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LOW-DIMENSIONAL SYSTEMS

Electron Transport in Coupled Quantum Wells with Double-Sided Doping

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Abstract—The conductivity and Hall mobility have been measured in heterostructures with coupled quantum wells (QW) as functions of temperature and the QW width. If a tunnel-transparent barrier is inserted in the middle of a QW, the mobility increases in narrow wells and decreases in wide wells. The experimental data have been compared with the calculated dependences. It has been shown that the number of filled quantum-well subbands depends on the well width and the presence of a barrier. The magnetoresistance and Hall resistance were measured at a temperature of 4.2 K in the range of magnetic fields of 1–40 T. The filling of subbands was determined from a Fourier analysis of the Shubnikov–de Haas oscillations, and good agreement with the calculated data was obtained. *© 2003 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

The electrical characteristics of AlGaAs/GaAs/AlGaAs quantum wells (QW) are of interest both for fundamental physics and commercial applications. These structures are widely used nowadays in the fabrication of photodetectors, optical modulators, high-power transistors, etc. A QW located between symmetrical AlGaAs barriers makes it possible to obtain the desired spectral characteristics of optoelectronic devices. Quite often, the parameters of these structures are improved by using coupled QWs produced by dividing a GaAs QW with a thin, about 3–4 monolayers (ML) thick, AlAs barrier [1, 2].

In field-effect transistors (FETs) for microwave applications, the double-sided doping of AlGaAs/GaAs/AlGaAs structures provides considerable enhancement of the output power [3–5]. In this type of heterostructure, the phonon spectrum is quantized similarly to the electron energy spectrum. According to calculations [6], this effect should suppress the electron–phonon scattering and thus enhance the mobility of electrons. As follows from theoretical calculations [7, 8], at a certain QW size, the insertion of a thin AlAs barrier should considerably reduce the rate of intrasubband scattering and may lead to an additional increase in mobility. This can further improve the transistor characteristics. All these facts show that the study of QWs with thin barriers is topical.

In this report, we present results concerning electron transport in AlGaAs/GaAs/AlGaAs structures with QWs of different widths. To perform a comparative analysis, similar structures were grown without a barrier and with a thin AlAs barrier in the middle of a QW. Components of the resistivity tensor were measured as functions of the magnetic field intensity at 4.2 K in a quantizing magnetic field.

2. SAMPLE PREPARATION AND MEASUREMENT PROCEDURE

The samples were grown by MBE on semi-insulating (100) GaAs substrates misoriented by 2° in the [110] direction. First, a 0.5-μm-thick GaAs buffer layer was grown. Then, an $Al_{0.2}Ga_{0.8}As$ barrier, a GaAs QW, an ~1.8-nm-thick AlAs barrier, a GaAs QW, and an $Al_{0.2}Ga_{0.8}As$ barrier were grown. Finally, an 8-nm-thick GaAs capping layer was grown. Both QWs in the structure had the same width. Several parameters of the samples under study, including the AlAs barrier thickness *d* and the total width of the QWs *W*, are listed in the table. The thickness of the AlGaAs barriers was the same (33 nm) in all the structures. One half (across the thick-

Surface densities n_H and mobilities μ_H of electrons as defined from the Hall measurements at a temperature of 4.2 K

Sample no.	*W*, nm	*d*, nm	n_H, 10^{12} cm^{-2}	μ_H, cm^2 V^{-1} s^{-1}
2	13	0	1.33	10000
3	13	1.8	1.31	12800
4	26	0	2.07	11900
5	26	1.8	2.09	12500
6	35	0	2.02	15000
7	35	1.8	2.02	13000

ness) of each barrier adjacent to the QW remained undoped, whereas the other half was doped with Si to ~10^{-18} cm^{-3}. The same concentration of Si was in the capping layer. GaAs and AlAs layers were grown at a temperature of 600°C, and AlGaAs, at 640°C. The ratio of As to Ga fluxes in the zone of growth was 30. For purposes of comparison similar structures were grown without a central AlAs barrier in the QW. As an example, Fig. 1 shows the band diagram calculated for sample 3.

