Metal contacts to gallium nitride

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We report measurements on the nature of aluminum and gold contacts to GaN. The GaN films were deposited onto the *R*-plane of sapphire substrates by molecular beam epitaxy and are autodoped *n*-type. Metal contacts were deposited by evaporation and were patterned photolithographically. Current-voltage characterization shows that the as-deposited aluminum contacts are ohmic while the as-deposited gold contacts are rectifying. The gold contacts become ohmic after annealing at 575 °C, a result attributed to gold diffusion. The specific contact resistivity of the ohmic aluminum and gold contacts were found by transfer length measurements to be of device quality (10^{-7}–10^{-8} Ω m^2). The results of these studies suggest a direct correlation between barrier height and work function of the metal, consistent with the strong ionic character of GaN.

Gallium nitride (GaN) is a direct, wide band-gap semiconductor ($E_g \simeq 3.4$ eV) whose conduction band structure allows for a high saturation velocity (3×10^7 cm/s).[1,2] Due to these unique properties GaN is expected to find applications in optical devices (LEDs, lasers, detectors) operating in the spectral region from the blue to near-UV and in electronic devices such as high temperature, high power, and high frequency transistors.

GaN films are generally *n*-type[3] with carrier concentrations between 10^{18} and 10^{20} cm^{-3} and electron mobilities of about 20 cm^2/V s. The *n*-type autodoping is attributed to nitrogen vacancies. The most important recent development is the discovery that AlN[4] and GaN[5–10] buffers lead to lateral growth which significantly improves the surface morphology and the electrical properties of the films.

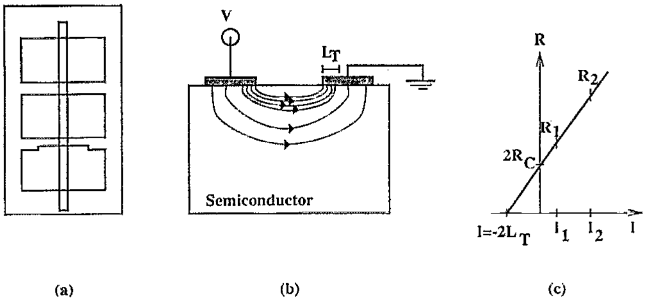
In this letter, we report our initial investigation of metal/GaN contacts. Metals investigated include Al and Au. Current-voltage (*I-V*) measurements and transfer length measurements (TLM) of the specific contact resistivity are presented.

The GaN films used in this study were grown by the ECR-MBE method without a GaN buffer layer.[11,12] All films were deposited on sapphire substrates with *R*-plane orientation. X-ray diffraction studies show that the films have the wurtzitic crystal structure with ($11\bar{2}0$) orientation, which leads to a faceted surface morphology.[12] The faceted surface makes these films unsuitable for planar devices, however, the metal contact results presented in this letter should be applicable to GaN films grown on other substrates and orientations. The transport coefficients were determined by Hall effect measurements using the Van der Pauw configuration. The investigated films were *n*-type with resistivities of about 10^{-1} Ω cm, carrier concentration of 3×10^{18} cm^{-3} and Hall mobilities of about 20 cm^2/V s. The thickness of the films was 1.6 μm.

The Au and Al contacts were deposited on the GaN films by thermal evaporation and patterned using photolithography and liftoff techniques.[13] The base pressure of the evaporation unit was 10^{-7} Torr and the system was cryopumped to keep the chamber oil-free. Tungsten evaporation boats were used to evaporate 99.999% pure Al and Au. The substrates were kept at room temperature during the evaporation. Prior to photolithography, the samples were degreased. Following metal deposition, the metals were patterned using liftoff techniques which consisted of ultrasonic baths in acetone and methanol. The contacts were patterned in TLM structures which consist of three square contacts separated by known distances [see Fig. 1(a)]. The same contacts were also used in pairs to evaluate the rectifying nature of the metal/semiconductor interface by *I-V* characterization. Because these pairs of contacts were deposited on the surface of the GaN films, they constituted back-to-back Schottky barrier systems.

I-V characterization was carried out by injecting up to ±20 mA with a current source and measuring the voltage across the same contacts with an electrometer. *I-V* characterization was performed on both as-deposited metal contacts and metal contacts which had been annealed in a reducing atmosphere for 10 min at 575 °C. All of the measurements were made in atmosphere at room temperature.

