Delta-doped ohmic contacts to *n*-GaAs

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A new type of nonalloyed ohmic contact to GaAs is realized by molecular beam epitaxy. The ohmic characteristic of the metal-semiconductor junction is obtained by placing a highly δ-doped donor layer a few lattice constants away from the metal-semiconductor interface of the contact and thus keeping the tunneling barrier extremely thin. The current-voltage characteristic of the δ-doped contacts is strictly linear. The measured contact resistance is in the $10^{-6}\ \Omega\ \text{cm}^2$ range. Theoretical analysis of the tunneling current through the triangular barrier predicts contact resistances in the range 10^{-7}–$10^{-9}\ \Omega\ \text{cm}^2$. In spite of the high doping concentration (10^{20}–10^{21} cm^{-3}) the surface morphology of the sample shows no degradation.

Ohmic contacts which exhibit a linear current-voltage characteristic are an important part of all semiconductor devices, such as field-effect transistors, light-emitting diodes, and lasers. Ohmic contacts eliminate the inherently strong influence of the highly resistive surface depletion region on the current-voltage characteristic of a metal-semiconductor junction. The surface depletion region was first explained by the difference in work functions of the metal and the semiconductor, later by Fermi-level pinning at the semiconductor surface.[1] The Fermi level in turn is pinned by surface states energetically located in the middle of the forbidden energy gap. Previously, two basic ways have been employed to produce ohmic contacts to a semiconductor. (i) A metal can be alloyed into the semiconductor, with the metal impurities acting as donors or acceptor in the semiconductor. Recent results on alloyed ohmic contacts to GaAs show that in addition to the simple diffusion a formation of domains with different chemical composition occurs.[2] (ii) A second interesting way to form an ohmic contact was proposed by Stall *et al.*[3] They grew a thin Ge layer on top of an *n*-GaAs epitaxial layer. Charge carriers must overcome *two low barriers* (metal-Ge and Ge-GaAs) of height $\frac{1}{2}\phi_B$ instead of *one barrier* of height ϕ_B.[3] The resulting increase of the current due to thermal emission is equal to

$$2\exp(-q\phi_B/2kT)/\exp(-q\phi_B/kT). \tag{1}$$

This ratio amounts to 6.5×10^7 at room temperature and shows the significant resistance decrease of the proposed method.

In this letter we investigate for the first time the fabrication of ohmic metal-semiconductor contacts employing the δ-doping technique.[4] First we outline the theoretical principle of the new contact and calculate the tunneling current and the contact resistance. Next, experimental results on the current-voltage characteristic, the contact resistance, and the surface morphology are presented.

The energy-band diagram of a δ-doped epitaxial layer is shown in Fig. 1. Donors are located at a distance z_D from the surface and the doping profile can be described by the delta function,

$$N_D(z) = N_D^{2D}\delta(z - z_D), \tag{2}$$

where N_D^{2D} denotes the two-dimensional doping concentration. The Dirac delta function is a useful way to describe analytically the charge in δ-doped layers, even though the δ-doped function is strictly a singular relation with a problematic physical meaning at $z \simeq z_D$.

The thickness t of the tunneling barrier depends on the applied voltage V according to

$$t = z_D\phi_B/(\phi_B - V) \quad (V \leqslant 0). \tag{3}$$

We will restrict ourselves to the case $V \leqslant 0$ which inherently has a larger resistance than the case $V > 0$. The basic idea of the new ohmic contact is to keep the tunneling barrier thin and consequently make quantum-mechanical tunneling through the barrier the dominant transport mechanism. A major fraction of electrons originating from donors of the δ-doped layer occupy surface states at the metal-semiconductor interface, as illustrated in Fig. 1. Assuming (i) Fermi-level pinning at an energy $q\phi_B$ below the conduction-band edge, and (ii) a Fermi energy that coincides with the conduction-band edge for $z \geqslant z_D$, the (minimum) two-dimensional (2D) donor concentration is given by

