Quasi-1D electron channels and 2D electron gas in structures with vicinal faces of GaAs δ-doped with tin

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Structures with vicinal faces of GaAs δ-doped with tin, i.e., GaAs(δ-Sn) structures, have been synthesized. The anisotropy of the conductivity was studied at $0.35 < T < 300$ K. The quantum Hall effect, the Shubnikov–de Haas effect in fields up to $B = 40$ T, and the negative magnetoresistance at low temperatures were also studied. The anisotropy of the conductivity and features of the quantum Hall effect are explained in terms of a coexistence of 2D electrons with a fairly high mobility and of quasi-1D electron channels in the GaAs(δ-Sn) structures.

1. Among the various methods available for fabricating reduced-dimensionality electronic systems,[1] molecular-beam epitaxy, in which the structure is grown on a profiled (faceted) surface of a semiconductor, has a definite advantage.[2,3] We have developed and implemented a method for fabricating quasi-1D conducting wires of tin, embedded in an i-GaAs matrix in GaAs(Cr) substrates misoriented 0.3° from the (001) plane toward the (110) basal plane, through molecular-beam epitaxy. The method involves forming a system of steps on vicinal faces of the crystal and decorating the ends of these steps with atoms of an electrically active, shallow donor impurity.

2. As the electrically active dopant for the δ-doping we selected tin. Since the atomic radius of tin is quite different from that of gallium, and since tin has a high diffusive mobility, tin should accumulate predominantly at the edges of steps. After the deposition of the tin we grew a layer of gallium arsenide at low epitaxy temperatures, which resulted in the formation of a large number of growth islands on the plateaus of terraces. This effect should help keep the tin distribution nonuniform.

The effectiveness of the segregation of the tin at the edges of the steps (the terraces) and the limitation on the diffusion of tin in the buried layer of i-GaAs were optimized by choosing the appropriate substrate temperatures in the various stages of the growth and by varying the relative flux densities of gallium and arsenic. To intensify the segregation of tin at the ends of the profiled surface, we deposited some excess gallium (a fraction of a monolayer) on the ends of the profiled surface before the δ-doping. The physical and other conditions during the growth of the structures were monitored by Auger spectroscopy, high-energy electron diffraction, and quadrupole mass spectroscopy.

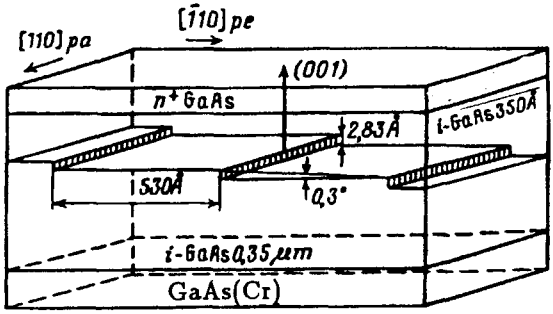

FIG. 1. Overall view of the GaAs(δ-Sn) structure.

The reflection high-energy electron diffraction revealed that when the electron beam was incident along the normal to the terrace texture (i.e., when the electron beam was incident on the structure along the [$\bar{1}$10] direction), there was a characteristic fine structure in the diffraction pattern. This fine structure was not present when the beam was incident along the terraces, i.e., along the [110] direction. It was found that the size of the terraces in the [110] direction was $\approx$ 1 mm.

In this manner, systems of chains of tin atoms, stretched out along the [110] direction and embedded in the GaAs matrix crystal, were fabricated. The average distance between the chains of tin atoms according to the misorientation angle was 53 nm.

Here are the parameter values of the structures which were grown: The thickness of the *i*-GaAs buffer layer was 0.3–1.0 μm, the δ-Sn had a surface density of atoms up to 10^{13} cm^{-2}, the thickness of the upper *i*-GaAs layer was 10–55 nm, and the n^+-GaAs contact layer, with a thickness of about 15 nm, was doped with silicon to a level of 10^{18} cm^{-3}. Figure 1 is a schematic diagram of the structure.

