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Nonalloyed ohmic contacts on low-temperature molecular beam epitaxial GaAs: Influence of deep donor band

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The Ohmic nature of the nonalloyed metal contact on molecular beam epitaxial GaAs grown at 200 °C was studied. The specific contact resistances at room temperature and 120 K were 1.5×10^{-3} and 7.0×10^{-1} Ω cm^2, respectively. These values are anomalously low considering that the conduction-band electron concentration in this material is less than 10^{11} cm^{-3} at room temperature. The experimental results indicate that the carrier transport at the metal/semiconductor interface is dominated by a dense ($\sim3\times10^{19}$ cm^{-3}) EL2-like deep donor band, rather than the usual conduction band.

Recently low-temperature (LT) growth molecular beam epitaxial (MBE) GaAs has been attracting a growing attention because its use as a buffer material for metal-semiconductor field-effect transistor (MESFET) applications can significantly reduce the side-gating effect,[1] which is a big issue for realizing GaAs integrated circuits (ICs) on a practical basis. The physical nature of this material is being extensively studied and several remarkable features have been revealed: (1) the stoichiometry is heavily shifted toward As rich;[2] (2) a large quantity ($>10^{19}$ cm^{-3}) of an EL2-like deep level [3](probably $\mathrm{As}_{\mathrm{Ga}}^{2}$) exists; (3) hopping conduction via a dense defect band accounts for the anomalous electrical properties;[3] (4) very weak photoluminescence,[1] and a peculiar photocurrent response[4] are observed. The major differences between LT MBE and conventional material are related to the very large defect concentration which is introduced by the low-temperature growth.

Although it has recently been pointed out that a metal contact on LT MBE GaAs shows ohmic characteristics without alloying,[3,5] its mechanism has not been understood. Our preliminary results on the contact resistance at room temperature showed a specific contact resistance of mid 10^{-3} Ω cm^2. This is surprising because the conduction-band electron concentration in this material is less than 10^{11} cm^{-3}. In this letter we report temperature-dependent contact resistance data for MBE GaAs grown at 200 °C. We show that the unexpectedly low contact resistance can be explained by a carrier transport model in which electrons travel from the metal directly to the dense EL2-like deep donor band by passing over an 0.12 eV barrier (extrapolated to 0 K).

MBE layers with a thickness of 5 μm were grown on (100) undoped semi-insulating GaAs at a substrate temperature of 200 °C in a Varian 360 system. No post-growth annealing was carried out. Detailed growth conditions are the same as those described elsewhere.[3] A standard transmission line model (TLM) pattern[6] for the measurement of the contact resistance was formed by the evaporation and lift-off method. Before the metal deposition, the GaAs surface was treated by typical cleaning procedures, namely, a HCl:H$_2$O(1:1) soak (30 s) and de-ionized (DI) water rinse, followed by a buffered HF soak (30 s) and DI water rinse. The size and interspacing of the electrodes on the TLM pattern were 75×50 μm^2, and 2–11 μm, respectively. The electrode metal consisted of multilayered Ni/Ge/Au and the TLM measurements were performed at 90–400 K, under vacuum without alloying the contacts. The Hall effect measurements were carried out over a temperature range of 80–400 K, using a high-impedance van der Pauw apparatus.[6]

From the TLM measurements, we can obtain the specific contact resistance and the material resistivity (knowing the thickness). First, we compare the resistivity data from the Hall effect and TLM methods, respectively. Figure 1 shows the resistivity data of the LT MBE layers as a function of $T^{-1/4}$. The two sets of data agree fairly well except for the data taken at $T<120$ K; below this temperature, the TLM method gives inaccurate results due to the large resistances involved. Note that the linear relationship in Fig. 1 at low temperature indicates variable-range hopping conduction via the dense EL2-like 0.75 eV band, as reported.[3]

