Low resistance ohmic contacts on wide band-gap GaN

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We report a new metallization process for achieving low resistance ohmic contacts to molecular beam epitaxy grown n-GaN ($\sim 10^{17}$ cm^{-3}) using an Al/Ti bilayer metallization scheme. Four different thin-film contact metallizations were compared during the investigation, including Au, Al, Ti/Au, and Ti/Al layers. The metals were first deposited via conventional electron-beam evaporation onto the GaN substrate, and then thermally annealed in a temperature range from 500 to 900 °C in a N_2 ambient using rapid thermal annealing techniques. The lowest value for the specific contact resistivity of $8\times 10^{-6}\ \Omega\ \mathrm{cm}^2$, was obtained using Ti/Al metallization with anneals of 900 °C for 30 s. X-ray diffraction and Auger electron spectroscopy depth profile were employed to investigate the metallurgy of contact formation.

Recent progress in the growth of high quality GaN epilayers has paved the way for nitride-based electronic and optical devices. These devices include bright p-n junction GaN light emitting diodes,[1,2] GaN metal-semiconductor field-effect transistors (MESFETs),[3] as well as modulation-doped field-effect transistors (MODFETs).[4] However, it is well known that parasitic resistances, in the form of contact resistance, substantially reduce the overall performance of these electronic and optical devices.[5] Often the major loss of performance is due to high resistance metal-semiconductor "ohmic" contacts. Therefore, in order to attain optimum device performance, minimization of the contact resistance is absolutely necessary.

Low resistance ohmic contacts for GaN are particularly challenging, as compared to the other well studied III-V compounds (GaAs and InP), because of its large band gap (3.4 eV). Although the nitrides, GaN, AlN, and InN, show great potential for use as ultraviolet and blue optical devices as well as high temperature/high power electrical devices, there still remains much more work to be done in obtaining ohmic contacts with small specific resistivities.

In an earlier attempt to achieve ohmic contacts on GaN epilayers, Foresi *et al.*[6] used Al and Au contacts with 575 °C anneal cycle. However, the specific contact resistivity of these contacts was relatively poor ($10^{-3}\ \Omega\ \mathrm{cm}^2$). In this letter, we report the results of an ohmic contact study of four separate metallization schemes: Au, Al, Ti/Au, and Ti/Al. Electrical characterization of the contacts was done using standard transmission line measurements (TLM) and the material characterization included x-ray diffraction (XRD) as well as Auger electron spectroscopy (AES).

GaN films for this study were grown on (0001) sapphire substrates which were cleaned by hydrogen plasma treatment prior to growth.[7] After cleaning, the substrates were then transferred, via an ultrahigh vacuum (UHV) transfer line, to a Perkin Elmer 430 molecular beam epitaxy (MBE) system equipped with an electron cyclotron resonance (ECR) source for nitride growth. This process produced unintentionally doped GaN films having a typical carrier concentration of about 10^{17} cm^{-3}. For the experiments performed here, the GaN sample were nominally 1 μm thick and had an electron concentration of about 1×10^{17} cm^{-3} with a room-temperature electron mobility of 100 cm^2/V s.

After the GaN films were grown, the substrates were patterned and then etched generating the mesa structure for the TLM measurements. The substrates were again patterned for the lift-off procedure, thus providing a linear configuration of rectangular pads of dimensions 250 μm wide and 80 μm long. The gap between the contact pads varied between 1 and 20 μm in 12 steps.

The specific metal layers were deposited via e-beam evaporation. One contact scheme utilized a single layer of either Al or Au with a thickness of 100 nm. The second scheme of bilayer contacts consisting of a 20 nm Ti deposited directly on GaN, followed by a 100 nm capping layer of either Au or Al. A four-point probe arrangement was used to eliminate the probe contact resistance.

Figure 1 shows current-voltage (I-V) characteristics of four different contact schemes prior to annealing. Only the Ti/Al contact on GaN exhibit near linear I-V characteristics for small current levels. The other three metal contacts ex-

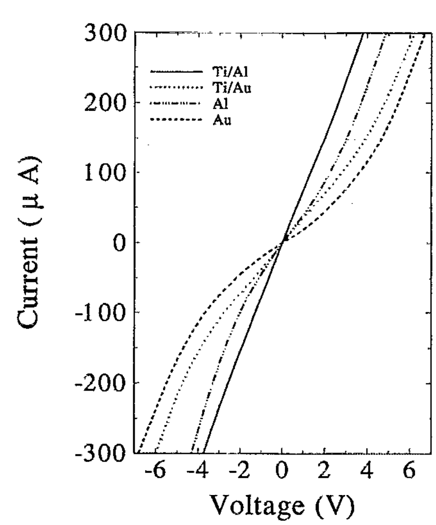

FIG. 1. I-V characteristics of as-deposited metal contacts on GaN samples measured at room temperature.

