

## Low-resistance ohmic contacts to *p*-type GaN

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(Received 18 January 2000; accepted for publication 7 March 2000)

The specific contact resistance of two types of ohmic contacts to *p*-type GaN is analyzed. First, an ohmic contact formed by a metal electrode deposited on a highly doped *p*-type GaN layer. Second, an ohmic contact formed by a metal electrode deposited on a thin GaN layer with an internal electric field caused by polarization effects. It is shown that contacts mediated by polarization effects can result, for typical materials parameters, in low contact resistances comparable or better than contacts mediated by dopant-induced surface fields. A type of contact is proposed and demonstrated. These contacts employ polarization charges to enhance tunneling transport as well as high doping. Experimental results on Ni contacts to *p*-type Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN doped superlattices are presented. The contacts have linear current-voltage characteristics with contact resistances of  $9.3 \times 10^{-4} \Omega \text{ cm}^2$ , as inferred from linear transmission-line method measurements. The influence of annealing at temperatures ranging from 400 to 500 °C on the contact resistance is studied. © 2000 American Institute of Physics. [S0003-6951(00)01219-5]

Low-resistance ohmic contacts to *p*-type GaN are required for high efficiency light-emitting diodes (LEDs) and lasers as well as for bipolar transistors. Ohmic contacts to *p*-type GaN have been demonstrated using high-work function metals such as Ti, Ni and Pt deposited on a highly doped GaN surface layer.<sup>1,2</sup> Annealing of contacts has been shown to decrease the contact resistance.<sup>3,4</sup>

In this letter, two types of ohmic contacts are analyzed, namely contacts formed by a highly doped GaN surface layer and contacts mediated by the surface electric field caused by polarization effects. The tunneling current and specific contact resistance of the structures are theoretically calculated. In addition, ohmic contacts to *p*-type Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN doped superlattices are fabricated and analyzed, including the specific contact resistance and the annealing characteristics of the contacts.

The tunneling current density through an arbitrarily shaped tunnel barrier with the potential  $\varphi(x)$  is given by<sup>5</sup>

$$J = \frac{e^2}{2\pi h(\Delta s)^2} \{ \bar{\varphi} e^{-A\sqrt{e\bar{\varphi}}} - (\bar{\varphi} + V) e^{-A\sqrt{e(\bar{\varphi} + V)}} \}, \quad (1)$$

where  $\bar{\varphi}$  is the *average* barrier height defined by

$$\bar{\varphi} = \frac{1}{\Delta s} \int_{s_1}^{s_2} \varphi(x) dx, \quad (2)$$

the constant  $A$  is given by

$$A = (4\pi\Delta s/h) \sqrt{2m_{\text{hh}}} \quad (3)$$

and the other symbols have their usual meaning.

The tunneling distance through the barrier,  $\Delta s$ , can be inferred from the depletion approximation of a uniformly doped semiconductor which exhibits a parabolic potential in the depletion region. The tunneling distance is given by

$$\Delta s = \sqrt{\epsilon/(eN_A)} (\sqrt{2(\Phi_B - V)} - \sqrt{-2V}). \quad (4)$$

At zero bias, the tunneling distance reduces to the depletion region thickness  $\Delta s = W_D = [2\epsilon/(eN_A)\Phi_B]^{1/2}$ , where the approximation  $V_{\text{bi}} \approx \Phi_B$ , valid for highly doped semiconductors, is used. Even though the acceptors in GaN have a large activation energy, e.g., 200 meV, they are likely ionized in the depletion region of the metal-semiconductor contact.

Assuming that tunneling is the dominant transport mechanism through the barrier, the contact resistance is given by

$$\rho_c = (dJ/dV)^{-1}. \quad (5)$$

Values of the contact resistance are evaluated numerically from Eqs. (1) and (5).

Figure 1 shows the calculated contact resistance of a metal/*p*-type GaN contact as a function of the electrically active acceptor concentration. Barrier heights ranging from 0.25 to 2.25 V are used in the calculation. The inset in Fig. 1 schematically shows the band diagram of the structure. Inspection of the figure reveals that to attain contact resistances of  $10^{-5} \Omega \text{ cm}^2$ , doping concentrations of  $7 \times 10^{19} \text{ cm}^{-3}$  are required, assuming a barrier height of 1 V.

