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Letter

Dependence of ohmic contact resistance on barrier thickness of AlN/GaN HEMT structures

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A multi-faceted study on the reduction of ohmic contact resistance to AlN/GaN-based heterostructures is presented. Minimum contact resistance of 0.5 Ω mm has been achieved by partially etching the AlN barrier layer using a chlorine-based plasma dry-etch prior to ohmic contact metallization. For thin GaN-capped AlN/GaN heterostructures, we find it is necessary to remove the GaN cap in the vicinity of the contact metal in order to obtain a linear current–voltage relationship. We compare our results of the pre-metallization etched contacts to those without an etch as well as to results reported in the literature.

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1. Introduction

Recently, the ultra-thin barrier AlN/GaN HEMT has been gaining research momentum, due mostly to the relatively new achievements in extremely low sheet resistance from optimized growth [1–3]. Despite its technological immaturity, the AlN/GaN HEMT has already set records for III-N HEMT technology in DC current density and transconductance [4]. Consequently, noteworthy RF metrics for GaN-based HEMTs have been obtained [5,6]. However, the reported HEMTs are still largely limited in both DC and RF performance by very high ($> 1\ \Omega$ mm) contact resistance (R_c) when fabricated using basic contact schemes [7]. Of the lowest R_c reported are those by Wang et al. showing $R_c \sim 0.46\ \Omega$ mm for Ti/Al/Mo/Au contacts to an ∼2.7 nm AlN barrier HEMT structure [8]. Chabak et al. presented similar findings for contacts to 2.7 nm thick barrier AlN/GaN MOSHEMTs with a Cl-based surface pre-treatment [9] demonstrating a R_c value the same as Wang. While this is a reasonable contact resistance value to a GaN-based FET, it is still higher than desired for the minimization of parasitic access resistance. The exploitation of a shallow recess etch prior to ohmic metallization provides a means to further lower R_c. Buttari et al. demonstrated an optimum pre-ohmic Cl_2 dry-etch that reduced contact resistance in AlGaN/GaN HEMTs to $\sim 0.3\ \Omega$ mm [10]. In this letter we show that contact resistance to AlN/GaN heterostructures increases with an increase in AlN barrier thickness as suggested by Zimmermann et al. [4]. However, a low R_{sh} window exists for AlN barriers with thicknesses between 3 and 5 nm as shown by Cao [11]. Therefore, in order to take advantage of the low sheet resistance window while simultaneously achieving sub-1 Ω mm contact resistance a pre-metallization etch offers a viable solution. This method has allowed us to obtain contact resistances to AlN/GaN HEMTs with 5.5 nm thick barriers as low as 0.5 Ω mm. Due to surface sensitivity of AlN/GaN structures, GaN capping layers were also explored. We find that for thin (3 nm) GaN-capped AlN/GaN HEMTs the removal of the GaN cap before metallization is necessary for contacts to become ohmic.

2. Experiment

The AlN/GaN heterojunctions were grown by plasma-assisted MBE on 2-in. diameter semi-insulating 4H-SiC substrates. The procedures for SiC substrate preparation are similar to those described elsewhere [12]. A 60 nm thick AlN nucleation layer was grown, followed by subsequent unintentionally doped (UID) GaN buffer and AlN barrier layers with thicknesses of 1 μm and 3–5 nm, respectively. The AlN barrier thicknesses were chosen on the basis of work by Cao et al. who showed a minimum sheet resistance in single heterojunction AlN/GaN HEMTs with AlN thicknesses between 3 and 5 nm [11]. For some of the samples described herein, the AlN barrier was followed by a 3 nm GaN cap. Both the GaN and AlN growth rates were determined to be 1.2 Å/s from optical

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reflectance measurements. All epitaxial layers were grown without interrupts.

Prior to any processing, the pre-metallization $Ar/BCl_3/Cl_2$ plasma dry-etch procedure was developed in an Oxford Instruments inductively coupled plasma (ICP) etch system. The etch conditions that were determined included an $Ar/BCl_3/Cl_2$ (10/10/20 sccm) chemistry, a chamber pressure of 5 mTorr, and plasma power of 100 and 25 W applied to the ICP coil and substrate electrode, respectively. An etch rate for crystalline AlN of 0.5 Å/s ± 0.1 Å/s was determined by Atomic Force Microscopy for the given etch conditions.