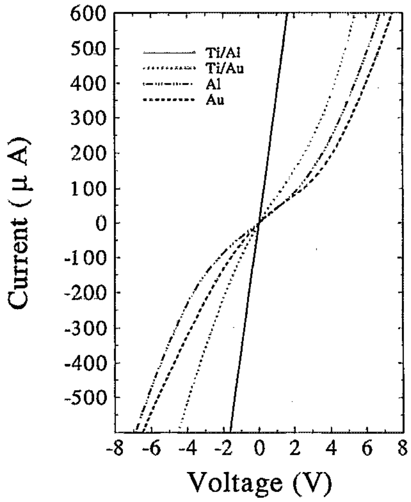

FIG. 2. I-V characteristics of metal contacts on GaN samples after annealing at 700 °C for 20 s.

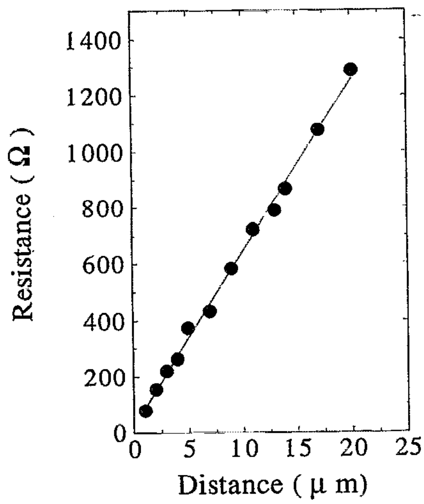

FIG. 3. Least-squares linear regression of Ti/Al contacts on GaN layers alloyed at 900 °C for 30 s.

hibited nonlinear I-V characteristics even for small currents, which is probably due to the formation of rectifying Schottky contacts. The barrier heights are strongly dependent on the type of contact metals. In general, the bilayer samples having the 20 nm Ti interface layer had lower barrier heights as compared with contacts made with only Al or Au. A brief annealing step performed as 500 °C in a N_2 environment reduced the barrier heights in all samples.

Contact resistances were derived from the I-V data of the measured resistance versus gap spacing by TLM. The method of least squares was used to obtain the intercepts needed to calculate the transfer length. After the 500 °C anneal, the specific contact resistivity of Al, Au, and Ti/Au were of the order 10^0–10^{-1} $\Omega\,\mathrm{cm}^2$ while the Ti/Al contact was 10^{-3} $\Omega\,\mathrm{cm}^2$. Upon further annealing, using the RTA method at 700 °C for 20 s the contact resistances of both Al/Ti and Au/Ti decreased markedly. Figure 2 shows the I-V characteristics for all four metal contacts after the 20 s anneal at 700 °C. Although the I-V curves of Al and Au contacts were not perfectly symmetric, contact resistances of Ti/Au and Ti/Al improved due to the higher temperature anneal. The specific contact resistivities of Ti/Au and Ti/Al are in the range of 10^{-2} and low 10^{-3} $\Omega\,\mathrm{cm}^2$ order.

The two samples, Al/Ti and Au/Ti, were further annealed to even higher temperatures at 900 °C for 30 s. This high temperature anneal resulted in a substantial increase in the contact resistance for the Ti/Au contacts. However, in the case of the Ti/Al contact, the specific resistivity of improved substantially to the very low value of 8×10^{-6} $\Omega\,\mathrm{cm}^2$ (see Fig. 3).

The relationship between the annealing time (900 °C) and specific contact resistivity was further investigated and the results are shown in Fig. 4. The unexpected high contact resistivity after annealing for 60 s may be caused by high oxygen content incorporated into the Al layer and formed a thin insulating Al_2O_3 layer on the surface which makes the measurement of the contact resistance at the GaN interface more difficult.

The metallurgical reactions of the Ti/Al contacts were investigated by XRD and AES analysis. The nonalloyed contacts, as expected, show little interaction between the Al and Ti layers as deduced from the XRD data. However, after annealing at 900 °C for 20 s the Al and Ti diffraction peaks were absent suggesting that both metal layers had been completely consumed during the anneal. New peaks in the XRD data of the annealed samples were observed after the anneal and were identified as face-centered-tetragonal TiAl indicating substantial interaction between the Al and Ti layers.

