Intersubband scattering in n-GaAs/AlGaAs wide quantum wells

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Abstract

Slow magnetooscillations of the conductivity are observed in a 75 nm wide quantum well at heating of the two-dimensional electrons by a high-intensity surface acoustic wave. These magnetooscillations are caused by intersubband elastic scattering between the symmetric and asymmetric subbands formed due to an electrostatic barrier in the center of the quantum well. The tunneling splitting between these subbands as well as the intersubband scattering rate are determined.

I. INTRODUCTION

Quantum structures with more than one occupied levels of size quantization represent an intermediate case between ultra-quantum and bulk systems. A presence of a few two-dimensional subbands allows studying interactions between electronic states of different types. An interesting example is intersubband scattering by a disorder potential. The typical systems with a few levels are quantum wells with two or more subbands under the Fermi level and double quantum wells. There is also another type of structures, doped wide quantum wells (WQWs). They represent a bilayer system because the Coulomb repulsion results in a potential barrier in the middle of the WQW pushing the carriers towards the interfaces [1]. If these two layers are independent, they act in transport as two parallel conducting channels. These two channels are identical with equal Fermi energies and relaxation times provided the WQW is perfectly symmetric. In contrast, when tunneling through the potential barrier is not negligible, these two channels interact to each other, and the system’s eigenstates are the symmetric (S) and anti-symmetric (AS) states with the tunneling energy gap $\Delta_{\text{SAS}}$. This gap has been studied in a variety of WQWs, for a review see Ref. [2]. Usually $\Delta_{\text{SAS}}$ is determined from the Fourier analysis of the magnetoresistance in the region of weak magnetic fields $B < 0.5$ T.

The presence of two channels results in a reach picture of conductivity oscillations in quantizing magnetic fields. In addition to the usual Shubnikov-de Haas effect, the other type of magnetooscillations periodic in $1/B$ takes place. These oscillations are caused by elastic scattering between the S and AS subbands, the so-called magneto-intersubband oscillations (MISO). They appear at $\Delta_{\text{SAS}}/\hbar\omega_c = K$, where $\omega_c$ is the cyclotron frequency and $K$ is an integer number. Since this condition does not contain the Fermi energy, MISO are not damped by the Fermi distribution smearing. Therefore, in contrast to the Shubnikov-de Haas oscillations, MISO amplitude is almost insensitive to the temperature increase. MISO are well studied in various systems with two or three occupied subbands, for a review see Ref. [3] and references therein. Recently, a temperature dependence of MISO amplitude in a quantum well with three populated subbands has been explained by temperature variation of quantum electron lifetime [4], an energy spectrum reconstruction by a parallel magnetic field has been shown to affect MISO strongly [5, 6], and the thermoelectric power magnetophonon resonance has been studied in two-subband quantum wells [7].

MISO are possible to observe only if they are not superimposed on the Shubnikov-de Haas oscillations. However both types of oscillations are present in the same magnetic field range in high-mobility WQWs. The Shubnikov-de Haas oscillations can be damped by increase of temperature. However, heating of the sample in dc regime also results in an increase of the lattice temperature. This leads to an enhancement of electron scattering by phonons which damps MISO as well. Therefore MISO in high-mobility WQWs have not been observed so far.

We used acoustic methods with a surface acoustic wave (SAW) of high intensity applied in the pulsed regime with the duty factor equal to 100. This allowed heating of the electron system up to $T > 500$ mK while the lattice temperature was kept 20 mK. As a result, the Shubnikov-de Haas oscillations were damped, and clear MISO were observed. We analyzed MISO in WQWs and determined the energy gap $\Delta_{\text{SAS}}$ and the intersubband scattering rate. We show that the theory of magnetooscillations describes well the experimental data.

