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Characteristic features of transport phenomena in alternatively doped $GaAs/Ga_{1-x}Al_xAs$ heterostructures

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The temperature and magnetic-field dependences of the conductivity of heterostructures alternatively doped with silicon — δ-doping of GaAs and simultaneous uniform doping of the $Al_xGa_{1-x}As$ layer — are investigated. The concentration and mobility of the two-dimensional electrons in quantum-well subbands are determined from the experimental data. The band diagrams of the structures with different distances of the δ layer from the heteroboundary are calculated. It is shown that such structures can have a much higher conductivity than ordinary structures. © *1996 American Institute of Physics.* [S1063-7826(96)00904-0]

INTRODUCTION

There is definite scientific interest in two-dimensional systems in which the density of two-dimensional carriers is high and electrons occupy several quantum-well subbands.[1-3] Strictly speaking, such systems cannot be regarded as being purely two-dimensional, since, if more than one subband is occupied, the wave functions of the electrons in the higher subbands are not as strictly localized in a direction perpendicular to the two-dimensional layer as are the wave functions of the first subband. The behavior of electrons in such systems is much more complicated than in purely two-dimensional systems. Electrons in different subbands interact with one another and intersubband electron scattering is strong, which causes the electron mobilities in each subband to be different. On the other hand, for practical applications, it is of interest to develop powerful transistors based on heterostructures, which requires that the concentration of two-dimensional electrons be increased. There exist different methods for doping heterostructures.[4,5] We report here the results of our study of structures with alternative doping; i.e., the GaAs layer was δ-doped with silicon on one side of the heterojunction and the ternary compound $Al_xGa_{1-x}As$ was uniformly doped on the other side of the heterojunction The Shubnikov–de-Haas effect and the Hall effect were investigated, and the band diagrams of the experimental structures were calculated self-consistently on the basis of the experimental results.

SAMPLES

A diagram of the structure is shown in Fig. 1. An i-GaAs buffer layer (1 μm) was grown on a semi-insulating substrate GaAs(Cr), after which a δ layer of silicon was deposited on the surface and buried by a i-GaAs layer with thickness L_δ. Next, the standard heterostructure was grown — an i-$Al_xGa_{1-x}As$ spacer with thickness $d=4$ nm ($x=0.36$) and $d=5$ nm ($x=0.25$), a doped n-$Al_{0.25}Ga_{0.75}As$ layer with thickness $d=25$ nm, and a variable-gap i-$Al_xGa_{1-x}As$ layer with $d=9$ nm (with x decreasing from 0.25 to 0). The structure was covered with a 10-nm-thick GaAs contact layer. The δ layer of silicon was located at distances $L_\delta=$ 20, 40, 60, 75, 100, and 120 nm in the samples 1–6, respectively. All structures were grown in a single technological process with the same degree of doping with silicon $N=2\times10^{18}$ cm^{-3} in the δ layer and in the ternary compound in the As-stabilized regime.

To perfect the technology for synthesizing such structures, we investigated the growth regime. Special attention was devoted to the growth of gallium arsenide, which determines the geometry of the microrelief of the heterojunction

Layer	Thickness
n^+ - GaAs	100 Å
i - $Al_xGa_{1-x}As$ ($x\to0$)	90 Å
n - $Al_{0.25}Ga_{0.75}As$	250 Å
i - $Al_{0.35}Ga_{0.65}As$	50 Å
i - $Al_{0.36}Ga_{0.64}As$	40 Å
δ - Si	L_δ
i - GaAs	1 μm
GaAs (Cr)	

FIG. 1. Arrangement of the experimental structures.

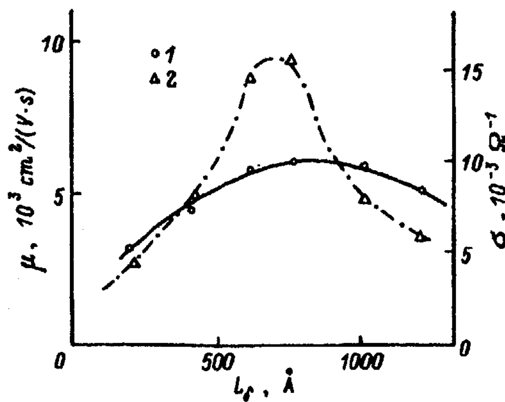

FIG. 2. Conductivity σ (*1*) and Hall mobility $\mu=R\sigma$ (2), plotted as a function of the distance L_δ of the δ layer from the heterojunction at a temperature of 77 K.

boundary (roughness, growth islands). The RHEED method was used to monitor the quality of the GaAs/GaAlAs boundary. The rate of growth of gallium arsenide and aluminum arsenide were monitored simultaneously, to a high degree of accuracy, by using this method. The main factors determining the quality of the structures obtained were the substrate temperature and the interruption of growth of GaAs. When the growth of GaAs is interrupted by closing the shutter of the gallium source while holding the substrate temperature at 500–650 °C, the GaAs surface becomes smoother.

