Very low resistance multilayer Ohmic contact to *n*-GaN

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A new metallization scheme has been developed for obtaining very low Ohmic contact to *n*-GaN. The metallization technique involves the deposition of a composite metal layer Ti/Al/Ni/Au (150 Å/2200 Å/400 Å/500 Å) on *n*-GaN preceded by a reactive ion etching (RIE) process which most likely renders the surface highly *n* type. Of the several attempts and with annealing at 900 °C for 30 s, contacts with specific resistivity values of $\rho_s = 8.9\times10^{-8}\ \Omega\ \mathrm{cm}^2$ or lower for a doping level of $4\times10^{17}\ \mathrm{cm}^{-3}$ were obtained. The physical mechanism underlying the realization of such a low resistivity is elucidated. © *1996 American Institute of Physics.* [S0003-6951(96)02712-5]

During the course of the last few years significant progress has been made in the growth and characterization of GaN and its alloys with AlN and InN.[1] This progress has led to the realization of several electronic and optoelectronic devices including metal-semiconductor field-effect transistors (MESFETs), modulation doped field-effect transistors (MODFETs), metal-insulator field-effect transistors (MISFETs), and light-emitting diodes (LEDs).[1,2]

Low resistance Ohmic contacts are imperative in the successful implementation of all these devices, particularly high power devices which require high power conversion efficiency and heat management. Owing to very wide band gaps of nitrides, these Ohmic contacts must be quite different from those of GaAs, InP, and Si. During the past years several attempts have been made to obtain low-resistance Ohmic contacts to GaN.[3–6] When Au or Al was used after annealing at 575 °C, the initial attempt of Foressi and Moustakas[3] led to the formation of a metal contact to *n*-GaN with a resistivity of $\rho_s \approx 10^{-3}\ \Omega\ \mathrm{cm}^2$. The contact was later significantly improved by Lin *et al.*,[4] who employed a Ti/Al bilayer deposited via conventional electron beam evaporation onto GaN substrate, and then thermally annealed at 900 °C for 30 s in a N_2 ambient using rapid thermal annealing (RTA) technique. The Ti/Al metallization yielded $\rho_s = 8\times10^{-6}\ \Omega\ \mathrm{cm}^2$. This metallization has the characteristic that the annealing process causes the metal to turn to be highly resistive, being very sensitive to the anneal temperature. To circumvent this problem, Wu *et al.*[5] added a second set of Ti/Al following the annealing step which requires realignment. This effort brought about an improvement in the Ohmic contact for *n*-GaN with resistivity $\rho_s \approx 3\times10^{-6}\ \Omega\ \mathrm{cm}^2$. In this letter we describe a technique, yielding very low Ohmic contact resistivities, which does not require realignment and second metallization step, and is more suitable for high-temperature Ohmic contact to GaN.

The layer structure of the GaN films grown for this study by molecular beam epitaxy (MBE) method on (011) sapphire substrates (~400 μm) and the growth procedure are as follows: The substrates were cleaned by hydrogen plasma treatment prior to the growth. After cleaning, the substrates were transferred to the MBE chamber, and an undoped AlN buffer layer was grown. This was followed by the growth of a GaN layer, 2 μm thick, and doped with Si to N_d $3\times10^{18}\ \mathrm{cm}^{-3}$. Finally a second *n*-GaN layer, 5000 Å thick, was grown on the first GaN layer. The doping level of the second GaN layer varied between 10^{17} and $5\times10^{17}\ \mathrm{cm}^{-3}$. Since the metal system under investigation does not noticeably penetrate and remains on the surface, the metal semiconductor contact can be considered as that between the $\sim10^{17}\ \mathrm{cm}^{-3}$ layer and the metal.