Samples in the shape of Hall bridges were prepared for galvanomagnetic measurements. Temperature dependences of the resistance were measured in the range $4.2 < T < 300$ K, as was the Hall effect at 4.2 K and in the range $77 < T < 300$ K. The temperature dependences of the Hall density of electrons in the structure, n_H, and their mobility μ_H were determined in the temperature range $77 < T < 300$ K. The values of these parameters at 4.2 K for all of the structures are listed in the table. The resistance ρ_{xx} and Hall resistance ρ_{xy} were measured in the Hall bridges at liquid helium temperature in a magnetic field up to 40 T.

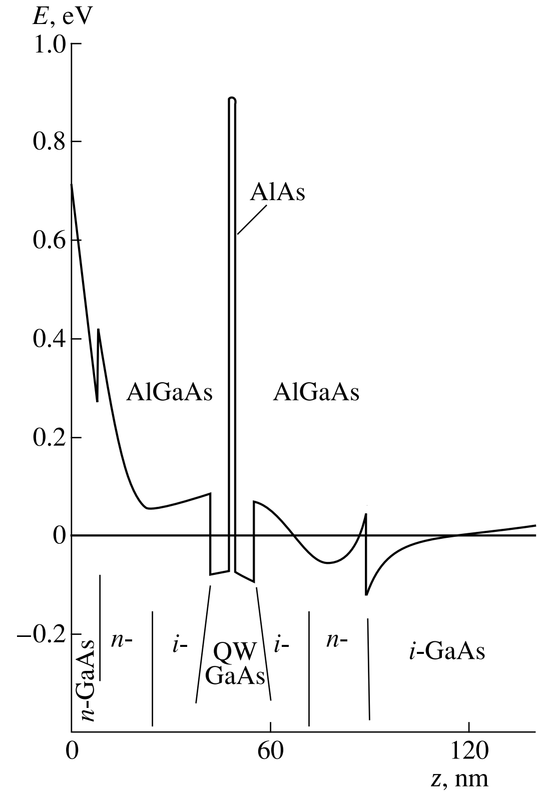

Fig. 1. The energy-band diagram of sample 3. The energy is reckoned from the Fermi level.

3. RESULTS AND DISCUSSION OF GALVANOMAGNETIC MEASUREMENTS

Figure 2 shows the resistance of structures versus temperature. In all samples, the resistance decreases with decreasing temperature to 60 K. At $T < 60$ K, the resistance of samples 5 and 6 slightly increases with decreasing temperature, which can be attributed to weak localization of carriers. The decreasing of the resistance with decreasing temperature in the range $T >$ 60 K is due to an increase in the electron mobility. Indeed, the measured Hall mobility μ_H increases with decreasing temperature (Fig. 3). It is easily seen that the insertion of an AlAs barrier raises the Hall mobility in a narrow QW with $W = 13$ nm. As the temperature decreases, the mobility ratio μ_{H3}/μ_{H2}, where μ_{H2} and μ_{H3} are, respectively, the Hall mobilities in samples 2 and 3, increases (Fig. 3). With temperature varied in the range 77 K $< T <$ 280 K, the ratio of mobilities is within the range $1.21 > (\mu_{H3}/\mu_{H2}) > 1.06$. At the same time, the insertion of a barrier in both of the wide QWs reduces the mobility in comparison with samples without a barrier (Fig. 3). However, the temperature dependences of the ratio of mobilities are different in these cases. In the same temperature range, the samples with $W = 26$ nm demonstrate $1.05 < (\mu_{H4}/\mu_{H5}) < 1.206$; i.e. the ratio decreases with decreasing temperature. However, in the samples with $W = 35$ nm we have $1.176 < (\mu_{H6}/\mu_{H7}) <$ 1.1; i.e. the ratio increases with decreasing temperature. As is seen, these variations are not great; they do not exceed 15% in the entire temperature range.