Next we consider a metal-semiconductor structure in which sheet charge of magnitude  $N_s^{2D}$  at the semiconductor surface is due to polarization effects and induced charges in the metal. It is well known that such sheet charges occur in the Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN materials system due to spontaneous and piezoelectric polarization effects.<sup>6-8</sup> A triangularly shaped barrier results from such a charge distribution. Here

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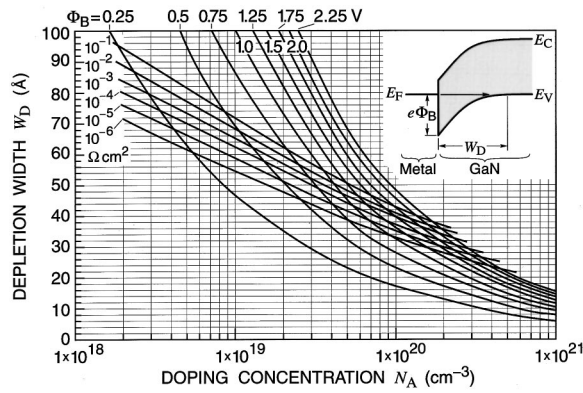


FIG. 1. Calculated specific contact resistance and depletion width vs acceptor doping concentration of a metal-to-*p*-type-GaN contact for barrier heights ranging from 0.25 to 2.25 V.

we assume that the top layer is GaN and that this layer has a thickness *d*. The tunneling current through the triangular barrier can be calculated from Eq. (1). However, for this case, the contact resistance can be expressed in terms of an analytic formula<sup>9</sup>

$$\rho_c^{-1} = \left( \frac{e}{2\pi\hbar d} \right)^2 (\hbar + d\sqrt{em_{hh}\Phi_B}) \exp\left( -\frac{2d}{\hbar}\sqrt{em_{hh}\Phi_B} \right). \quad (6)$$

To allow for tunneling transport between the metal electrode and valence band states, the potential drop in the semiconductor (*eEd*) must be equal or larger than the barrier height  $\Phi_B$ . Thus, the thickness *d* of the GaN top layer must be at least

$$d = \Phi_B / \mathcal{E} = \epsilon\Phi_B / (eN_s^{2D}). \quad (7)$$

Figure 2 shows the calculated contact resistance of *p*-type GaN having a surface charge of magnitude  $N_s^{2D}$ . Barrier heights ranging from 0.25 to 2.25 V are used in the calculation. The inset in Fig. 2 schematically shows the band diagram of the structure. To attain a contact resistance of  $10^{-5} \Omega \text{ cm}^2$ , a surface charge of approximately  $3 \times 10^{13} \text{ cm}^{-2}$  is required, assuming a barrier height of 1 V. Note that polarization charges in the  $10^{13} \text{ cm}^{-2}$  range are readily attainable in  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  heterostructures.<sup>10</sup>

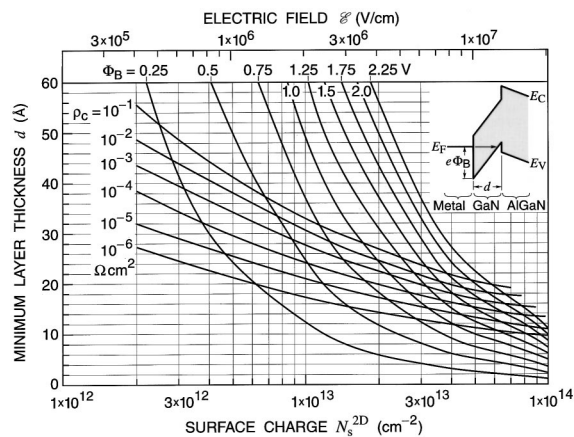


FIG. 2. Calculated specific contact resistance and minimum GaN layer thickness vs polarization charge density of a metal-to-GaN contact for barrier heights ranging from 0.25 to 2.25 V.

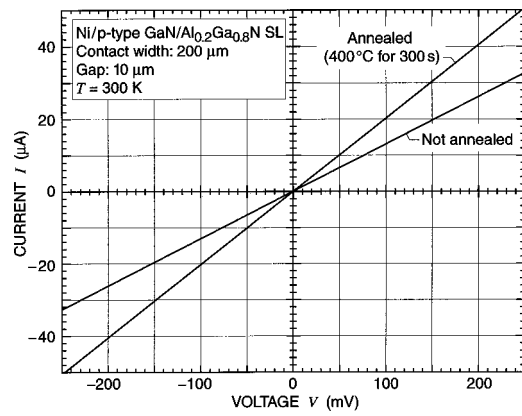


FIG. 3. Current-voltage (*I*-*V*) characteristic of a Ni contact on a Mg-doped, *p*-type  $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}/\text{GaN}$  superlattice before and after annealing.

Comparison of the results illustrated in Figs. 1 and 2 reveals that high doping can provide low contact resistances to *p*-type GaN for acceptor concentrations in the  $10^{19} \text{ cm}^{-3}$  range. The comparison also shows that low specific contact resistances can be attained in contacts based on polarization fields at lower doping levels. Thus polarization-charge-based contacts are a viable alternative to ohmic contacts based on highly *p*-type doped GaN layers.