II. EXPERIMENT

The high quality samples were multilayer n-GaAlAs/GaAs/GaAlAs structures with a 75 nm wide quantum well. The quantum GaAs well was $\delta$-doped on both sides and located at the depth $\approx 197$ nm below the surface of the sample. While cooling the sample down to 15 K and illuminating it with infrared light of emitting diode, we achieved the electron density of $1.4 \times 10^{11}$ cm$^{-2}$.
and the mobility of $2.4 \times 10^7 \text{ cm}^2/(\text{Vs})$ (at $T = 0.3 \text{ K}$).

In the present paper we employ a SAW technique \cite{8, 9} illustrated in Fig. 1. A sample is pressed by means of springs to the surface of a piezoelectric crystal of lithium niobate (LiNbO$_3$), on which the interdigitated transducers (IDT) are formed. A radio frequency electrical pulse signal is applied to one of the IDTs. Due to the piezoelectric effect, a SAW is generated and propagates along the surface of LiNbO$_3$. Simultaneously, an ac electric field, accompanying the SAW and having the same frequency, penetrates into the sample and interacts with the charge carriers. This interaction results in a change of the SAW amplitude and in its velocity. The measurements were carried out in a dilution refrigerator in a magnetic field perpendicular to the sample plane.

A. Experimental results

The dependences of the attenuation $\Gamma(B)$ and the relative velocity change $\Delta v(B)/v_0$ of the surface acoustic wave were measured in a magnetic field of up to 1 T in the temperature range 20–500 mK and the frequency range 28.5–300 MHz at different SAW intensities. Figure 2 shows the experimental dependencies of the SAW attenuation $\Gamma$ and velocity shift $\Delta v/v_0$ at the frequency 30 MHz, measured at the temperature $T \approx 20 \text{ mK}$ with the SAW power introduced into the sample of $1.2 \times 10^{-6} \text{ W/cm}$. During the measurements, the magnetic field was swept from $-1$ to 1 T (red curve), and then went back to $-1$ T (blue curve) ramping as 0.05 T/min. The curves of these forward and reverse field sweeps are almost identical. A Hall probe was used to measure the magnetic field strength.

The SAW attenuation and the velocity change are governed by the complex ac conductance $\sigma(\omega) \equiv \sigma_1(\omega) - i\sigma_2(\omega)$. Both the real $\sigma_1$ and imaginary $\sigma_2$ components of $\sigma(\omega)$ could be extracted from our acoustic measurements. The procedure of the determination of the ac conductance is described in Ref. [9] and is based on using that work Eqs. (1)–(7).

The dependences of the real part $\sigma_1$ of the high-frequency conductance, calculated from the SAW attenuation and velocity change, on the reversed magnetic field $1/B$ measured at various temperatures from 20 mK to 510 mK are presented in Fig. 3(a). The dependences $\sigma_1(1/B)$ recorded at several SAW intensities are plotted in Fig. 3(b), where effective SAW power introduced into the sample ranged from $3.7 \times 10^{-10} \text{ W/cm}$ to $3.7 \times 10^{-5} \text{ W/cm}$.

As seen in Fig. 3, the Shubnikov - de Haas oscillations are observed at low SAW intensities. These fast oscillations undergo a beating. At high temperatures their amplitudes decrease. Moderate increasing of the SAW power affects the real part of ac conductance $\sigma_1$ in the same way as the temperature rising does, see Fig. 3(b). However, with further growth of the SAW power, these fast oscillations virtually vanish, and the slow oscillations emerge. The latter dominates at the highest SAW intensities. The positions of the slow oscillations minima are independent of the SAW frequency. We assume that the slow oscillations are not distinguishable in Fig. 3(a) due to the small signal-to-noise ratio in the low-power regime used when we acquired the curves presented in this figure.