RESULTS

The conductivity σ (1) and the Hall mobility $\mu=R\sigma$ [Eq. (2)] are shown in Fig. 2 as functions of the distance L_δ of the δ layer from the heterojunction at a temperature of 77 K. We note that the conductivity on a square in the experimental samples at the liquid-nitrogen temperature is $\sigma\simeq(5-9)\times10^{-3}\ \Omega^{-1}$ is much higher than in the well-known analogs: $\sigma\simeq10^{-4}\ \Omega^{-1}$,[6] $\sigma\simeq3\times10^{-4}\ \Omega^{-1}$ (Ref. 7), and $\sigma\simeq2\times10^{-3}\ \Omega^{-1}$. (Ref. 8).

The temperature dependences of the resistance on a square of samples 2, 3, and 5 are shown in Fig. 3. At first, a

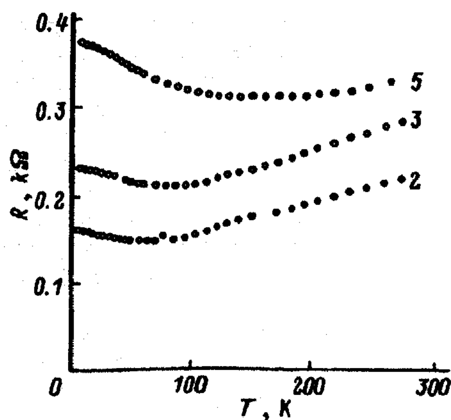

FIG. 3. Temperature dependence of the resistance on a square for samples 2, 3, and 5.

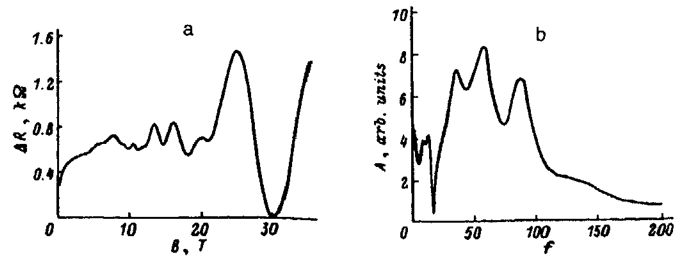

FIG. 4. Oscillations of the transverse magnetoresistance at $T=4.2$ K (a) and their Fourier spectrum (b) for sample 2 with $L_\delta=40$ nm.

metallic behavior of $\sigma(T)$ is observed, and as the temperature decreases further, the resistance of the samples increases.

Investigation of the Shubnikov–de Haas effect revealed a complicated oscillatory pattern of the beats of different frequencies. It is natural to associate this pattern with oscillations from different filled subbands. The quantum oscillations of the magnetoresistance of sample 2 at $T=4.2$ K are shown in Fig. 4a and their Fourier spectrum is shown in Fig. 4b.

DISCUSSION

The electron concentrations and mobilities in each of the two-dimensional subbands were determined by the following method. It is known that the magnetic-field dependence of the oscillating part of the magnetoresistance ρ_{xx} for the ith subband is given by the expression[9]

$$(\Delta\rho_{xx}/\rho_0)_i=A_i(X/\sinh X)\exp(-\pi/\mu_iB)\times\cos\{[2\pi(E_f-E_i)/\hbar\omega_c]+\pi\}, \quad (1)$$

where E_f-E_i is the position of the ith subband relative to the Fermi energy, $X=2\pi^2k_BT/\hbar\omega_c$, and $\omega_c=eB/m^*$. Since the density of states in the two-dimensional case is equal to $m^*/\pi\hbar^2$, the electron concentrations n_i in the two-dimensional subbands can be determined by performing a numerical Fourier transform of the oscillating part of the experimental function $\rho_{xx}(1/B)$ because the oscillation frequencies are equal to $\pi\hbar n_i/e$.

The theoretical dependence of the Shubnikov–de Haas oscillations was fit to the experimental data by the search-optimization method by varying the amplitude A_i and the mobility μ_i.[10] The mobilities and concentrations for the

TABLE I.

