Ultra-low resistance ohmic contacts to GaN with high Si doping concentrations grown by molecular beam epitaxy

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Ti/Al/Ni/Au ohmic contacts were formed on heavily doped n+ metal-polar GaN samples with various Si doping concentrations grown by molecular beam epitaxy. The contact resistivity (RC) and sheet resistance (Rsh) as a function of corresponding GaN free carrier concentration (n) were measured. Very low RC values (<0.09 Ω mm) were obtained, with a minimum RC of 0.035 Ω mm on a sample with a room temperature carrier concentration of ~5 × 1019 cm−3. Based on the systematic study, the role of RC and Rsh is discussed in the context of regrown n+ GaN ohmic contacts for GaN based high electron mobility transistors. © 2012 American Institute of Physics.

Wide bandgap, high breakdown voltage, high electron saturation velocity, and high thermal conductivity are properties that make GaN attractive for high temperature, high power, and high frequency electronic device applications. GaN based high-electron-mobility transistors (HEMTs) have been studied extensively, and excellent performance has been demonstrated.1−7 Further improvement, such as operation at higher frequencies and higher efficiency, requires low resistance ohmic contacts (RC < 0.1 Ω mm) since it usually dominates the total parasitic resistance. The challenge in forming ohmic contacts to GaN stems from its large bandgap and large Schottky barrier height to most metals. Various methods have been applied to fabricate low-resistance ohmic contacts to GaN.8−11 Out of these, the lowest contact resistivity values reported so far are <0.08 Ω mm (Ref. 7) for Ga polar GaN and <0.027 Ω mm (Ref. 6) for N-polar GaN employing molecular beam epitaxy (MBE) regrown n+ GaN and graded InGaN with InN cap, respectively. However, a systematic study of the contact resistivity and sheet resistance of the regrown regions is still missing, and constitutes the main aim of this work. Here we systematically investigate annealed Ti/Al/Ni/Au ohmic contacts formed on MBE grown heavily doped n+ GaN samples by varying the Si doping concentration. The goal is to relate the RC and Rsh to the free carrier concentration (n) in the heavily doped GaN layers. The implication of these findings is significant. Low-parasitic resistance GaN HEMTs is also discussed.

A series of ~200 nm thick n+ GaN films were grown using MBE with a rf-plasma nitrogen source. Semi-insulating GaN on SiC templates grown by metal organic chemical vapor deposition (MOCVD) were chosen as substrates. The templates were thoroughly cleaned in organic solvents using ultrasonication, introduced into the loadlock chamber of the MBE system, and outgassed at 200 °C. They were then transferred into a buffer chamber and outgassed further at 450 °C for 1.5 h. The growth was performed under slightly Ga-rich condition with a low growth rate of ~100 nm/h. The growth temperature as measured by a thermocouple was 660 °C. Samples labeled A, B, C, and D were grown using Si cell temperatures of 1250, 1280, 1300, and 1320 °C, respectively. Atomic force microscopy (AFM) was used to measure the surface roughness of the grown films. Hall-effect measurements were performed to measure the electronic transport properties of the samples. Transmission line measurement (TLM) structures were then fabricated by contact lithography followed by a 1 min descum in oxygen plasma at low power (125 W). The samples were then dipped in HCl/deionized water (1:1) solution for 20 s and rinsed in deionized water for 30 s to get rid of native oxides remaining on the surface before ohmic metal deposition. Ti/Al/Ni/Au (15/120/40/50 nm) stacks were deposited by electron beam evaporation to form the metal contacts. The TLM pads were then etched into mesas using reactive ion etch (RIE) with a mixture of BCl3, Cl2 and Ar gas for isolation. A rapid thermal annealing was performed at 840 °C for 15 s under nitrogen environment with a flow rate of 5 cm3 per minute at STP (SCCM). The fabricated TLM structures were then measured using the four-point probe technique. A control sample consisting n+ GaN (~50 nm)/undoped GaN (~50 nm) layers was grown by MBE where the Si doping in the successive n+ GaN layers was varied using the same cell temperatures used for the series of four n+ GaN samples. Secondary ion mass spectrometry (SIMS) was carried out on this control sample to determine the concentration of Si doping in the individual layers.