For the measurements we prepared samples in the form of Hall bridges with a width $W=0.15$ mm and a length $L=1.5$ mm with [110] and [$\bar{1}$10] orientations.

3. The conductivity σ falls off monotonically with decreasing temperature for both samples (Fig. 2). There is also a decrease in σ_{pe}/σ_{pa}, the ratio of the conductivities of the sample in the [$\bar{1}$10] and [110] directions. Beginning at $T\approx 10$ K, the $\sigma(T)$ dependence is linear in a logarithmic temperature scale for both samples. In the temperature interval $1 < T < 50$ K the Hall coefficient is independent of the temperature and has a value $R_H \approx 3.8\times 10^6$ cm^2/C for the sample in the [110] direction and $R_H \approx 5.6\times 10^6$ cm^2/C for that in the [$\bar{1}$10] direction.

In the test samples we observed a negative magnetoresistance, which was considerably larger in the case of the [$\bar{1}$10] samples. In magnetic fields $B > 0.4$ T this negative magnetoresistance is a logarithmic function of the magnetic field. Figure 3 shows the conductivity versus the magnetic field for the [110] sample at various temperatures. As the temperature is raised, the absolute value of the negative magnetoresistance decreases. The [$\bar{1}$10] sample exhibits the same behavior.

At liquid-helium temperatures, the samples exhibit Shubnikov–de Haas oscillations and a quantum Hall effect. Figure 4 shows the transverse resistivity ρ_{xx} and the

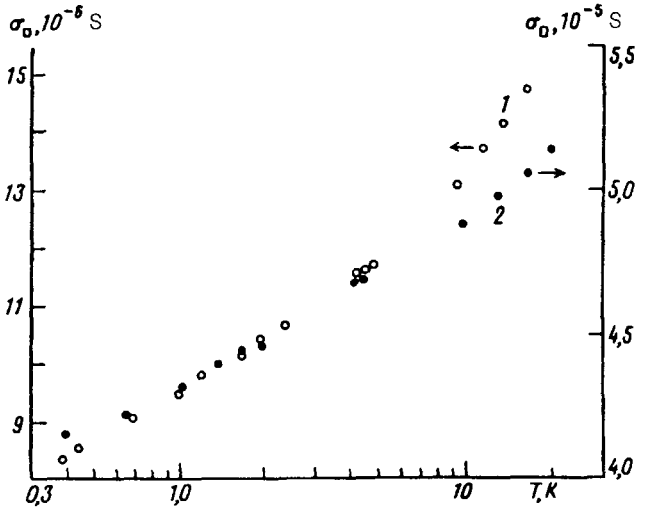

FIG. 2. Temperature dependence of the conductivity along the [$\bar{1}$10] direction (○) and along the [110] direction (●).

Hall resistivity ρ_{xy} of the samples versus the magnetic field. We can calculate the concentration of 2D electrons, n, from the oscillation period and also from the position of the ρ_{xy} plateau in the magnetic field. The two methods yield the same value, $n \approx 5.5 \times 10^{12}$ cm^{-2}; the value is the same for the samples in the two orientations. The values of ρ_{xy} on the plateau are smaller than their quantum values, while at its minimum ρ_{xx} is not zero, because of a parallel conduction channel (quasi-1D channels on the vicinal faces).