In all of the samples, the Hall density decreases with decreasing temperature (Fig. 4). It can be inferred that the observed $n_H(T)$ dependence is related to the specific features of the band structure of the samples under study. As is seen from the band diagram (Fig. 1), the sample conductance consists of the conductances of the potential well on the substrate side, the doped parts of the AlGaAs barriers, and a QW. As is known, the Hall

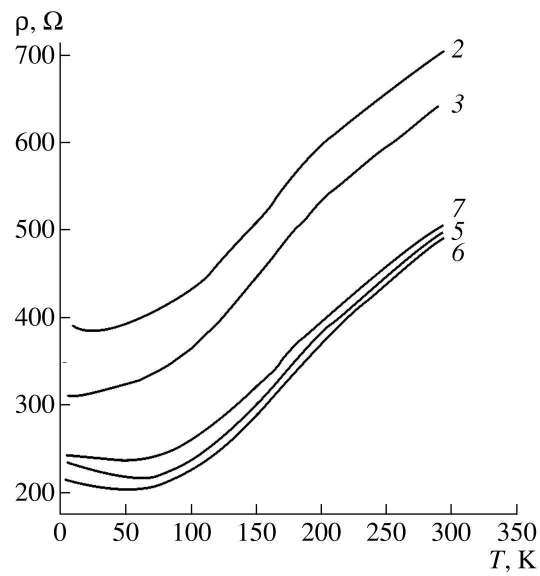

Fig. 2. Temperature dependences of the resistance of structures under study. Curve numbers correspond to sample numbers in the table.

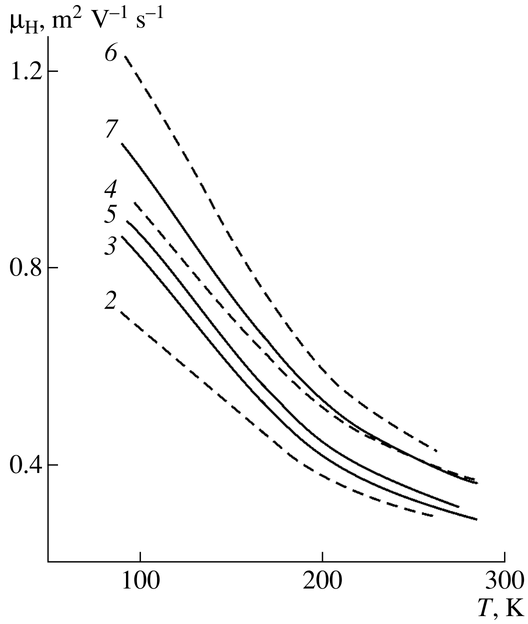

Fig. 3. Temperature dependences of the Hall mobility of electrons μ_H in different samples. Curve numbers correspond to sample numbers in the table. Solid and dashed lines: samples with and without an AlAs barrier in the QW, respectively.

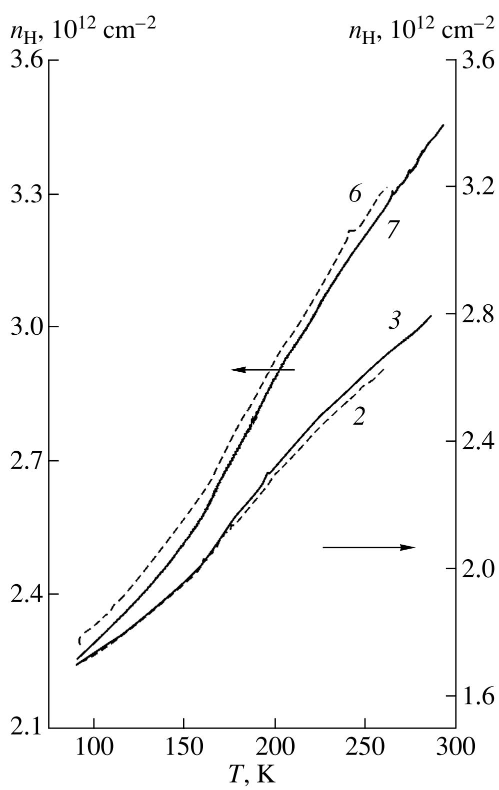

Fig. 4. Temperature dependences of the Hall density of electrons in samples 2 and 3 with a narrow (W = 13 nm) QW, and 6 and 7 with a wide (W = 35 nm) QW. Curve numbers correspond to sample numbers in the table.

