN HEMTs. The extracted regrowth interface resistance of 0.05 $\Omega \cdot$ mm suggests the following: 1) there is still room for improvement by optimizing our regrowth processes and 2) the band diagram along the channel in the present device can be represented by Fig. 3 [17], [18]. At the n^+ GaN–2DEG interface, the GaN conduction band edge is likely raised up due to impurities and broken bonds that are in part likely caused by the etch damage; however, it is still below the Fermi level, thus, resulting in a reasonably low contact resistance.

This physical picture provides us some interesting insight on ohmic contact formation in wide-bandgap semiconductors. Note that in (1), the minimum contact resistance depends only on n_s and no other material parameters such as effective mass m^*. As a result, the lowest quantum contact resistance is expected in a heterostructure that can offer the highest n_s, which is the case for Si and wide-bandgap semiconductors due to their large effective mass in comparison to the narrow-bandgap ones. Although it is easy to form alloyed ohmic contacts to semiconductors with narrow bandgap, they are also plagued by surface Fermi-level pinning, which may explain why the regrown ohmic contacts do not necessarily compare favorably to the alloyed ones in narrow-bandgap semiconductors [19]. Furthermore, we speculate that the metal-rich growth condition afforded by GaN MBE may also play a critical role to remove interface impurities and unpin the Fermi level at the GaN surface; on the contrary, the MOCVD (re)growth of III-V is conventionally performed under group-V rich environments. The best reported regrown ohmic contact in GaN HEMTs by MOCVD is 0.23 $\Omega \cdot$ mm [8]; unfortunately, no direct comparison can be made at this stage since the regrowth interface resistance was not extracted in [8]. Our ongoing and future work focuses on understanding the impact of regrowth conditions (e.g., Ga rich versus N rich) and recess etch conditions in the HEMT ohmic region as well as improving the contact resistance between metal and regrown n^+ (In)GaN using methods including appropriate surface treatments prior to metal deposition [18], increase of doping concentration, postmetal deposition annealing, and regrowth of graded n^+ InGaN [6].

IV. Conclusion

In summary, MBE-regrown nonalloyed ohmic contacts were fabricated on InAlN/AlN/GaN HEMTs. A regrowth interface resistance of $\sim$0.05 $\Omega \cdot$ mm was obtained, which can be further reduced to be $< 0.02\ \Omega \cdot$ mm according to the quantum contact resistance theory.

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