After the growth of the GaN films, the surface was exposed to a reactive ion etching (RIE). This was followed by a mesa structure defined by RIE for transmission line method (TLM) measurements. The mesa etching was performed first with Cl_2 for 20 s and next with BCl_3 for another 20 s. During the RIE process, the flow rate of the etchant was 15 sccm, the flow pressure was 50 mTorr, and the power was 150 W. The GaN sample was then transferred to the evaporator for metallization. The composite metal layer was Ti/Al/Ni/Au (150 Å/2200 Å/400 Å/500 Å). While Ti and Ni were deposited by electron beam evaporation, Al and Au were deposited by thermal evaporation. A liftoff process was employed to form a linear configuration of rectangular pads of contact area $(210\times90)\mu\mathrm{m}^2$. The spacing between the contact pads varied between 1 and 16 μm in 12 steps. The metal liftoff was followed by RTA annealing which was performed at 900 °C for 30 s. Two measurements of specific resistivity were conducted, first before RTA, and then after RTA.

Current–voltage ($I-V$) characteristics of metal contacts to *n*-GaN before and after alloying are shown in Fig. 1. Curves corresponding both to alloyed and nonalloyed cases exhibit near-linear characteristics even at sufficiently large current levels (100 mA). We should note that this metallization does not lead to Ohmic behavior when deposited on as-grown GaN and that RIE damage is responsible for the observed Ohmic behavior. Contact resistances were derived from the plot of the measured resistance versus gap spacing by TLM. Note that mesa structure prevented current flow at the contact edge. The resistance R_T between the two contacts was measured at 300 K using a four-point probe arrangement. The contact resistivity ρ_s was derived from a plot of R_T versus gap length. The method of least-squares was used to fit a straight line to the experimental data. These straight lines, and the actual experimental results for both alloyed

[a)]On sabbatical at Wright Laboratory.

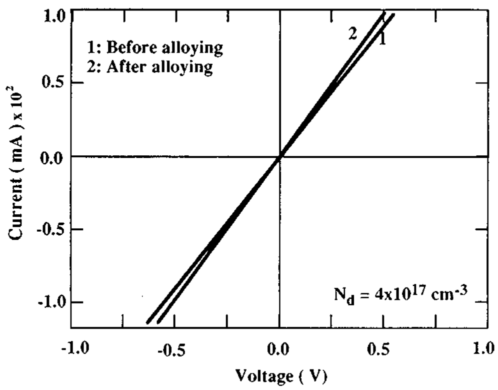

FIG. 1. Current–voltage characteristics of metal contacts on GaN samples before and after annealing at 900 °C for 30 s.

and nonalloyed contacts are shown in Fig. 2. In general, the higher the doping concentration, the lower the contact resistivity. While this resistivity for n-GaN with doping level 2×10^{17} cm^{-3} is $\rho_s=1.19\times10^{-7}$ Ω cm^2, this for n-GaN with $N_d=4\times10^{17}$ cm^{-3} is $\rho_s=8.9\times10^{-8}$ Ω cm^2. That alloying led to a significant improvement in the resistivity is apparent from curves 2 and 3 of this figure. Both of these curves correspond to the GaN doping level 4×10^{17} cm^{-3}. Curve 2 indicates that for nonalloyed Ohmic contact the resistivity $\rho_s=3.3\times10^{-6}$ Ω cm^2. Similar attempts for alloyed contacts led to even lower specific contact resistivities, in the 10^{-9} Ω cm^2 range, which are well beyond the accuracy of the TLM method which is reasonably accurate down to 10^{-7} Ω cm^2. Other methods which are more accurate at these low specific resistivities are being explored to determine the exact resistivity values. In any event, it allowed us to confidently state that the Ohmic contact resistivities well below 10^{-7} Ω cm^2 can be obtained which bode well with high power applications.

Resistance R_T includes the resistance of the contact metallization, the semiconductor layer underneath the contacts, and the actual specific contact resistivity for the metal-semiconductor interface. In the TLM method and thus the present study, the contact resistivity is calculated by assuming that the semiconductor sheet resistance underneath the contacts remains unchanged. With alloying procedure though, the semiconductor sheet resistance under contacts may change. This may lead to some inaccuracy in determining the resistivity of alloyed Ohmic contacts using the TLM method. Although, in the strict sense, the semiconductor resistance remaining unchanged is true for nonalloyed contacts, this assumption has been very successfully applied to alloyed contacts as well. Generally resistivities down to 10^{-7} Ω cm^2 can be determined fairly accurately using this technique. This is the reason behind our motivation of not emphasizing the obtained specific contact resistivities in the 10^{-9} Ω cm^2 range.