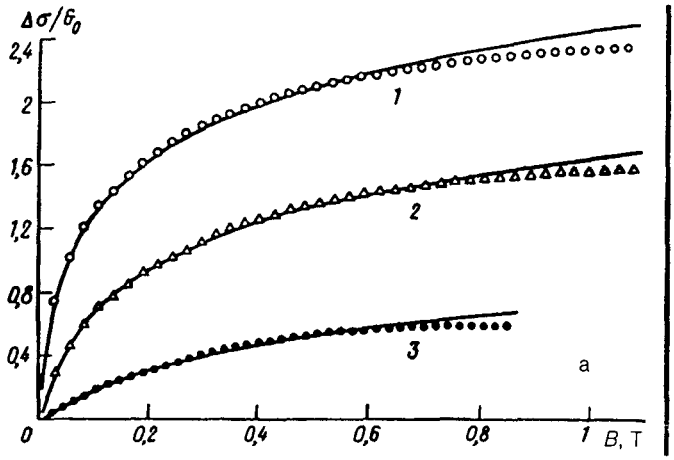

FIG. 3. Reduced conductivity versus the magnetic field of a longitudinal [110] sample at various temperatures T, K: *1*—4.2; *2*—11; *3*—29. Points) Experimental data; solid curves) calculated from Eq. (2).

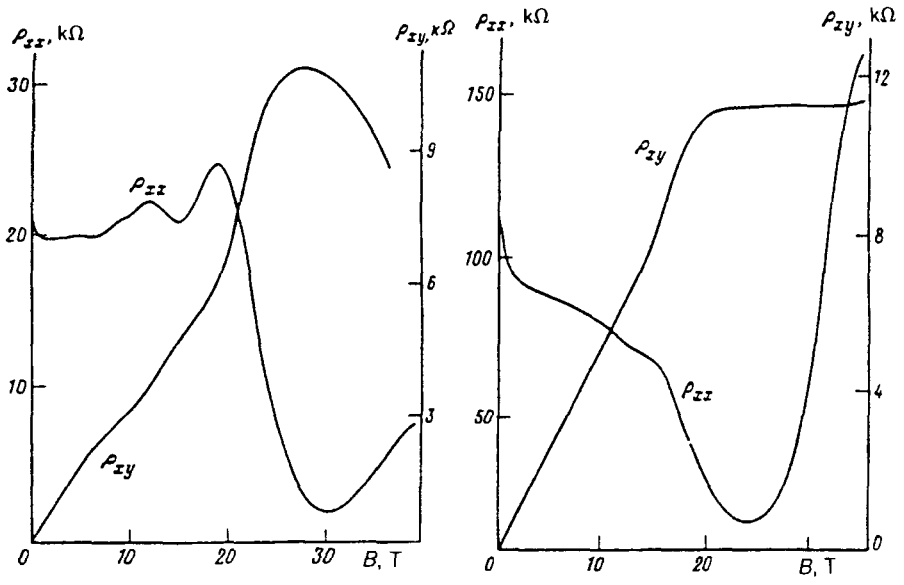

FIG. 4. The transverse resistivity ρ_{xx} and the Hall resistivity ρ_{xy} versus the magnetic field for a [110] sample (a) and for a [$\bar{1}$10] sample (b). $T=4.2$ K.

4. In the low-temperature region, the $\sigma(T)$ dependence for the 2D electrons is described by the relation[4,5]

$$\Delta\sigma(T)=[\beta+(1-\beta)p+\Lambda_2]G_0 \ln\ T/T_0, \tag{1}$$

which is used in the theory of quantum corrections to the conductivity. Here $G_0=1.23\times10^{-5}$ Ω/□, Λ_2 is the constant of the e–e interaction in the diffusion channel, $\beta(T)$ is a coefficient which determines the Maki–Thompson correction, and p is the exponent in the temperature dependence of the phase relaxation time of the electron wave function, τ_φ: $\tau_\varphi \propto T^{-p}$. The experimental results (Fig. 2) correspond to expression (1). In this theory (the interaction of electrons is ignored), and in the 2D case, the negative magnetoresistance is given by

$$\Delta\sigma(B)=[1-\beta]G_0 \ln(4DeB\tau_\varphi/\hbar), \tag{2}$$

where D is the diffusion coefficient. Knowing D, we can work from (2) to fit the experimental results on the negative magnetoresistance, using τ_φ as a parameter. In this manner we find the temperature dependence of τ_φ. Experimentally we observed a negative magnetoresistance corresponding to quantum corrections to the conductivity in the 2D case. Working from the Einstein equation $D=E_F\mu/e$, the Fermi energy E_F, and the mobility μ, we can estimate the diffusion coefficient D. The Fermi energy was calculated from the concentration of 2D electrons, itself found from the Shubnikov–de Haas effect. To determine the mobilities we also used oscillation data in

the method described in Refs. 6 and 7. These calculations yield the values $\mu_{pa} \approx 0.4$ m^2/(V·s) and $\mu_{pe} \approx 0.1$ m^2/(V·s) for the [110] and [$\bar{1}$10] samples, respectively.