mobilities and densities in layered structures are determined from the relations

$$\mu_H = \frac{\sum_i \gamma_i \mu_i^2 n_i}{\sum_i \mu_i n_i}, \quad n_H = \frac{\left(\sum_i \mu_i n_i\right)^2}{\sum_i \gamma_i \mu_i^2 n_i}, \qquad (1)$$

where μ_i, n_i are the mobility and surface density of electrons in the layers; γ_i is the Hall constant; and i is the index of summation over the layers. The solution to a system of self-consistent Kohn–Sham equations for the potential and quantum wells, similar to that obtained in [9], shows that the electron density changes only slightly with temperature. Calculations show that the electron gas is either degenerate or nearly degenerate in all the samples in the temperature range under study. Therefore, in our calculations, we assumed that $\gamma_i = 1$. In this case, it is easily shown using (1) that the decrease in the Hall density with decreasing temperature is due to a decrease in the ratio

$$\frac{\mu_3 n_3}{\mu_1 n_1 + \mu_2 n_2}, \qquad (2)$$

where the parameters with indices 1 and 2 refer to, respectively, the potential and quantum wells, and index 3, to the doped section of the AlGaAs barrier. At a temperature of 4.2 K, the mobility in the doped barrier is very small and the conduction in this layer can be disregarded. Then, (1) yields the relation $n_1 < n_H < n_1 + n_2$. The proximity of n_H to one limit or another depends on the ratio $p = \mu_2/\mu_1$.

The solution of the system of self-consistent Kohn–Sham equations for the surface densities in the wells yields $n_1 = 1.2 \times 10^{12}$ cm^{-2} and $n_2 = 1.06 \times 10^{12}$ cm^{-2}. Using (1) and the data for T = 4.2 K listed in the table, we obtain the mobility ratios: $p \approx 0.1$ for narrow QWs and $p \approx 0.6$ for wide wells. At the same time, at high temperatures, $n_1 < n_H < n_1 + n_2 + n_3$. As is seen in Fig. 4, the value of n_H in wide QWs is close to the total electron density in a structure. For narrow QWs, n_H is significantly smaller (Fig. 4). This results from a lower mobility of electrons in narrow QWs.

The samples under study were grown in approximately the same conditions. Therefore, the electron mobilities and densities in the barriers and QWs for all of the structures must be approximately the same. Then, as can easily be shown from (1), the value of μ_2 must be higher in the structure with larger $n_H\mu_H^2$. As is seen in Fig. 4, the n_H values virtually coincide in the structures with and without a barrier. Therefore, the ratio between the values of μ_H in the structures with and without a barrier qualitatively reflects the ratio between the values of μ_2 in these structures. Hence, the insertion of an AlAs barrier raises μ_2 in narrow QWs and reduces it in wide wells. Further, as is seen in Fig. 3, μ_2 at $T >$ 77 K increases with increasing W regardless of the presence of an AlAs barrier.

A weak temperature dependence of ρ indicates that the observed dependences of μ_H and, correspondingly, μ_2 on the structure parameters are due to the quantum confinement. The influence of the width of a rectangular QW on mobility has been widely discussed in the literature (see [7] and references therein), and it was shown that $\mu_2 \propto W$ in moderately wide wells. This is not quite the case when there is a high electron density and, correspondingly, when a potential profile is present in a well. The scattering on polar optical phonons prevails in GaAs at $T > 77$ K. In this case, as is shown in [10], when there is a single filled quantum-well subband

$$\mu_2 \propto \left[\int \psi^4(z)dz\right]^{-1}, \quad (3)$$

where ψ is the wave function in the direction of quantum confinement. The dependence $\mu_2 \propto W$ is a particular case of (3) for a rectangular well. The solution of the system of self-consistent Kohn–Sham equations for the structures under study shows that the number of filled subbands in different samples is different: one in sample 3; two in samples 2, 4, and 5; and three in samples 6 and 7. A direct extension of (3) to the case of several filled subbands is the relation

$$\frac{\mu_2}{\mu_{20}} = \sum_j \alpha_j \left[\int \psi_j^4(z)dz\right]^{-1}, \quad (4)$$