Processing was initiated with the patterning of the source-drain contacts using standard photolithographic techniques. The exposed AlN was then etched using the $Ar/BCl_3/Cl_2$ plasma to reduce the thickness in the contact region. A 47 s etch time yielded an ~2.5 nm (± 0.5 nm) etch depth, reducing the 5.5 nm thick AlN barrier to ~3 nm in the contact region. The 5.5 nm barrier thickness was chosen for the pre-metallization etch as it best demonstrates the capability to reduce contact resistance for the AlN/GaN heterostructure since we found that R_c increased with increasing AlN thickness. The metal stack Ti/Al/Ni/Au (30/200/40/10 nm) was deposited by electron beam evaporation and then annealed at 800 °C for 30 s in N_2. Lastly, a BCl_3/Cl_2 plasma etch was utilized for mesa isolation. On-wafer Hall effect measurements show for the 5.5 nm thick AlN barrier sample in particular, an average sheet resistance of 350 Ω/□ with a 2DEG sheet density of 2.5×10^{13} cm^{-2} and mobility of 700 cm^2/Vs.

3. Results and discussion

Immediately after metal deposition and just prior to annealing, two-point probe current–voltage (IV) characteristics were taken on circular transfer length measurement (CTLM) structures with a 4 μm pad separation and retaken following a rapid-thermal-anneal (RTA) at 800 °C for 30 s in N_2. The 30 s, 800 °C RTA profile seems to be close to optimal for minimal channel degradation while simultaneously reducing R_c. Representative results are shown in Fig. 1 for a 5.5 nm AlN barrier structure comparing characteristics between devices with and without the pre-metallization etch. It can be seen that for the pre-metallization etched sample the annealed IV characteristics show a lower resistance through a steeper current–voltage slope (Fig. 1). Drawing attention to the as-deposited IV characteristics in Fig. 1, it is interesting to note that the pre-etched contact current is much lower than those of the contacts without the pre-etch. We speculate this is due primarily to the thinning of the AlN barrier causing the 2DEG density at the AlN/GaN interface to consequently be reduced following the same 2DEG-AlN thickness relationship discussed by Cao et al. [1]. After the 800 °C RTA the IV characteristics improve to low-resistive ohmic type. Chlorine surface treatment and/or enhanced tunneling through the thinned barrier may also play a role to reduce R_c for the pre-metallization etched contacts. The RTA may also anneal out any plasma damage from the pre-metallization ICP etch.

Circular TLM measurements were made to extract R_c. Gap distances of the CTLM annuli and contact radii were measured by scanning electron microscopy. It follows that the contact resistance for the pre-metallization etched ohmic contacts after annealing was on average $0.7\,\Omega\,mm \pm 0.2\,\Omega\,mm$ with the lowest R_c being 0.5 Ω mm (inset to Fig. 1) compared to contacts without the pre-metallization etch which showed $R_c \sim 1.6\,\Omega\,mm$ on average. The corresponding range of transfer lengths for the given range of pre-metallization etched contact R_c values was 0.6–1.9 μm.

Several groups have reported on the use of thin GaN caps (1–3 nm) to AlN/GaN HEMT structures to take advantage of the protective qualities of an MBE-grown cap [2,8]. It is assumed that such

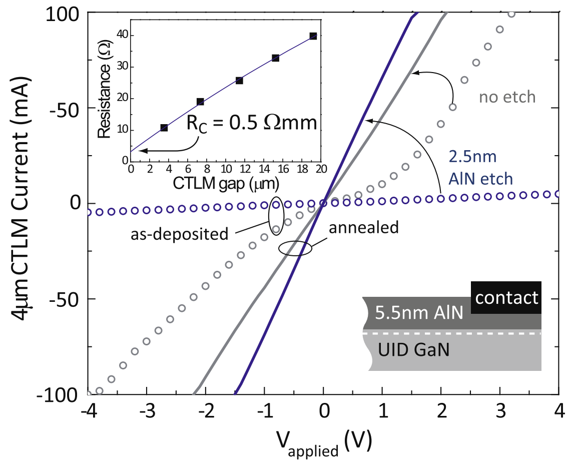

Fig. 1. Two-point current–voltage characteristics comparing the 2.5 nm pre-metallization etched and non-etched contacts to AlN/GaN for as-deposited and post-annealed metal. IV characteristics demonstrate the reduction in contact resistance due to the pre-metallization etch. Inset showing CTLM measurement and fit data for the lowest R_c value of 0.5 Ω mm obtained through the pre-metallization etch.

a thin GaN cap shows little resistance to metal diffusion for ohmic contact formation. However, we have found this not to be the case when the combined GaN and AlN layers are more than 8.5 nm thick. The same measurement procedure as previously discussed was adopted for the analysis of a 3 nm GaN-capped AlN/GaN HEMT with a 5.5 nm barrier layer. Shown in Fig. 2 is the comparative evolution for contacts with the 3 nm GaN cap removed versus remaining. It can be seen that the GaN-capped structure showed a reduction in resistance but remained slightly rectifying after the RTA. This contrasts with the test structures that had the GaN cap removed by dry-etching which showed linear IV characteristics after the anneal. This comparison suggests that it is necessary to remove the 3 nm GaN cap for the proper formation of annealed ohmic contacts. However, the precise GaN-cap and AlN thickness combinations that cause this necessity was not the purpose of this study and therefore was not explored in detail. R_c for the data shown of the removed GaN cap structure was 1 Ω mm.