Measurements of the specific contact resistivity were made using the TLM method which is employed widely in the characterization of ohmic contacts to semiconductors.[14–16] The technique requires the formation of contacts



(a) (b) (c)

FIG. 1. (a) Sample configuration for *I-V* and TLM characterization. The thin vertical stripe is a 10 μm wide area of exposed GaN. The three wide rectangles are metal contacts separated by 20 and 15 μm. (b) Schematic of current flow through planar contacts. Nearly all of the current flows through one transfer length, L_t, of the contacts' front edges. (c) Plot of the measured resistance against the contact separation.

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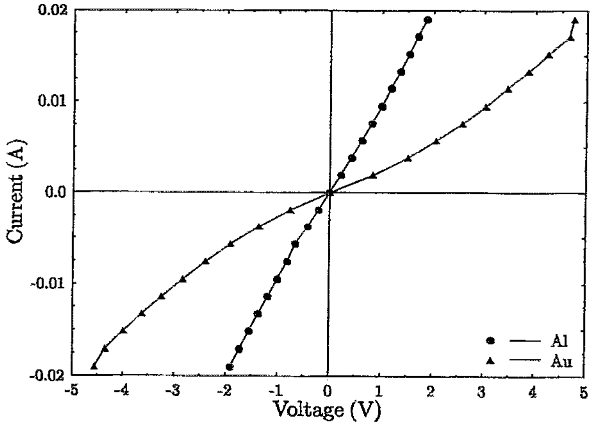

FIG. 2. *I-V* characteristics of as-deposited Al/*n*-GaN and Au/*n*-GaN structures.

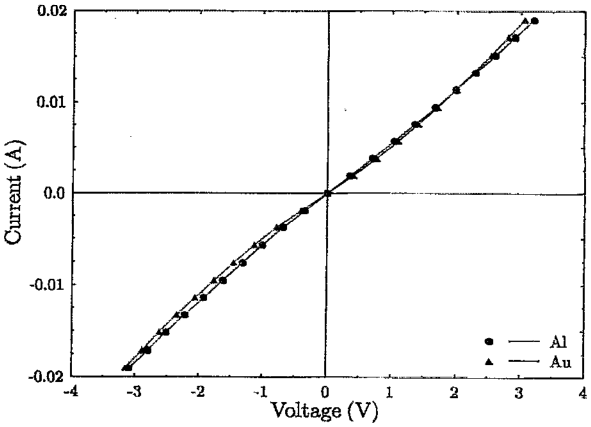

FIG. 3. *I-V* characteristics of annealed Al/*n*-GaN and Au/*n*-GaN structures.

with controlled geometry and evaluates the difference in resistance between equally sized pairs of contacts separated by different distances. The specific contact resistivity (ρ_c) is calculated from a measurement of the effective contact resistance (R_c), the contact width (W), and the transfer length (L_T):

$$\rho_c = R_c W L_T. \tag{1}$$

The effective contact resistance is given by:

$$2R_c = \frac{R_2 l_1 - R_1 l_2}{l_1 - l_2}, \tag{2}$$

where R_1 is the resistance measured between contacts spaced l_1 apart and R_2 is the resistance measured between contacts spaced l_2 apart. In a planar contact configuration, nearly all of the current enters the semiconductor through a small area at the edge of the contact.[17] The parameter L_T is the length of this area as indicated in Fig. 1(b). This quantity is estimated by plotting the resistance of two pairs of contacts against the distance separating the individual contacts within each pair. The line connecting the points R_1 and R_2 crosses the resistance axis at the $2R_c$ point and intersects the distance axis at the $-2L_T$ point [see Fig. 1(c)].

The TLM technique relies on the assumption that the semiconductor material under the contact has not been doped differently than the bulk material, and the accuracy of the method depends on the ability to control the separation between the contacts. Due to the faceted surface morphology in our films, the determination of the contact areas was difficult and limited the accuracy of the specific contact resistivity to within an order of magnitude.