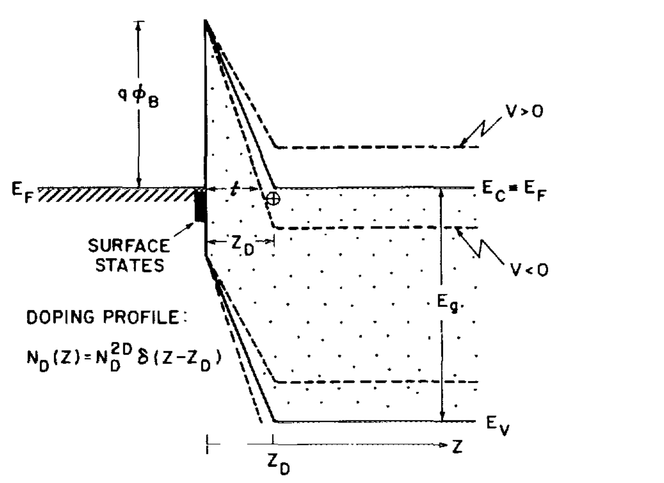

FIG. 1. Energy-band diagram of a δ-doped n-type semiconductor-metal junction. The donors are located at a distance z_D from the metal-semiconductor interface. The thickness of the tunneling barrier depends on the applied voltage.

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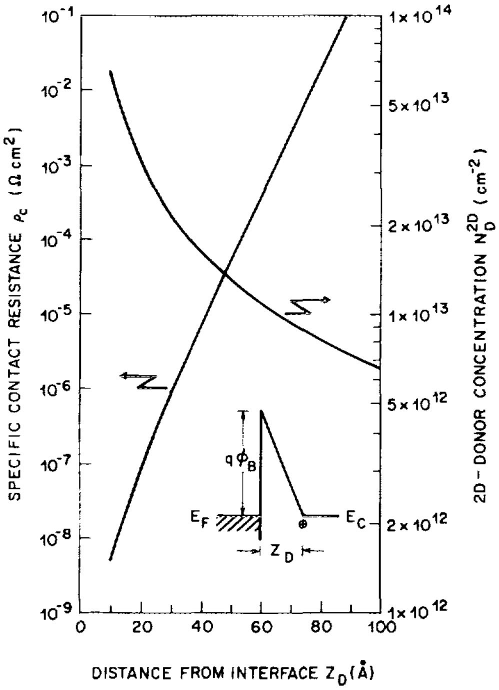

FIG. 2. Specific contact resistance ρ_c [Eq. (7)] (left ordinate) and minimum donor concentration [Eq. (4)] (right ordinate) as a function of the distance z_D of the dopant atoms from the interface, as shown in the inset.

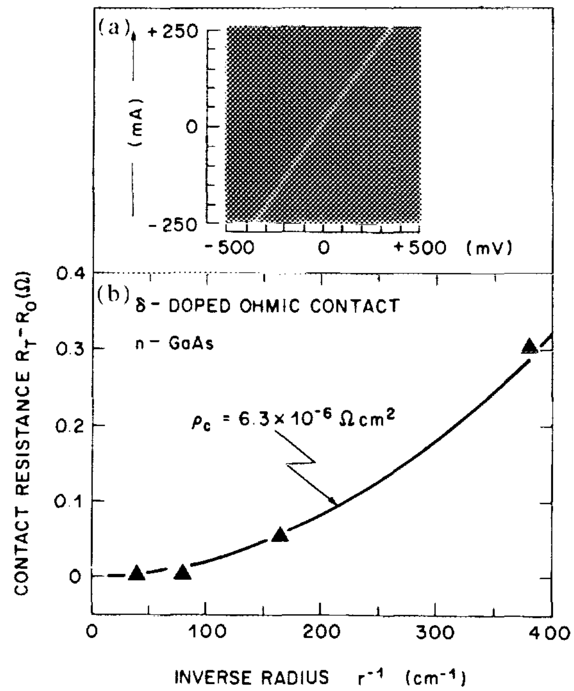

FIG. 3. (a) Current-voltage characteristic of a δ-doped ohmic contact ($r = 255\ \mu$m). The total resistance amounts to $R_t = 1.4\ \Omega$. (b) Contact resistance of δ-doped ohmic contacts as a function of inverse radii. The specific contact resistance of $\rho_c = 6.3\times 10^{-6}\ \Omega\ \text{cm}^2$ is obtained by fitting Eq. (9) to the experimental results (dark triangles).