The concentration of this deep donor level in our sample is approximately 3×10^{19} cm^{-3}, which is determined by both electrical and optical measurements.[3] With this value and a fitted acceptor concentration of 7×10^{14} cm^{-3}, which is also reasonable for our sample,[3] a conduction-band electron concentration of 7×10^{10} cm^{-3} can be calculated.[7] Therefore, the Fermi level position at room temperature is 0.398 eV from the conduction-band minimum. The specific contact resistances at 400, 300, and 120 K were 5.4×10^{-4}, 1.5×10^{-3}, and 7.0×10^{-1} Ω cm^2, respectively. These values are remarkably low, in view of the low conduction-band electron concentration. In theory, the resistance of a metal-semiconductor contact can be completely described,[8,9] if the various carrier transport mechanisms are known. In most cases, three modes of the transport are important: thermionic, thermionic field, and field emission tunneling. However, these mechanisms are obviously not applicable for our samples because the conduction-band electron concentration is too low. Furthermore, a pure-tunneling mechanism is evidently ruled out because it implies a temperature-independent contact resistance, which is not observed.

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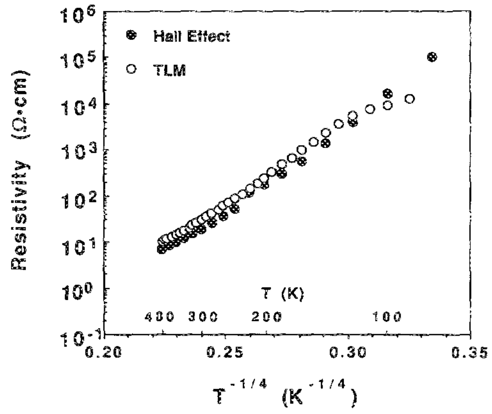

FIG. 1. Temperature-dependent resistivity data on 200 °C growth MBE GaAs measured by the Hall effect and TLM methods, respectively. The $T^{-1/4}$ dependence indicates variable range hopping conduction.

Figure 2 describes a model for the carrier transport at the contact. Figure 2(a) shows a band diagram for the metal-semiconductor contact at zero bias. Note that the position of the Fermi level (E_C − 0.4 eV at 296 K) is determined by a very large concentration ($\sim 3\times 10^{19}$ cm^{-3}) of EL2-like deep donors and a relatively small concentration ($\sim 7\times 10^{14}$ cm^{-3}) of acceptors. We have assumed that the Schottky barrier height ($q\phi_B$) is approximately 0.8 eV, and temperature independent; then $q\phi_B > E_C - E_T$, where E_C and E_T are the energy levels of the conduction-band minimum and the deep donor level, respectively. The deep donor level is almost completely occupied with electrons in most of the material. However, because of the band bending near the contact, an unoccupied region is formed. An electron residing in the deep donor band at the Fermi level must then overcome a small barrier ($q\phi$) to move into the metal. Since $q\phi = q\phi_B - (E_C - E_T)$, and $E_C - E_T \sim 0.65$ eV at room temperature,[10] the approximate value of $q\phi$ will be around 0.15 eV. We will give a measured value later. At equilibrium, of course, the same flux of electrons in the metal must jump into the unoccupied deep donor state over the barrier ($q\phi$). This mode is similar to the usual thermionic emission involving conduction-band electrons. In the forward bias case, shown in Fig. 2(b), the deep donor states are totally occupied and there is no barrier for an electron in a deep donor to move into the metal. In the reverse bias case, shown in Fig. 2(c), an electron in the metal can move into an unoccupied donor state and then into the bulk via the hopping mechanism. This phenomenon should dominate the normal conduction-band processes when the concentration of the deep donor is sufficiently high.