The *I-V* characteristics of the as-deposited Al and Au contacts are shown in Fig. 2. For both metals the *I-V* curves are symmetric about the origin as is expected for back-to-back Schottky barriers where the characteristic is that of a reverse-biased barrier irrespective of the current polarity.[17] The Al contact *I-V* characteristics are linear indicating that the contact is ohmic with no apparent barrier to current flow. In contrast, the *I-V* characteristics of the Au contact exhibit curvature associated with the formation of a Schottky barrier. This Schottky barrier is leaky due to tunneling effects arising from the high carrier concentration of the films and the possible existence of an interfacial native oxide layer.[13] These results indicate that the barrier height depends on the metal used.

The *I-V* curves for the same contacts after annealing, shown in Fig. 3, suggest that both the Al and Au contacts have changed during annealing. The *I-V* curves of the Al contacts acquired a slight curvature and the calculated resistance increased by about 50%. These changes may be attributable to the formation of an interfacial AlN layer during the annealing process. No experimental work was performed to confirm the existence of such a layer. The *I-V* curves of the Au contacts became practically linear. A similar result has been observed in Au contacts to GaAs and attributed to Au diffusion in GaAs.[18] Analytic measurements and electron microscopy have not been performed to confirm Au diffusion. The GaN material, however, has 10^{18}–10^{19} cm^{-3} nitrogen vacancies which should facilitate the Au diffusion even though the material is tightly bonded.

The specific contact resistivities of Al and Au contacts were measured by the TLM method after annealing. The results in Table I show specific contact resistivities measured for a number of contact pairs on a single GaN sample. The variations in the contact resistivities can be attributed to the nonuniformity of the film. All of the contacts measured have specific contact resistances in the 10^{-7}–10^{-8} Ω m^2 range. The lowest specific contact resistivities

TABLE I. Specific contact resistivities for Au/*n*-GaN and Al/*n*-GaN after annealing. Measurements correspond to different TLM studies of a single sample.

Metal	Specific contact resistivity (10^{-7} Ω m^2)	Metal	Specific contact resistivity (10^{-7} Ω m^2)
Au	1.6	Al	0.12
	2.0		4.4
	3.1		1.3
	3.0		. . .

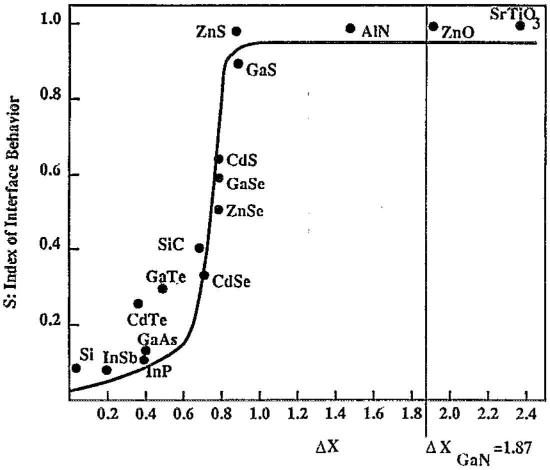

FIG. 4. Dependence of $S=d\phi_b/d\chi_m$ (change in barrier height over the change in metal work function) on the electronegativity difference between the components of the compound (after Ref. 20).

reported for GaAs are $\simeq 10^{-9}$ Ω m^2 for high quality AuGeNi contacts.[18]

The simplest considerations of Schottky barrier formation between metals and semiconductors rely on the difference in work functions of the two materials to predict the barrier height. For a large number of important semiconductors, Si and GaAs included, the dependence of barrier height on work function difference has not been observed, a result attributed to the existence of surface states which pin the Fermi level at the interface.[19] The dependence of the barrier height on the work function difference has been correlated to the ionicity of the semiconductor by Kurtin and co-workers[20] as shown in Fig. 4. In this figure, the vertical axis is a parameter S which is defined as the change in barrier height over the change in metal work function ($d\phi_b/dx_m$) and the horizontal axis is the electronegativity difference between the components of a compound which is a measure of the compound's ionicity. The direct dependence of the barrier height on the work function for the semiconductors with large electronegativity differences results from the bunching of surface states near the band edges where they have less effect on the surface Fermi level position.[17]

The electronegativity difference for GaN is 1.87 eV.[21,22] This puts GaN above the knee of the curve implying that Schottky barriers on GaN should have barrier heights which depend directly on the work function difference between the metal and GaN. The work function of GaN has been measured to be 4.1 eV.[23] Therefore, any metal with a work function equal to or lower than that of GaN should form essentially ohmic contacts to n-type GaN and any metal with a work function higher should form a rectifying contact to n-type GaN. The work function of Al is 4.08 eV (Ref. 22) putting Al in the ohmic category. The work function of Au is 4.82 eV (Ref. 22) which puts it in the rectifying category. Our results on Al and Au contacts to n-GaN are in agreement with the predictions of this model.