$$N_D^{2D} = \epsilon\phi_B/qz_D, \tag{4}$$

where ϵ and q are the permittivity of the semiconductor and the elementary charge, respectively. The 2D donor concentration given by Eq. (4) is shown on the right-sided ordinate of Fig. 2 as a function of the distance z_D. The formation of impurity tail states is not included in this present approach. The tunneling current density through a triangular barrier is according to Simmons[5]

$$j = \frac{q^2\phi_B/2}{(2\pi)^2\hbar t^2}\left\{\exp\left[-\alpha\left(\frac{\phi_B}{2}\right)^{1/2}\right] - \left(1+\frac{2V}{\phi_B}\right)\exp\left[-\alpha\left(\frac{\phi_B}{2}+V\right)^{1/2}\right]\right\}, \tag{5}$$

with

$$\alpha = (2t/\hbar)\sqrt{2qm^*}.$$

Regarding only the first term[6] of Eq. (5) we obtain the well-known Fowler–Nordheim equation,

$$j = \frac{q^2(\phi_B/2)}{(2\pi)^2\hbar t^2}\exp\left(-\frac{2t}{\hbar}\sqrt{2qm^*}\sqrt{\phi_B/2}\right). \tag{6}$$

The contact resistance is then obtained by inserting Eq. (3) into Eq. (6) and differentiating Eq. (6) with respect to V:

$$(\rho_c)^{-1} = \left(\frac{q}{2\pi\hbar z_D}\right)^2(\hbar + z_D\sqrt{qm^*\phi_B}) \times\exp\left(-\frac{2z_D}{\hbar}\sqrt{qm^*\phi_B}\right). \tag{7}$$

The specific contact resistance obtained by Eq. (7) is plotted in Fig. 2 (left-sided ordinate). Extremely low calculated contact resistances in the range 10^{-7}–$10^{-9}\ \Omega\ \text{cm}^2$ are obtained for sufficiently small distances z_D. Rewriting Eq. (6) in the form ($V\simeq 0$),

$$j \sim \exp(-z_D/d_0), \tag{8}$$

yields

$$d_0 = \hbar/\sqrt{4qm^*\phi_B} = 5.62\ \text{Å}.$$

Accidentally the length d_0 coincides approximately with the lattice constant $a_0 = 5.6533$ Å of GaAs. The contact resistance is consequently low, as long as z_D is on the order of the lattice constant. A dopant layer in proximity to the semiconductor surface is therefore essential for a low-resistance ohmic contact. The plot of Fig. 2 is drawn for $z_D > 10$ Å, because the calculation relies on the effective mass approximation (EMA) which requires a periodic lattice potential. For lengths $z_D \cong a_0$ the EMA is hardly fulfilled.

The growth of the δ-doped contacts is performed in a Vacuum Generator V80 molecular beam epitaxy (MBE) system equipped with two growth chambers interconnected by a trolley interlock stage. In this system we use conventional effusion cells for evaporation of the group III elements. Arsine (AsH_3) that is cracked when entering the MBE chamber is used as arsenic supply. The growth of n-GaAs:Si is interrupted for 23 min by closing the Ga effusion cell to form the δ-doped layers yielding a two-dimensional concentration of $N_D^{2D} = 5\times 10^{13}\ \text{cm}^{-2}$. The distance z_D between δ-doped layer and surface is selected to be 25 Å. A total number of five δ-doped planes, each separated by 25 Å, is used to facilitate ohmic contact formation and to make the epitaxial layer n type. A doped buffer layer ($N_D = 10^{18}$ cm^{-3}, $d = 1\ \mu$m) is used on top of the heavily doped n^+-GaAs substrate. The physical three-dimensional concentration of the δ-doped layers in this study is $(N_D^{2D})^{3/2} = 3.5\times 10^{20}\ \text{cm}^{-3}$ and exceeds significantly the concentration used in earlier studies on MBE grown ohmic contacts.[7]

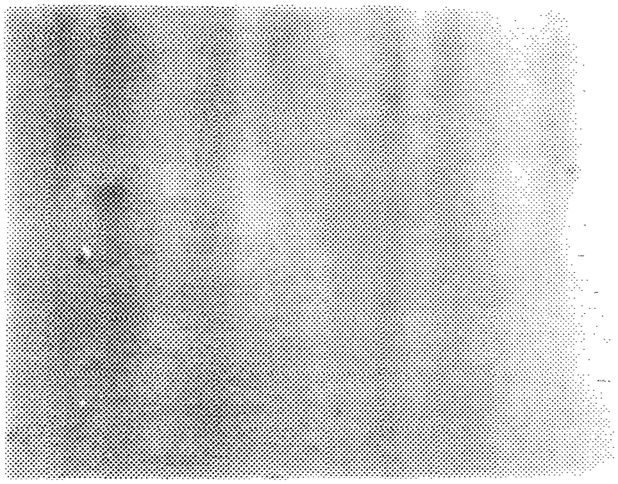

FIG. 4. Surface morphology of a highly δ-doped GaAs surface used for ohmic contact fabrication (Nomarski contrast photomicrograph at 700× magnification).