where μ_{20} is the mobility in an extremely wide QW, α_j is the relative filling of a subband with electrons, and the summation is done over all of the quantum-well subbands. Figure 5 shows the dependences of the ratio μ_2/μ_{20} on the width of a QW without a barrier and with a 1.8-nm-thick AlAs barrier, calculated for $T = 100$ K using relation (4). In the calculation, the subbands with a relative filling greater than 0.03 were taken into account. The number of such subbands for each of the samples was indicated above. The calculation also shows that the dependences vary only slightly in the temperature range $77 < T < 300$ K. The results obtained in solving the system of self-consistent Kohn–Sham equations were used for the calculation. As is seen, the dependences are in qualitative agreement with the experimentally determined ratios of the Hall mobilities. Further, calculation by Eq. (4) yields $\mu_{23}/\mu_{22} = 1.11$, $\mu_{26}/\mu_{27} = 1.13$, and $\mu_{24}/\mu_{25} = 1.1$, where the second index is the sample number. As is seen, these values fall within the range of variation of the ratios between the measured Hall mobilities.

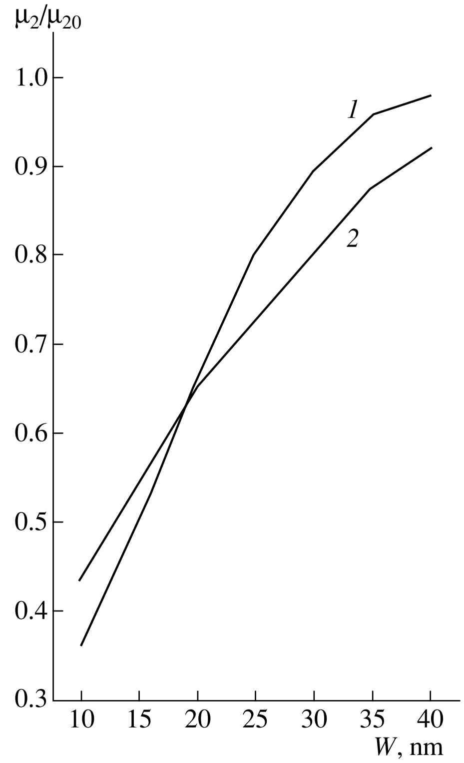

Fig. 5. Dependences of the normalized mobility μ_2/μ_{20} (see Eq. (4)) on the QW width: (*1*) without a barrier; (*2*) with a 1.8-nm-thick AlAs barrier. μ_2 is the mobility in the first subband of a GaAs QW, and μ_{20} is that in a very wide QW.

4. MAGNETOTRANSPORT IN A QUANTIZING MAGNETIC FIELD

Figure 6 shows the dependences of resistance ρ_{xx} and Hall resistance ρ_{xy} on the magnetic field intensity B for samples 6 and 7. At 4.2 K, the magnetic field with an intensity $B > 0.2$ T is a quantizing field in GaAs. Indeed, Shubnikov–de Haas oscillations were observed in all samples. However, they are not periodic in an inverse magnetic field $1/B$. This is due to the presence of two QWs in a structure with several filled quantum-well subbands. To determine the filling of these subbands, we performed a Fourier transform of the $\rho_{xx}(1/B)$ dependences for samples 6 and 7. The surface densities of electrons in the subbands were calculated from the frequencies F corresponding to the Fourier spectra peaks using the relation for the electron density

$$n = \frac{qF}{\pi\hbar}. \quad (5)$$

The insets to Fig. 6 show the Fourier spectra (for samples 6 and 7) as functions of density n, with two peaks clearly seen. The more pronounced peak corresponds to $n = 1.08 \times 10^{12}$ cm^{-2}. This value is close to the calculated filling of the potential well (see above). The second peak corresponds to $n = 4.5 \times 10^{11}$ cm^{-2} and 5.3×10^{11} cm^{-2} for samples 6 and 7, respectively. The