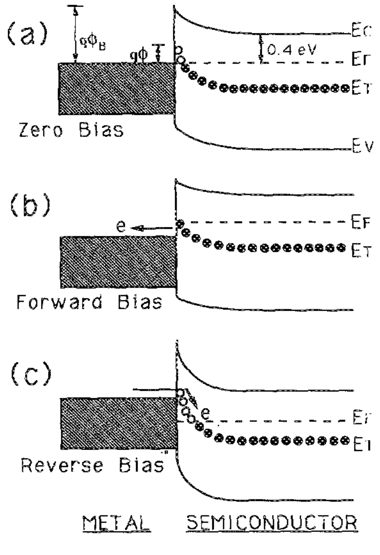

FIG. 2. Band diagram for the metal-semiconductor contact. The semiconductor Fermi level is about 0.4 eV from the conduction-band minimum.

To model the metal-semiconductor current transport, it is instructive to first review the standard formalism, which applies to *conduction-band* electrons in the semiconductor being transported to the metal. The basic physics here is relatively simple and can be approximately described as follows. Electrons at the interface ($x = 0$) will move into the metal if their velocity vector is in the right direction. The current density ($J_{s\to m}$) will then be given by

$$\begin{aligned} J_{s\to m} &= qv_x n(0) \\ &= q\left(\frac{kT}{2\pi m^*}\right)^{1/2} N_C \exp\left(\frac{-q(\phi_B - V)}{kT}\right) \\ &= \frac{4\pi q m^* k^2}{h^3} T^2 \exp\left(\frac{-q(\phi_B - V)}{kT}\right) \\ &= A^* T^2 \exp\left(\frac{-q(\phi_B - V)}{kT}\right) \\ &= 7.0\times 10^5 \exp\left(\frac{-q(\phi_B - V)}{kT}\right) \text{A/cm}^2 \text{ at 296 K.} \end{aligned} \tag{1}$$

Here, A^* is Richardson's constant (~ 8 A/cm^2/K^2, for n-GaAs), N_c is the effective density of states in the conduction band and the velocity $\sqrt{(kT/2\pi m^*)} \cong 1\times 10^7$ cm/s is an appropriately averaged thermal velocity, analogous to setting $m^* v^2/2 = kT$; the details can be found in various sources[9] but such a model can also be criticized on different grounds.[11] In any case, the basic physics describing the present situation is quite different, because the electrons are not moving freely in the conduction band, but instead are hopping in a deep, defect band. A hopping rate R between nearly degenerate sites can be roughly approximated by[12,13]

$$R \cong \nu_{\text{phonon}} \exp\left(\frac{-\gamma}{a N_D^{1/3}}\right), \tag{2}$$

where we will set $\nu_{\text{phonon}} \cong k\Theta_D/h \cong 8.7\times 10^{12}$ s^{-1}, where Θ_D is the Debye temperature, $\gamma \cong 1.8$[13], $a = h/2\pi\sqrt{(2m^* E_{D0})} \cong 8.7$ Å, and $N_D = 3\times 10^{19}$ cm^{-3} (Ref. 3). Then $R = 1.1\times 10^{10}$ s^{-1}, and $v_{\text{eff}} = R(3/4\pi N_D)^{1/3} = 2.2\times 10^3$ cm/s, since $(3/4\pi N_D)^{1/3}$ is the average distance between defects. In analogy with Eq. (1), we then would approximate $J_{s\to m}$ by

$$J_{s\to m}\cong qv_{\text{eff}}N_D\exp\left(\frac{-q(\phi-V)}{kT}\right)$$

$$=q\nu_{\text{phonon}}\exp\left(\frac{-\gamma}{aN_D^{1/3}}\right)\left(\frac{3}{4\pi N_D}\right)^{1/3}$$

$$\times N_D\exp\left(\frac{-q(\phi-V)}{kT}\right)$$

$$=1.1\times 10^4\exp\left(\frac{-q(\phi-V)}{kT}\right)\text{A/cm}^2, \qquad (3)$$

where the pre-exponential term is smaller by a factor of ~ 60 at 296 K than predicted by Eq. (1), which of course does not apply in this situation. From Eq. (3),

$$\rho_c=\left(\frac{\partial J}{\partial V}\right)^{-1}_{V=0}$$

$$=\frac{kT}{q^2\nu_{\text{phonon}}\exp(-\gamma/aN_D^{1/3})(3/4\pi N_D)^{1/3}N_D}\exp\left(\frac{q\phi}{kT}\right)$$

$$=8.1\times 10^{-9}T\exp\left(\frac{q\phi}{kT}\right)\Omega\text{ cm}^2. \qquad (4)$$