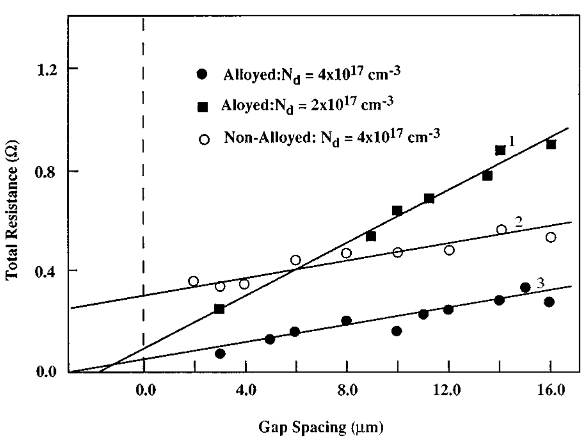

FIG. 2. Least-squares linear regression of the multiple-layer Ohmic contacts on GaN.

The cause for such low Ohmic contact resistances hinges in part on the damage caused by the RIE process employed prior to deposition of the contact metallization. Unless metal semiconductor interaction takes place and/or the semiconductor itself is altered with damage such as increased electron concentration due to, e.g., nitrogen vacancy formation, etc., it is difficult to form an Ohmic contact to a wide bandgap GaN with energy band gap of 3.42 eV, generally because a metal does not exist with a low enough work function ϕ_m to yield a low barrier to current transport. This excludes the possibility of thermionic emission to be a mechanism for carrier transport through the contact. Tunneling of carriers through this contact may, however, take place if GaN in the neighborhood of metal-semiconductor interface is so heavily doped that there occurs a significant band bending of the conduction band. Such a band bending causes the semiconductor region at the interface to be very thin allowing easy passage of electrons via tunneling. If the damage causes the semiconductor surface electron concentration to increase, as alluded to earlier, tunneling can be the primary transport mechanism through the contact in which case the total contact resistance R_T would be given by

$$R_T \approx R_{Bn} \exp\left(\frac{q\phi_{Bn}}{E_{Bn}}\right) \exp\left[\frac{2\sqrt{\epsilon_s m^*}}{\hbar}\left(\frac{\phi_{Bn}}{\sqrt{N_d}}\right)\right], \qquad (1)$$

where ϕ_{Bn} is the metal-semiconductor barrier height, ϵ_s is the dielectric constant, m^* is the effective mass of electrons, $\hbar=h/2\pi$, and h is the Planck's constant. From Eq. (1) it is thus apparent that resistivity ρ_s depends inversely on the square root of the doping concentration. That this is indeed the case in the present investigation is evident from our experimental data, albeit only two different doping levels investigated, which demonstrates that ρ_s increases with decrease in doping concentration.

It is known that, for Ohmic contacts to n-type semiconductors, pre-metal-deposition ion etching can result in a low metal-to-semiconductor contact resistivity by (a) removing the surface oxide layer on the semiconductor,[7] (b) forming a donorlike layer in the ion-damaged region,[8] and (c) in the case of compound semiconductors such as GaAs, preferentially sputtering As, thus generating As vacancies with donor characteristics.[9] Although surface analysis technique is required to determine if mechanism (c) operates, preferential sputtering of N from TiN thin films has been reported.[10]

We carried out measurements of contact resistivities of 900 °C annealed *n*-GaN samples (from the same wafer) with and without RIE treatment, and found that the resistivity of the *n*-GaN contacts with RIE treatment is 2–5 times lower than the resistivity of the same *n*-GaN contacts without RIE treatment. These measurements strongly demonstrated that it is mechanism (a), rather than mechanism (c), which renders the surface highly conductive. If the mechanism (c) would dominate, the difference observed in the resistivities of the as deposited samples would vanish after the annealing, because the donor-rich surface region of the RIE treated samples would either recover to its pre-etch states after annealing[9,11] or be consumed by Ti/GaN reactions. The difference in contact resistivities of the two samples persisted even after the annealing plausibly because the surface oxide layer was broken by the reactions due to RIE treatment at least at some localized weak points.