Subband No.	Sample 2: n, 10^{12} cm^{-2}	Sample 2: μ, m^2/(V·s)	Sample 3: n, 10^{12} cm^{-2}	Sample 3: μ, m^2/(V·s)	Sample 5: n, 10^{12} cm^{-2}	Sample 5: μ, m^2/(V·s)
1	4.25	0.124	4.47	0.125	4.10	0.087
2	2.82	0.127	2.61	0.13	2.24	0.107
3	1.66	0.123	2.21	0.124	1.40	0.270
4	0.90	0.90	0.77	0.65	···	···
5	0.57	2.1	0.24	4.0	···	···

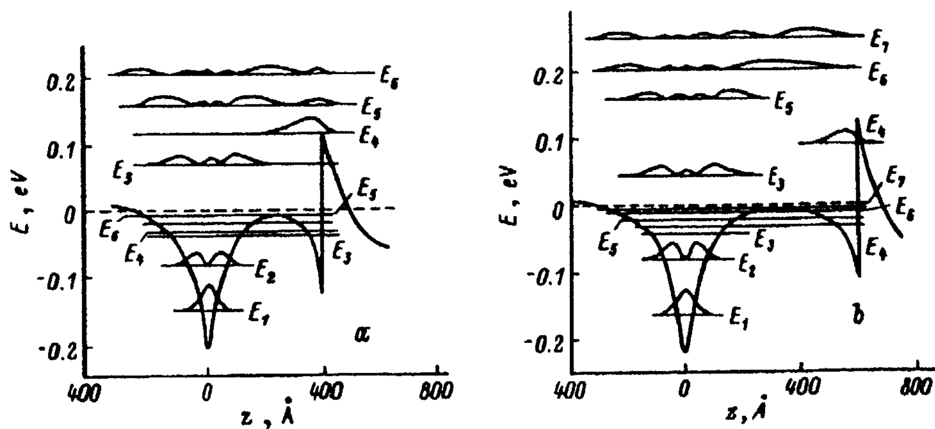

FIG. 5. Band diagrams for samples Nos. 2a and 3b.

third and fourth subbands (in samples 2 and 3) were determined in weak magnetic fields where oscillations from the low-mobility electrons can be disregarded. As a result, we determined the electron mobility and concentration in each subband. The results for samples 2, 3, and 5 are presented in Table I.

The experimental values obtained for the electron concentrations in the subbands were used to calculate the band diagrams of the structures. The profile $E_c(z)$ of the conduction band, the energy spectrum, and the wave functions for the system of coupled quantum wells (one well is formed by a heterojunction and the other by δ doping) in the region of the heterojunction were calculated by solving self-consistently the Schrödinger equation

$$[(\hbar^2/2m^*)d^2/dz^2+E_c]\psi_{sn}(z)=E_x\psi_{sn}(z) \tag{2}$$

and the Poisson equation

$$d^2E_c(z)/dz^2=-[N^+_{d(z)}-N^-_{a(z)}-nz]/\varepsilon\varepsilon_0. \tag{3}$$

Here $N^+_{d(z)}$, $N^-_{a(z)}$, and $n(z)$ are, respectively, the concentrations of the ionized donors, acceptors, and electrons and ε and ε_0 are the permittivities. The calculation was performed at $T=4.2$ K with the band cutoff parameter $\Delta E_c/\Delta E_g=0.6$, assuming a quadratic dispersion law. The donor concentration in the region of the δ layer and in the ternary doped compound n-GaAlAs were equated in the calculation to the sum of the experimental values of the electron concentrations in the subbands. The donor distribution in the δ layer was assumed to be 60 Å thick. The computational result is shown in Fig. 5 for heterostructures 2 and 5. The following tendency was found. The lower levels are localized in the δ layer, and the electron mobilities in them are quite low. The higher levels are localized at the heterojunction or are common levels, and the electron mobilities in them are quite high. As the distance of the δ layer from the heterojunction increases, more and more levels become localized in the δ layer, where the mobility of the electrons is lower. With the doping method employed by us, there is thus an optimal distance of the δ layer in the ternary compound from the heterojunction for which the electron concentration and mobility are high enough.

CONCLUSIONS

The synthesis technology and the composition of heterostructures were optimized on the basis of an investigation of the electrical properties of alternatively doped structures. This made it possible to obtain in the conducting channel an electron concentration close to that in the δ layer but with a higher mobility. Such a structure can be used for powerful field-effect transistors operating in strong electric fields. In this case a high electron density is very important, and it exceeds the existing analogs in the structures investigated by us.

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