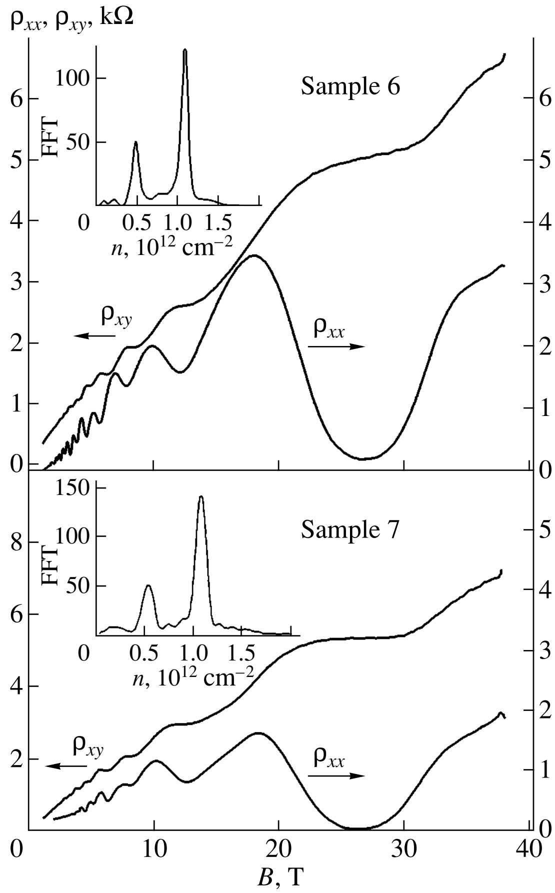

Fig. 6. The magnetoresistance and Hall resistance of samples 6 and 7 at a temperature of 4.2 K. Insets: Fourier spectra of the ρ_{xx} oscillations.

calculated fillings of three quantum-well subbands in a QW are as follows: 4.7×10^{11}, 4.4×10^{11}, and 1.5×10^{11} cm^{-2} for sample 6; and 4.6×10^{11}, 4.5×10^{11}, and 1.6×10^{11} cm^{-2} for sample 7. As is seen, the second peak for both samples corresponds to two subbands with nearly the same filling. This degeneracy of subbands is due to the QW symmetry. As is seen in Fig. 1, such a QW has two potential wells near the heterojunctions. At low temperatures, the wave functions of the lowest energy levels are weakly coupled and the energies of the levels become close. Calculations show that, with rising temperature, the levels diverge, and the higher the temperature the stronger their fillings. The total surface density of electrons in a QW remains virtually unchanged in this situation. A weak peak is observed for sample 6 in the range of small n. This peak is presumably related to the third filled subband. It may be assumed that a similar peak for sample 7 merges with the zero-frequency component of the Fourier spectrum. We believe that the presence of this feature leads to a shift of the peak corresponding to two filled subbands for sample 7 to higher n values.

As is seen in Fig. 6, the average value of $\rho_{xx}(B)$ increases almost linearly with increasing magnetic field in the range $B < 8$ T. Similar dependences were also observed in other samples. It is known that the classical magnetoresistance of degenerate 2D electron gas with one filled subband equals zero. The only known mechanism responsible for a positive magnetoresistance is the filling of several subbands with different mobilities or the presence of several layers in the system. As is shown in [11], the average values of $\rho_{xx}(B)$ and $\rho_{xy}(B)$ of 2D electrons in a quantizing magnetic field are described by the same relations. Therefore, for a structure with two conducting layers, we obtain

$$\delta = \frac{\rho_{xx}(B)}{\rho_0} - 1 = \frac{a}{p}\frac{x^2(p-1)^2}{(1+ap)^2 + x^2(1+a)^2},$$

where $a = n_2/n_1$ and $x = \mu_2 B$. This dependence is quadratic in the weak field range, when $x \ll 1$. In a high field, the magnetoresistance tends to a limiting value and

$$\delta_{max} = \frac{a}{p}\left(\frac{p-1}{a+1}\right)^2.$$

Our calculations yield $a \approx 0.85$ and $d_{max} \approx 0.066$ for samples 6 and 7. In contrast, almost linear $\rho_{xx}(B)$ dependences are observed in experiment. At $B = 5$ T, we obtain $\delta = 2.7$ and $\delta = 1.6$ for samples 6 and 7, respectively. The reasons for such a large magnetoresistance and the significant disagreement with theory are still unclear.

5. CONCLUSION

The temperature dependences of the conductance and mobility of electrons in coupled quantum wells of various widths have been studied. As is shown, these quantities increase as the well width increases in the entire temperature range under study. The insertion of a thin AlAs barrier reduces the electron mobility in wide QWs and raises it in narrow ones. The variation in mobility is due to the changing intensity of the electron–phonon coupling. This results from the strong reconstruction of the electron wave functions and a change in the energy spectrum upon the insertion of an AlAs barrier.

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