Low-resistance ohmic contacts involve tunneling and thermionic emission of the electrons across the metal-semiconductor interface. A narrow tunneling barrier and low contact resistance is facilitated by high doping since the depletion depth is inversely proportional to the square root of the doping density. An Arrhenius plot of the Si concentration obtained from the SIMS calibration sample is shown in Fig. 1. Here A, B, C, D refer to Si cell temperatures same as those used for the four n+ GaN films. The inset of Fig. 1 shows the SIMS profile for Si and O concentrations. The data show the Si doping concentration is very high, ranging from ~1.7 × 1019 to ~9.4 × 1019 cm−3. This level of doping makes the n+ GaN films degenerate, i.e., the Fermi level in

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the bulk $n^+$ GaN is inside the conduction band. The activation energy of Si effusion from the Knudsen cell extracted from this plot is $5.15\text{ eV}$, in good agreement with the expected value. In Fig. 1 inset, an increased concentration of Si and O can be observed at the growth interface between substrate and epilayer, possibly due to interfacial defects and impurities on substrate surface, an observation that has been widely reported earlier. Special care was taken in the study to avoid any spurious conclusions from the high oxygen concentration at the growth interface; the heavily Si doped regions were far thicker than the relatively thin oxygen doped layer, and its effect on the study can safely be neglected.

The background oxygen doping, in addition to the intentional Si dopants of the $n^+$ GaN films, can contribute to the carrier transport depending on the fraction that is ionized. From Hall-effect measurement data shown in Fig. 2, we conclude a minor contribution ($\sim 10\%$ at most) from the background dopants. The Hall-effect data represent the trend of carrier concentration and electron mobility in the $n^+$ GaN films as a function of corresponding change in doping concentration reflected by the Si cell temperature. Both room temperature (300 K) and 77 K data show that $n$ increases with increasing Si doping. The electron mobility remains fairly constant, indicating again the degenerate carrier distribution. In degenerately doped semiconductors, the mobile electron concentration and the mobility are weak functions of temperature since they are effectively metallic, as shown in Fig. 2. An interesting observation from these measurements is the increase of carrier concentration and decrease in mobility as the Hall-effect measurement temperature is changed from room temperature to 77 K. Similar phenomena were reported by Kim et al. for Si doped zinc blende GaN. They attributed this behavior to simultaneous conduction in the conduction band, and in an impurity band associated with the heavy Si doping. According to their explanation, the conduction in high mobility conduction band dominates from room temperature down to around 70 K and below this temperature low mobility conduction via impurity band states dominates. Our observation supports similar mechanism for heavily Si doped wurtzite GaN.

Fig. 3 shows the measured resistivity versus gap spacing plots obtained from room temperature TLM measurements on the $n^+$ GaN samples using the four-point probe technique. For all 4 samples, $R_{sh}$ and $R_C$ are extracted from the slope and the y-axis (resistivity) intercept of their corresponding linear fits, respectively, as shown in Fig. 3. Fig. 4 shows the $R_{sh}$ values obtained from room temperature and 77 K Hall-effect measurements of the samples compared to those extracted from the TLM measurement. They are in good agreement. The sheet resistance decreases with increasing carrier concentration, as expected. We note that the net sheet resistances of the heavily doped 200 nm $n^+$ GaN layers are $\sim 30–120\, \Omega\square$. These values are much lower than the 2DEG sheet resistance of typical GaN HEMTs, which ranges from $\sim 150–300\, \Omega\square$. To find the dependence of the contact resistivity on the carrier concentration in the $n^+$ GaN films, $R_C$...
values are plotted against their room temperature carrier concentration values in Fig. 5. Interestingly, $R_C$ decreases from sample A to B, then increases from B to C and stays reasonably constant below 0.05 $\Omega$ mm for samples with higher carrier concentrations. A minimum $R_C$ of 0.035 $\Omega$ mm is obtained for sample B, which has a carrier concentration of $\sim 5 \times 10^{19}$ cm$^{-3}$. Adopting the TLM error analysis method described by Ueng et al., all extracted $R_C$ values are found to have an error less than 30%. The 2 $\mu$m x 2 $\mu$m AFM scan of sample B as-grown surface is shown in the inset of Fig. 5. The RMS roughness of $\sim 0.2$ nm indicates very smooth surface morphology. Similar AFM scans on all four $n^+$ GaN samples showed very smooth surfaces with RMS roughness values less than 1 nm. We note that unlike the case of heavy Si-doped GaN by MOCVD growth where degradation of surface and crystal structure is typically observed, MBE growth allows a smooth surface morphology. The smooth morphology also indicates that the surface roughness of as-grown samples is not the main cause of the different contact resistances.