To examine the effect of polarization fields on contact resistance, Ni contacts were deposited on Mg-doped  $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}/\text{GaN}$  superlattice structures. The surface layer of the superlattice consists of a  $100 \text{ \AA}$  GaN layer (Ga face) grown on top of a strained AlGaIn layer. This structure results in a *spontaneous* polarization vector pointed towards the substrate in each layer. In addition, a *piezoelectric* polarization is present in the strained AlGaIn which increases the net polarization of the layer.

An electric field pointing towards the surface is associated with the polarization present in the GaN and AlGaIn layers. This causes free charges to redistribute themselves to oppose the field since no potential drop may exist over the entire superlattice. The net result is an electric field in the GaN wells pointing away from the surface and an electric field in the AlGaIn barriers pointing towards the surface. This effect is exploited in our metal-semiconductor contact where the polarization field in the GaN layer enhances the depletion field, thereby reducing tunneling distance and hence contact resistance.

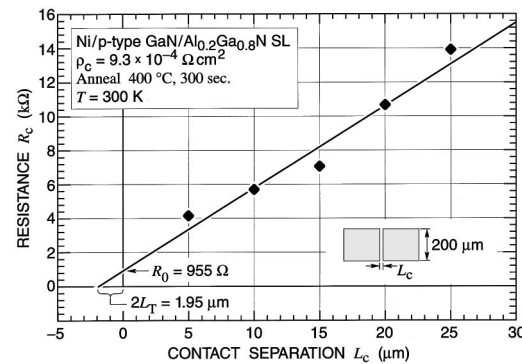


FIG. 4. Evaluation of the specific contact resistance of Ni contacts on a Mg-doped, *p*-type  $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}/\text{GaN}$  superlattice using the transmission-line method.

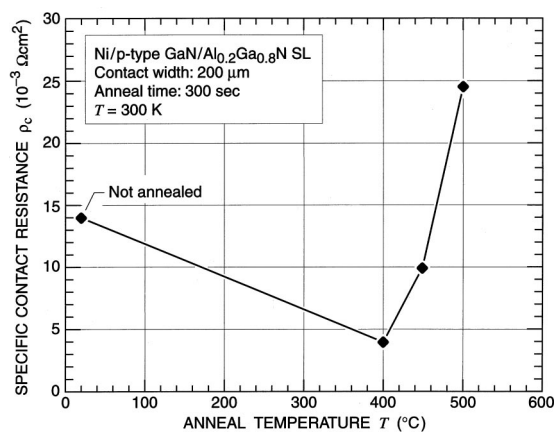


FIG. 5. Specific contact resistance of Ni contacts on a Mg-doped,  $p$ -type  $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}/\text{GaN}$  superlattice for annealing temperatures ranging from 400 to 500 °C.

The current–voltage ( $I$ – $V$ ) characteristics of the Ni contacts are shown in Fig. 3 for an as-deposited contact and after annealing at 400 °C. Both  $I$ – $V$  characteristics are ohmic without any indication of nonlinear behavior.

The lowest contact resistance obtained on the superlattices is  $9.3 \times 10^{-4} \Omega \text{cm}^2$  and the corresponding transmission-line method (TLM) measurement is shown in Fig. 4. We assume that even lower specific contact resistances can be obtained with Pt metallizations since Pt ( $\Phi_m = 5.65 \text{ V}$ ) has a higher metal work function than Ni ( $\Phi_m = 5.15 \text{ V}$ ) thereby lowering the barrier height at the metal–semiconductor interface.<sup>1</sup>

A systematic study of the contact resistance on the annealing temperature is shown in Fig. 5. Inspection of the result reveals that annealing at moderate temperatures such as 400 °C can lower the contact resistance. However, other

processing steps such as pre-metallization cleaning in different acidic and basic chemicals also have a substantial influence on the contact resistance.

In conclusion, the specific contact resistance of ohmic contacts mediated by a highly doped  $p$ -type GaN layer and by an electric field caused by polarization effects is calculated. It is shown that the contacts based on polarization effects can result, for typical materials parameters, in low contact resistances comparable or better than conventional contacts based on dopant-induced surface fields. A type of contact is proposed and experimentally demonstrated. These contacts employ high doping as well as polarization charges to enhance tunneling transport. Ni contacts on  $p$ -type  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  doped superlattices have a linear current–voltage characteristics with contact resistances of  $9.3 \times 10^{-4} \Omega \text{cm}^2$ , as inferred from linear TLM measurements. Annealing at moderate temperatures of 400 °C can reduce the specific contact resistance of Ni contacts.

This work was supported by the Office of Naval Research (Dr. C. E. C. Wood).

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