To date, little has been reported on low-resistive ($< 1\,\Omega\,mm$) ohmic contact technology for AlN/GaN heterostructures. However, the extremely shallow etch reported in this letter offers a

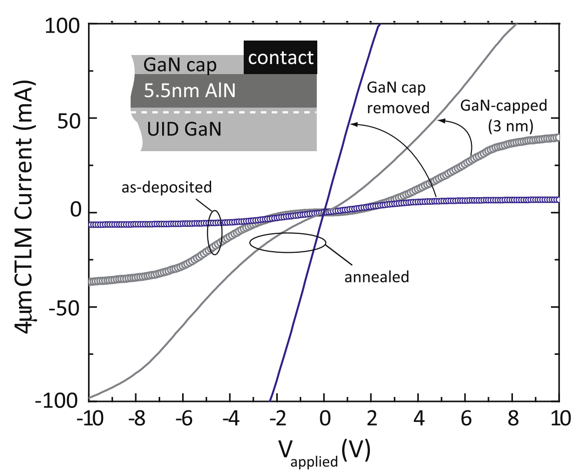

Fig. 2. Two-point current–voltage characteristics comparing contacts to 3 nm GaN-capped and removed GaN cap AlN/GaN for as-deposited and post-annealed metal. IV characteristics demonstrate the necessity to remove the 3 nm GaN cap in order to achieve a linear IV characteristic after annealing.

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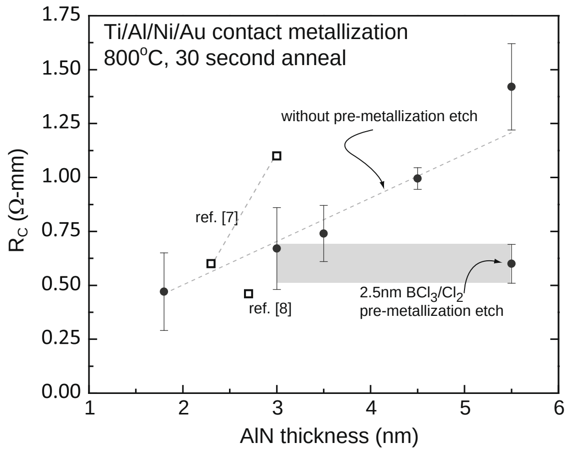

Fig. 3. Contact resistance comparison as a function of AlN barrier thickness. Closed circles represent our contact resistances to AlN/GaN heterostructures *without* the pre-metallization etch demonstrating an increasing R_c with increased AlN thickness (error bars denote one standard deviation from the mean). Contact resistances to AlN/GaN heterostructures *including* the 2.5 nm pre-metallization etch is plotted with its range in standard deviation in grey showing the significant reduction in resistance. Open squares represent contact resistances taken from the corresponding references.

convenient method for consistently lowering contact resistance, though etch rate tolerances are clearly critical given the thickness of the AlN barrier. A summary plot of R_c versus AlN barrier thickness for our non-etched contacts, pre-metallization etched contacts, and other reports in literature can be seen in Fig. 3 for a comparison. We find that for contacts without a pre-metallization etch, R_c increases monotonically with increasing AlN barrier thickness (closed circles). Shown on the lower right of Fig. 3 is the mean value of contact resistance for the pre-metallization etched ohmic contacts and their relative position to our un-etched ohmic contacts. For the 5.5 nm thick AlN barrier the mean contact resistance drops $\sim 0.8{-}0.6\ \Omega$ mm with a 2.5 nm deep pre-metallization etch. Our lowest value for R_c on the pre-metallization etched contacts was 0.5 Ω mm. These values correspond extremely well to those of the 3 nm non-etched AlN barrier contacts. It is anticipated that even lower values of R_c are obtainable for the AlN/GaN HEMT structure with a deeper pre-metallization etch. However, a similar trend is expected as that shown by Buttari et al. [10] where a minimum R_c window exists for an optimum pre-metallization etch depth of the barrier.

4. Conclusions

We have shown for the first time the utility of a Cl-based dry-etch to AlN/GaN HEMTs that provide some of the lowest reported contact resistances to AlN/GaN HEMTs to date. Through the pre-metallization etch a minimum R_c of 0.5 Ω mm has been achieved for a 5.5 nm thick AlN barrier HEMT. Additionally, the necessity of the removal of the GaN cap layer on GaN-capped AlN for the formation of ohmic contacts has been reported. With this method for the reduction in parasitic contact resistance the extrinsic DC and RF potential of the AlN/GaN HEMT may be more easily realized.

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