We observe that the effect of the carrier concentration is more pronounced on the sheet resistance than on the contact resistivity for $n^+$ GaN samples under such extremely high doping ($>10^{19}$ cm$^{-3}$).

We now discuss the roles of $R_{sh}$ and $R_C$ in the context of GaN based HEMTs where regrown $n^+$ GaN ohmic contacts have proven to be very useful in boosting device performance by lowering parasitic losses. If we consider a typical InAlN/AlN/GaN HEMT structure as shown in the inset of Fig. 6, the total contact resistivity ($R_{\text{total}}$) measured for the HEMT can be divided into three components: $R_l$, the resistivity between the ohmic metal and regrown $n^+$ GaN; $R_2$, resistivity of the $n^+$ GaN access region; and $R_{sh}$, resistivity between regrown $n^+$ GaN and the 2DEG channel. Based on our current study, we can predict how $R_l$ and $R_{sh}$ change depending on the amount of doping in the regrown $n^+$ GaN of such HEMT structures, while $R_2$ has been investigated in another work.

We consider four different cases of HEMTs with $n^+$ GaN regrown for source drain ohmics using growth conditions similar to those of the four $n^+$ GaN films studied here. Then $R_1 = R_C$, $R_2 = R_{sh} \times L$, where the distance $L$ (inset of Fig. 6) depends on the alignment of the source, drain metal pads to the regrown regions. So, $R_1 + R_2 = R_C + R_{sh} \times L$.

In Fig. 6, values of $R_1 + R_2$ are plotted using $R_C$ and $R_{sh}$ values of sample A, B, C, and D as a function of their corresponding carrier concentrations. We have chosen 4 typical values of $L$ ranging from 0.2 to 2 $\mu$m. There is a clear trend in change of $R_1 + R_2$ depending on the size of $L$ for heavily doped samples with carrier concentration $>5 \times 10^{19}$ cm$^{-3}$ (sample B, C, and D). We may draw some interesting conclusions for GaN based HEMTs with regrown $n^+$ GaN ohmics based on this observation. Only for structures fabricated with large $L$ ($>0.5 $ $\mu$m), the change in $R_1 + R_2$ with respect to doping concentration will be dominated by $R_{sh}$. On the contrary, structures with small $L$ ($<0.5 $ $\mu$m) will force $R_1 + R_2$ to follow the trend of $R_C$ in terms of change with carrier concentration.
respect to doping concentration. As a result, pushing any further to increase the doping concentration even higher than achieved here in the regrown $n^+$GaN will not contribute to lower the total contact resistivity of HEMTs employing such regrown contacts.

In summary, alloyed ohmic contacts were fabricated on a series of heavily doped 200 nm $n^+$GaN samples. The very low sheet resistance values achieved ($\sim 30 \Omega/\square$) and the ultra-low contact resistivities ($\sim 0.04 \Omega \text{mm}$) are most attractive for integration in GaN HEMTs. Though further studies are required to investigate the solubility limit of Si dopants in GaN grown by MBE, for doping densities approaching $10^{20} \text{cm}^{-3}$, the surface retains a smooth morphology. Further reduction in $R_{sh}$ may be possible if Si doping densities in the $n^+$GaN films can be pushed to the solubility limit.

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