There may also be another kind of mechanism. X-ray diffraction (XRD) and Auger electron spectroscopy (AES) data indicated[4] that prior to annealing there occurs marginal interaction between Al and Ti. However, due to annealing, for example, at 900 °C for 30 s, Al and Ti generate substantial interaction for each other leading to the formation of face-centered tetragonal TiAl crystal. The AES analysis indicated that TiAl layer is slightly Al rich. As the Al layer is 2000 Å thick, it prevents an outdiffusion of Ga from the metal-semiconductor interface to the top Au layer. Together with Ti, it prevents also the indiffusion of excess Ni and possibly Au from the top layer to the metal-semiconductor interface. As a result, there occurs a right amount of Au and Ni interdiffusion leading to the formation of a TiAl/AuNi phase in contact with GaN, a lower contact resistance, and a better surface morphology. The plausible scenario underlying the observation that AlTi/GaN interface was not, however, completely abrupt is that the interface layer contains reaction product involving all of the species (Ti, Al, Ga, N). As suggested earlier,[4] this reaction product may be TiN, which is formed when N is extracted from GaN without decomposing the GaN structure. The outdiffusion of N from the GaN lattice results in an accumulation of N vacancies in the neighborhood of metal-semiconductor interface. As noted earlier, these nitrogen vacancies in GaN act as donors,[12] causing the interface region to be doped so heavily that there occurs band bending of the GaN conduction band sufficient for tunneling.

To confirm that prevention of indiffusion of Ni (and possibly Au) to the semiconductor is very important for achieving a low Ohmic contact, we first repeated our experiments with the deposition of Ti/Al/Ni/Au (250 Å/1250 Å/450 Å/1000 Å) alloyed at 900 °C for 30 s, and next of Ti/Al/Ni/Au (250 Å/2200 Å/600 Å/500 Å) annealed at 750 °C for 30 s on two different *n*-GaN layers from the same wafer. The first contact yielded $\rho_s = 9.56\times10^{-6}\ \Omega\ \mathrm{cm}^2$ and the second one $\rho_s = 3.06\times10^{-8}\ \Omega\ \mathrm{cm}^2$. This difference in contact resistivity probably resulted because of the fact that in the first contact the 1250 Å Al layer was not thick enough to prevent the indiffusion of Ni into GaN, and that in the second contact the 2200 Å Al layer was thick enough to prevent similar indiffusion of Ni into GaN. The probability of indiffusion of Ni into GaN in the first contact was obviously higher due to higher annealing temperature. Notably, a thicker 1000 Å Au of the first layer contact had the marginal effect of the lowering of the contact resistivity.

The main drawback of our earlier Ohmic contact, as also noted by Wu *et al.*,[5] is that at high temperature Al melts and tends to ball up, resulting in a rough surface. Even when the temperature is not very high the Al surface oxidizes resulting most likely in the formation of Al_2O_3. Consequently, the less conductive Al_2O_3 layer creates a coating on Al, leading to an increase in the contact resistivity. There is another drawback as well. As the Al layer was not sufficiently thick (thickness: only 100 nm), it had some intrinsic resistance. The main advantage of the present Ohmic contact over our previous one[4] is that the AuNi alloy formed over the AlTi layer is very robust. This allows the Ohmic contact to be excellent even at very high temperature. Furthermore, it eliminates the possibility of the formation of an oxide layer with the deleterious effect of increasing the resistivity of the contact. The TLM patterns taken before and after alloying indicate that plausibly, due to the formation of a TiN, the quality of the interface between the metal and GaN improves after RTA. This may be the cause of why the contact resistivity decreases due to annealing.

In conclusion, it has been demonstrated that by using a composite metal layer Ti/Al/Ni/Au (150 Å/2200 Å/400 Å/500 Å) and a RIE exposure prior to metallization, excellent Ohmic contacts to GaN with specific resistivities of $\rho_s = 8.9\times10^{-8}\ \Omega\ \mathrm{cm}^2$, or much lower, can be achieved. While the TLM method is reasonably accurate down to about $10^{-7}\ \Omega\ \mathrm{cm}^2$, we can confidently state that extremely low Ohmic contact resistance is now possible on GaN which can pave the way for the exploitation of this material for high power/high efficiency amplifiers.

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