The structure of the fast and slow oscillations is presented in more detail in Fig. 4. Here the dependence of $\sigma_1(B)$ is shown for $f = 30 \text{ MHz}$ at 20 mK, the SAW power pushed into the sample was $1.2 \times 10^{-6} \text{ W/cm}$. This picture demonstrates the SdH oscillations marked with filling factors $\nu$. In lower fields $B < 0.4 \text{ T}$, one can observe a new series of oscillations denoted by letter $K$.\n
\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{(Color online) Sketch of the experimental setup.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{(Color online) Dependences of the SAW attenuation coefficient $\Gamma$ (top panel) and the SAW velocity change $\Delta v(B)/v_0$ (bottom panel) on the transverse magnetic field $B$ at $f = 30 \text{ MHz}$, $T = 20 \text{ mK}$; SAW power introduced into the sample is $1.2 \times 10^{-6} \text{ W/cm}$. Red and blue curves (almost identical) show forward and reverse field sweeps.}
\end{figure}
FIG. 3. (Color online) (a) Dependences of $\sigma_1$ on the inverse magnetic field as varied with temperature at the SAW power introduced into the sample of $3.7 \times 10^{-10}$ W/cm, and (b) as varied with the SAW powers at $T=20$ mK: 1 - $3.7 \times 10^{-10}$ W/cm, 2 - $1.2 \times 10^{-8}$ W/cm, 3 - $1.3 \times 10^{-7}$ W/cm, 4 - $3.6 \times 10^{-7}$ W/cm, 5 - $1.2 \times 10^{-6}$ W/cm, 6 - $2.3 \times 10^{-6}$ W/cm, 7 - $5.9 \times 10^{-6}$ W/cm, 8 - $1.2 \times 10^{-5}$ W/cm, 9 - $3.7 \times 10^{-5}$ W/cm; $f = 30$ MHz. Traces are offset vertically for clarity.

III. DISCUSSION

From the analysis of the slope of the dependence $\nu(1/B)$ shown in the inset (b) of Fig. 4 we determined the Fermi energy in the studied WQW as $E_F \approx 2.5$ meV.

The slow oscillations demonstrate a presence of an energy gap $\Delta \ll E_F$ in the electronic spectrum. We extracted this splitting from the dependence $K(1/B)$ drawn in the inset (a) of Fig. 4: $\Delta = 0.42 \pm 0.02$ meV.

In order to explain an origin of this energy splitting, we performed self-consistent calculations of the electrostatic potential and electron wavefunctions. First, the wave functions are calculated in the tight-binding approach [10]. Then, the electron wave functions are used to calculate the electron density distribution in the quantum well. Neglecting the dependence of the wave function on the lateral wave vector, the density is given by the following equation:

$$n(z) = \frac{n_{\text{total}}}{4} \sum_{i,s} |\psi_{i,s}(z)|^2,$$

where $\psi_{i,s}(z)$ is the wave function of a spin up(down) electron at $i$-th quantum confined level. The Fermi level lies between 2nd and 3rd levels, so the summation is performed over the first two subbands. The value of the total electron density extracted from our experiment is $n_{\text{total}} = 1.4 \times 10^{11}$ cm$^{-2}$. To compensate the charge inside the WQW and make the structure uncharged, we assumed that the charge $-n_{\text{total}}/2$ is uniformly distributed in the barriers starting from the position where the distribution of electron density $n(z)/n_{\text{total}}$ drops below $10^{-4}$. The electrostatic potential corresponding to the charged QW is found from the numerical solution of Poisson equa-
with the dielectric constant $\varepsilon = 12.9$. Then, we add $\phi(z)$ to the structure potential and compute the next approximation for the electron wave functions of the levels in the WQW. The procedure is repeated until the self-consistency of the electron wave functions and electrostatic potential is reached.

The results for the converged potential and the electron density distribution are presented in Fig. 5. The position of the first two levels is close to the local maximum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a). This fact makes a convergence of the calculation scheme slow for our quantum of the heteropotential, Fig. 5(a).