Further characterization of the annealed sample using Auger depth profiling was consistent with the XRD result: The Al and Ti layers interact forming a fairly uniform layer of AlTi. The AES analysis also indicated that AlTi layer was slightly Al rich. It was also shown in the AES profile data, that the AlTi/GaN interface was not completely abrupt. This may be due to a thin (150 Å) interface layer containing re-

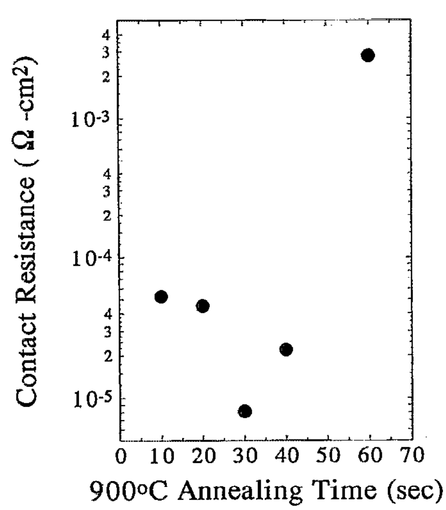

FIG. 4. The Ti/Al specific contact resistivity on GaN vs annealing time at 900 °C.

action products involving all of the species (Ti, Ga, Al, and N). This interface is key to understanding the mechanism of electronic transport across the interface. Further characterization of the interface microstructure using TEM analysis will be needed to further identify the reaction products at the GaN interface. Analysis of the system *a priori* is hampered by the absence of a quaternary Ga-N-Ti-Al phase diagram.

We now speculate on the nature of the reactions responsible for the low resistance contacts. Typically, two types of interfaces are associated with low resistance ohmic contacts; (i) low barrier Schottky contacts[8,9] using intermediate or graded band-gap interface material and (ii) tunneling contacts.

The first type of interface requires a semiconductor compound having an intermediate value band gap, thus eliminating both of the possible simple binary compounds of the reaction; AlN and TiN. AlN has a band gap [5.9 eV (Ref. 10)] which is larger than GaN and TiN's band gap is too low and behaves metallic. Other more complicated ternary and quaternary Ga, Ti, and Al nitrides compounds are possible low-barrier Schottky contact material, but further microstructure and phase identification of the interface will be necessary to link them with the observed low contact resistance found in this work.

The second type mechanism for ohmic contacts operates through the tunneling mode. For this to be applicable in our case, the GaN at the metal/GaN interface must become heavily doped during the anneal. One plausible process, whereby this may occur, involves the solid phase reaction between the Ti and GaN forming TiN. Suppose N is extracted from the GaN without decomposing the GaN structure, (i.e., N out-diffusion from the GaN lattice). Then an accumulation of N vacancies would be created in the GaN near the junction. And since N vacancies in GaN[10] act as donors, this region would be heavily doped n-GaN, which provides the configuration needed for tunneling contacts. We note that only two monolayers of TiN are needed to be formed in order to generate a 100 Å layer of GaN with an electron density of $10^{20}/cm^3$. High temperatures may be needed for this reaction since GaN decomposes only at high temperatures (980 °C in vacuum).[11]

In summary, metal contacts on GaN have been studied using the combinations of Ti, Al, and Au. Device quality ohmic contacts with contact resistivity values of 8×10^{-6} $\Omega\,cm^2$ have been obtained when Ti/Al contacts were annealed at 900 °C for 30 s. This method should provide a powerful way of making ohmic contacts on GaN layers.

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[1] H. Amano, M. Kito, X. Hiramatsu, and I. Akasaki, Jpn. J. Appl. Phys. **28**, L2112 (1989).
[2] S. Nakamura, T. Mukai, and M. Senoh, Jpn. J. Appl. Phys. **30**, L1998 (1991).
[3] M. A. Khan, J. N. Kuznia, A. R. Bhattarai, and D. T. Olson, Appl. Phys. Lett. **82**, 1786 (1993).
[4] M. A. Khan, A. Bhattarai, J. N. Kuznia, and D. T. Olson, Appl. Phys. Lett. **63**, 1214 (1993).
[5] T. C. Shen, G. B. Gao, and H. Morkoç, J. Vac. Sci. Technol. B **10**, 2113 (1992).
[6] J. S. Foresi and T. D. Moustakas, Appl. Phys. Lett. **82**, 2859 (1993).
[7] M. E. Lin, B. N. Sverdlov, G. L. Zhou, and H. Morkoç, Appl. Phys. Lett. **62**, 3479 (1993).
[8] L. H. Allen, L. S. Hung, K. L. Kavanagh, J. R. Phillips, and J. W. Mayer, Appl. Phys. Lett. **51**, 326 (1987).
[9] Z. Ma, L. H. Allen, B. Blanpain, Q. Z. Hong, J. W. Mayer, and C. J. Palmstrom, Mat. Res. Soc. Symp. Proc. **230**, 131 (1991).
[10] D. W. Jenkins and J. D. Dow, Phys. Rev. B **39**, 3317 (1989).
[11] R. Groh, G. Gerey, L. Bartha and J. I. Pankove, Phys. Status Solidi A **26**, 353 (1974).