A fit of Eq. (2) to the experimental results on the behavior of the negative magnetoresistance, with τ_φ being used as a parameter, shows that the $\tau_\varphi(T)$ dependence is described well by $\tau_\varphi \propto T^{-p}$ with $p=1$. At $T=4.2$ K we have $\tau_\varphi = 6.5 \times 10^{-12}$ s$_1$ for the [110] sample and $\tau_\varphi = 2.8 \times 10^{-12}$ s$_1$ for [$\bar{1}$10] sample. The primary mechanism for the phase relaxation in these systems at low temperatures is thus the mechanism of electron–electron collisions with a small energy transfer.[4]

The photoluminescence spectra confirm that the structures contain 1D channels. At 4.2 K for a structure with quantum wires one observes a shift of the emission line by an amount $\delta E \approx 5 \times 10^{-3}$ eV with respect to that of a GaAs(δ-Sn) control sample, on an ordinary (001) GaAs(Cr) singular face.[1)] A similar shift is usually observed in a study of the luminescence of quantum wells formed on vicinal faces.[8] Some large tin-doped regions remain in the central part of the terraces; i.e., the electronic system consists of electrons in quantum wells (1D) and electrons on terraces (2D). Evidence for this conclusion comes from the circumstance that the Hall coefficient is smaller than it should be for 2D electrons on the basis of the electron concentration found from the Shubnikov–de Haas effect. On the other hand, the mobility of the electrons in the quasi-1D channels is substantially lower, and these electrons are not manifested in the Shubnikov–de Haas effect or the temperature dependence of the conductivity. For 1D carriers, this temperature dependence should be considerably stronger than the logarithmic dependence observed experimentally (Fig. 2).

The island nature of the growth of the terraces implies discontinuities in the steps along the [$\bar{1}$10] direction. At these discontinuities, the quantum wires are probably short-circuited by Sn along the [$\bar{1}$10] direction, and the 1D and 2D electrons make contact in the short-circuiting regions. In a sample with a Hall bridge along the [110] direction, the transport occurs through two parallel 1D and 2D channels. In the sample with the other (transverse) orientation, the current is determined primarily by the concentration of electrons in the 2D channel, and transport is suppressed in comparison with that in the longitudinal sample. The concentration of 1D electrons can be estimated from the initial level of the doping with tin and from the width of the 1D channel, L_δ. With the figure $L_\delta = 5$ nm, which is typical of δ-doping, the concentration turns out to be $n_1 = 10^6$ cm^{-1}.

5. In summary, δ-doping with tin has made it possible to form a 2D electron gas with fairly high mobilities. The physical and other conditions and regimes developed in this study have made it possible to synthesize a GaAs(δ-Sn) semiconductor system with a textured profile of the dopant (tin) along the [$\bar{1}$10] direction. Such a distribution of a donor dopant implies the formation of quasi-1D electron channels with a δ-function potential profile in the two orthogonal directions [001] and [$\bar{1}$10]. Evidence that the structures contain quantum wires comes not only from the electron diffraction, the photoluminescence spectra, and the anisotropy of the conductivity, but also from the linear current–voltage characteristics at fields up to $E \approx 3000$ V/cm. These fields are many times those for structures with an ordinary 2D electron gas (with similar parameter values). The GaAs(δ-Sn) structures hold promise for implementa-

tion in devices with a high density of conducting channels (up to 10^6 cm^{-1}).

[1)]The photoluminescence spectra were measured in the laboratory of V. D. Kulakovskiĭ . An analysis of these spectra will be published separately.

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