The calculated S-AS splitting $\Delta_{SAS} = 0.57$ meV. In the triangular quantum wells formed near the structure edges, Fig. 5(a), the spin-orbit splitting is present which can give rise to the beating pattern in magnetooscillations [12, 13]. Our tight-binding method allows also to estimate the spin splittings of the two first subbands caused by the quantum confinement and electric field in the structure [14]. The calculations show that the spin-orbit splitting of the electronic states at the Fermi wavevector is $\Delta_{so} \approx 0.01$ meV in the WQW under study. Since $\Delta_{so} \ll \Delta_{SAS}$, we conclude that the spin-orbit splitting is negligible at so low carrier density.

The calculated S-AS energy splitting $\Delta_{SAS} = 0.57$ meV is close to the value $\Delta \approx 0.42$ meV determined from the experiment. Therefore we conclude that it is the intersubband scattering that results in slow magnetooscillations of the heated electron gas in the WQW under study.

The conductivity magnetooscillations with account for both S-AS splitting and scattering between S and AS subbands are described by the following expression [3, 15]:

$$\sigma_{xx} = \sigma_0 \left( \frac{\omega_c}{\tau} \right)^2 \left[ 1 - 4 \cos \left( \frac{2\pi}{\hbar \omega_c} \right) + \frac{\omega_c}{\hbar} \sinh \frac{X}{\sinh X} + 2 \frac{\tau}{\tau_{SAS}} \right]. \quad (3)$$

Here $\sigma_0$ is the conductivity at zero magnetic field, $\tau$ is the transport scattering time which determines the mobility, $\tau_q$ is the quantum scattering time, $\omega_c$ is the cyclotron frequency, and $X = 2\pi^2 k_B T / \hbar \omega_c$. The time $\tau_{SAS}$ is the time of elastic scattering between the S and AS subbands. This expression is valid in moderate magnetic fields where $e^{-\pi/\omega_c \tau_q} \ll 1$ but $\omega_c \tau \gg 1$, and at weak intersubband scattering, $\tau / \tau_{SAS} \ll 1$. The first oscillating term in Eq. (3) describes the beating pattern in the Shubnikov-de Haas oscillations in the two-subband system with close Fermi energies $E_F \pm \Delta_{SAS}/2$. These beatings are damped by heating of the electron gas due to smearing of the Fermi distribution as described by the factor $X/\sinh X$. In contrast, the second oscillating term caused by MISO, being inferior at low temperatures, dominates at high temperatures when $X/\sinh X \ll e^{-\pi/\omega_c \tau_q}$ [16, 17]. Eq. (3) indicates that the beating frequency to be two times smaller than that for the slow oscillations. Indeed, this is observed in our experiment, Fig. 3.

We estimated an intensity of intersubband scattering from the amplitude of MISO. Analysis of the data at the SAW powers $1.2 \times 10^{-6}$ W/cm and $1.3 \times 10^{-7}$ W/cm with help of Eq. (3) yields $\tau / \tau_{SAS} = 0.35 \pm 0.05$ and $\tau_q = 4 \times 10^{-11}$ s. The value of $\tau_q$ agrees with the quantum scattering time determined for similar WQWs [4]. The transport scattering time is known from mobility: $\tau = 0.9 \times 10^{-9}$ s at 0.3 K. This yields $\tau_{SAS} = 2.6 \times 10^{-9}$ s. The intersubband scattering time three times longer than the transport scattering time means that the intersubband scattering in the studied WQW is weaker than the intrasubband scattering but it is strong enough for observation of MISO.
IV. CONCLUSION

To conclude, we observed the magneto-intersubband oscillations of the conductivity in a WQW. The oscillations are shown to arise due to elastic intersubband scattering between the $S$ and $AS$ subbands formed due to Coulomb repulsion between the electrons. A tight-binding calculation of the electron states yields the splitting $\Delta_{SAS}$ close to the experimentally measured value. Our theoretical description of the magnetooscillations allowed to determine the quantum and the intersubband scattering times.

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