After crystal growth the samples are immediately mounted into the vacuum chamber of an evaporator. A molybdenum shadow mask with various hole sizes is used during evaporation of 200 Å Cr and 2000 Å Au.

Excellent ohmic characteristics of a circular δ-doped contact of radius $r = 255\ \mu$m are shown in Fig. 3(a). The total resistance of $R_T = 1.4\ \Omega$ demonstrates the high potential of the present ohmic contact method. The current-voltage characteristic exhibits strictly linear behavior with S- and N-shaped patterns absent on all scales. The contact resistance is evaluated according to the seminal publications of Cox and Strack,[8] who introduced the formula

$$R_T - R_0 = [(\rho d) + \rho_c]/(\pi r^2) \quad (\text{valid for } d \ll r), \tag{9}$$

where ρ is the specific resistance of the epitaxial layer, d the thickness of the epilayer, r the contact radius, and R_T and R_0 the total and back-side resistance, respectively. Due to the high doping concentration of the buffer layer ($N_D = 10^{18}$ cm^{-3}), the ρd term is not an essential contribution to the measured resistance R_T. The specific contact resistance is evaluated by plotting the measured $R_T - R_0$ values versus $(1/r)$ and by adjusting the specific contact resistance in Eq. (9) to get best agreement between the experimental points and the theoretical curve. The contact resistances are typically in the $10^{-6}\ \Omega\ \text{cm}^2$ range. The lowest contact resistance measured is $2.5\times 10^{-6}\ \Omega\ \text{cm}^2$. An example of a $(R_T - R_0)$ versus inverse radius $(1/r)$ plot is depicted in Fig. 3(b). The calculated fit to the experimental data yields a specific contact resistance of $6.3\times 10^{-6}\ \Omega\ \text{cm}^2$, which is a moderately good value. The surface of the ohmic contact metal remains smooth, because such contacts require no alloying. The problems of balling-up in conventionally alloyed AuGe-based contacts[2,8] are consequently avoided. The high three-dimensional Si concentrations ($N_D \cong 10^{20}$–10^{21} cm^{-3}) used in this study raise the question whether Si donors exhibit amphoteric behavior.[9] The low experimental contact resistance demonstrates, however, that compensation does not affect the properties of δ-doped ohmic contacts drastically.

Finally, we studied the surface morphology of δ-doped GaAs layers using an optical microscope. Figure 4 shows a Nomarski micrograph of a heavily δ-doped GaAs layer and reveals no defect such as cross hatch[10] or precipitates.[11] No defects originating from the δ-doped layers have been found. The microscopic formation of δ-doped donor planes needs further investigations. It is noteworthy that the reflection high-energy electron diffraction (RHEED) pattern revealed a transition from the 2×4 to the 1×3 surface reconstruction.[12] Delta-doped ohmic contacts have important implications on future electron devices and integrated circuits (IC). In three-dimensional GaAs IC's our new type of contact should not perturb lower device regions, as alloyed contacts do. Furthermore, δ-doped ohmic contacts can be used in ballistic GaAs structures for contacting the narrow base.[13]

In conclusion, we have realized a new type of ohmic contact by heavily δ doping GaAs 25 Å below the GaAs-metal interface. The characteristics of the δ-doped ohmic contacts grown by molecular beam epitaxy are strictly linear. The nonalloyed ohmic contacts have a specific contact resistance in the $10^{-6}\ \Omega\ \text{cm}^2$ range. Both epitaxial GaAs and the metal contact have an excellent surface morphology. The theoretical evaluation of the contact resistance by calculation of the tunneling current reveals contact resistance in the 10^{-7}–$10^{-9}\ \Omega\ \text{cm}^2$ range. The new ohmic contact can be used in future GaAs devices, such as ballistic transistors with narrow base widths and 3D GaAs integrated circuits.

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