Note that ϕ should be temperature dependent because it is related to E_T, which is temperature dependent. Although the deep donor discussed here is not precisely the same as EL2 itself,[3] it would be reasonable to use the reported temperature coefficient of EL2, because fitting the electrical data with this parameter was successful.[3] We set $E_C - E_T = E_{D0} - \alpha T$, where $E_{D0} = 0.75$ eV and $\alpha = 3.4\times 10^{-4}$ eV K^{-1}. This gives $E_T(296\text{ K}) = 0.65$ eV and $E_T(0\text{ K}) = 0.75$ eV, which are both experimentally observed.[10,14] Substituting this into Eq. (4), we obtain

$$\rho_c T^{-1}\exp(-\alpha/k)$$

$$=\frac{k}{q^2\nu_{\text{phonon}}\exp(-\gamma/aN_D^{1/3})(3/4\pi N_D)^{1/3}N_D}$$

$$\times\exp\left(\frac{q\phi_B-E_{D0}}{kT}\right). \qquad (5)$$

Therefore, the Arrhenius plot of the left-hand side in Eq. (5) gives the value of $q\phi_B - E_{D0}$, namely, the effective barrier height extrapolated to 0 K. Figure 3 presents the plot using the ρ_c data obtained at 120–400 K. From the figure, it can be seen that the expected linear relationship holds reasonably well over more than three orders of magnitude.

From the activation energy of the plot based on Eq. (5), we can obtain an effective barrier height of 0.12 eV at 0 K. As our model predicted, this barrier height is quite low and is consistent with the observed Ohmic characteristics. It is interesting to note that, from the definition of $q\phi$, $q\phi_B$ becomes 0.87 eV, which is a reasonable value for the Schottky barrier height on n-type GaAs.[9] Thus, our model for the carrier transport at the contact well explains the slope of the plot in Fig. 3; however, we see a slight difference in the pre-exponential term in Eq. (5) between the model (8.1×10^{-9} Ω cm^2 K^{-1}) and the experimental data (8.9×10^{-10} Ω cm^2 K^{-1}). We think that our rough approximation for v_{eff} is responsible for this discrepancy. If instead, we fit v_e to the experimental data, we obtain $v_{\text{eff(fit)}} = 2.0\times 10^4$ cm/s, which gives good agreement with the experimental data as seen in Fig. 3 (solid line).

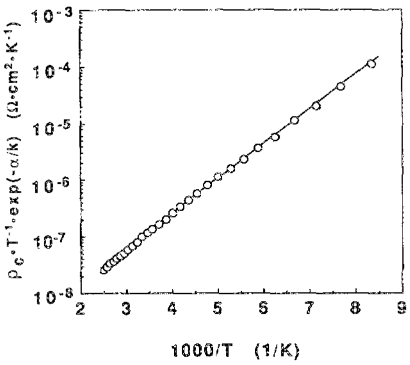

FIG. 3. Plots of $\rho_c T^{-1}\exp(-\alpha/k)$ as a function of $1/T$. ρ_c is the specific contact resistance, T is the temperature, k is the Boltzmann constant, and α is 3.4×10^{-4} eV K^{-1}.

In summary, we have studied the contact resistance of the 200 °C growth LT MBE GaAs at 90–400 K. The temperature-dependent contact resistance data can be understood if the dominant carrier transport at low bias involves electron emission via a dense EL2-like defect band. The Ohmic nature of the nonalloyed metal contact on the LT MBE GaAs follows naturally from this model.

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