Based on these findings a variety of metals can be chosen to form either ohmic or Schottky barriers to n- or p-type GaN. For example, Al can form ohmic contacts to n-type GaN and Au can form ohmic contacts to p-type GaN. Other factors may also play a role in choosing the proper metals for contacts to GaN. For example, Au appears to diffuse upon annealing in the GaN. Thus, the use of Au as a contact to GaN requires a thin interlayer of Ti or Cr as a diffusion barrier.[15] Also, annealing of Al contacts may result in the formation of a thin insulating AlN interlayer, which will increase its contact resistance.

In conclusion, the nature of Al and Au contacts to n-GaN were investigated. It was found that the as-deposited Al- and Au-contacts are ohmic and rectifying, respectively. This result is in direct agreement with data indicating that ionic materials do not suffer from Fermi level pinning at metal/semiconductor interfaces. The lack of Fermi level pinning greatly reduces the complication of creating ohmic contacts to GaN as it is only necessary to determine metals with appropriate work functions. Measurements of the specific contact resistivities of Al and Au annealed contacts on GaN give values in the range of 10^{-7}–10^{-8} Ω m ^{2} which are of device quality.

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[1] J. I. Pankove, MRS Symp. Proc. **162**, 515 (1990).
[2] P. Das and D. K. Ferry, Solid-State Electron. **19**, 76 (1976).
[3] R. F. Davis, Proc. IEEE **79**, 702 (1991).
[4] I. Akasaki and H. Amano, MRS Symp. Proc. **242**, 383 (1992).
[5] G. Menon, M. S. thesis, Boston University, 1990.
[6] T. Lei, M. Fanciuli, R. J. Molnar, T. D. Moustakas, R. J. Graham, and J. Scanlon Appl. Phys. Lett. **58**, 944 (1991).
[7] T. Lei, T. D. Moustakas, R. J. Graham, T. He, and J. Berkowitz, J. Appl. Phys. **71**, 4933 (1992).
[8] T. D. Moustakas, T. Lei, and R. J. Molnar, Physica B **185**, (1993).
[9] S. Nakamura, Jpn. J. Appl. Phys. **30**, L1705 (1991).
[10] R. J. Molnar, T. Lei, and T. D. Moustakas, Appl. Phys. Lett. **62**, 72 (1993).
[11] C. R. Eddy Jr., M. S. thesis, Boston University, 1990.
[12] C. R. Eddy, Jr., T. D. Moustakas, and J. Scanlon, J. Appl. Phys. **73**, 448 (1993).
[13] J. Foresi, M.S. thesis, Boston University, 1992.
[14] B. L. Sharma, *Metal-Semiconductor Schottky Barrier Junctions and Their Applications* (Plenum, New York, 1984).
[15] G. N. Maracas, *Gallium Arsenide Technology*, edited by D. K. Ferry (Howard W. Sams, Carmel, IN, 1989), Vol. 2.
[16] G. Stareev and A. Umbach, J. Electron. Mater. **20**, 1059 (1991).
[17] H. K. Henisch, *Semiconductor Contacts* (Clarendon, Oxford, 1984).
[18] E. H. Rhoderick and R. H. Williams, *Metal-Semiconductor Contacts* (Clarendon, Oxford, 1988).
[19] J. Bardeen, Phys. Rev. **71**, 717 (1947).
[20] S. Kurtin, T. C. McGill, and C. A. Mead, Phys. Rev. Lett. **22**, 1433 (1969).
[21] C. M. Wolfe, N. Holonyak, Jr., and G. E. Stillman, *Physical Properties of Semiconductors* (Prentice Hall, Englewood Cliffs, NJ, 1989).
[22] K. W. Böer, *Survey of Semiconductor Physics* (Van Nostrand, New York, 1990).
[23] J. I. Pankove and H. E. P. Schade, Appl. Phys. Lett. **25**, 53 (1974).