ANISOTROPY OF THE EFFECTIVE MASS OF 2D ELECTRONS IN A HETEROJUNCTION WITH A LATERAL SUPERLATTICE ON VICINAL FACES

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UDC 537.311.33

The anomalous shift in the maxima of the Shubnikov–de Haas transverse magnetoresistance oscillations in AlGaAs(Si)/GaAs with 2D electrons oriented in the [110] direction with respect to [110] in large magnetic fields is explained by the formation of a lateral superlattice with an increase of the effective mass \(m_{[110]}^* > m_{[110]}^*\).

It has been shown [1] that the introduction of a period potential in the \((x, y)\) plane into a heterostructure with 2D electrons leads to the formation of various electronic states, for example lateral superlattices. A periodic potential in the plane \((x, y)\) of a nanostructure layer is created by either alternation of the growth of narrow-band (GaAs) and wideband (AlAs or AlGaAs) semiconductors on a faceted surface [2, 3] or inclusion of wideband material (a fraction of a monolayer) in a narrowband host [4].

The synthesis of an AlGaAs(Si)/GaAs heterostructure with a single heterojunction containing a two-dimensional electron gas was reported in [5]. The structure was grown by molecular beam epitaxy on a strongly misoriented substrate of semiconducting gallium arsenide. The misorientation angle reached 10° on the (001) to (110) planes. This led to formation of a heteroboundary in the form of steps with a (001) plateau elongated in the [110] directions, running equidistantly in the [110] direction with a step of 16.6 Å. The main feature of the measured magnetokinetic coefficients consists in the strong anisotropy in the [110] and [110] directions.

The most interesting experimental fact, in our view, is the shift of the extrema of the Shubnikov–de Haas (ShdH) oscillations oriented in the [110] and [110] directions (\(\perp\) - and \(\parallel\) -samples in what follows). This shift in the oscillation curves is illustrated in Fig. 1 for \(\perp\) - and \(\parallel\) -samples of the two structures.

We identified the maxima of the oscillations proceeding from the resonance condition

\[
\xi_f = b \omega (N + 1/2),
\]

according to the ratios for the \(N\)-th and \((N+1)\)-th Landau levels

\[
N = (1.5B_{\perp}^{-1} - 0.5B_{\parallel}^{-1}) / \Delta (1/B),
\]

where \(\xi_f\) is the Fermi energy, \(\omega = (e/m^*)B\) is the cyclotron frequency, \(\Delta (1/B)\) is the ShdH oscillation period. The positions \(1/B_{\parallel}\) of maxima for the \(\parallel\) -samples correspond to integer values of \(N\) while the positions \(1/B_{\perp}\) of the \(\perp\) -samples have values close to half-integers. Thus the positions denoted by arrows correspond for \(\parallel\)-samples (Fig. 1a) to \(N = 3.96, 4.97,\) and 6.01 while for \(\perp\) samples \(N = 3.57, 4.60,\) and 5.60. For structure No. 2 (Fig. 1b) \(\parallel\)-sample \(N = 4.08, 5.10,\) and 6.06 and for the \(\perp\) sample \(N = 3.7, 4.6,\) and 5.5. The numerical values of \(N\) are given for the maxima denoted by \(\bigcirc\) and \(\blacksquare\) with arrows in Fig. 1a and b respectively.

The shifts of the oscillation extrema shown in Fig. 1 for the \(\perp\) -samples relative to the \(\parallel\) -samples in the ShdH oscillations of the transverse magnetoresistance were seen without exception in our investigated structures on the vicinal faces.

This is shown for example in a number of structures in Fig. 2. It should be noted that the oscillation period \( \Delta(1/B) \) and consequently also the 2D electron concentration for \( \perp \)- and \( \parallel \)-samples is the same. The phase of the oscillations is \( \varphi = -0.3\pi \) which is characteristic of two-dimensional electron systems [6]. The absolute value of the shift \( \Delta B_N = B_N(\perp) - B_N(\parallel) \) for \( N = 3-4 \) amounts to \( \approx 0.1 \) Tesla, while the relative shift for \( N = 3-5 \) is \( B_N(\perp)/B_N(\parallel) = 0.83-0.94 \).

We propose the presence of a built-in periodic potential created by the profiling of the heterojunctions on the vicinal faces. On the other hand, there is texturing in the \( [110] \) direction and distortion of the potential contour due to segregation of dopant impurities at the faces of the terrace steps. These factors are the basis for the formation of a lateral superlattice in the \( [110] \) direction with a period \( 16.6 \ \text{Å} \) and a corresponding change of the effective mass in this direction. In this case one should expect an anisotropic effective mass: for \( [110] \) \( m^*_\parallel \) and for \( [110] \) \( m^*_\perp \). The anisotropy of the effective mass is also the cause of an anomalous shift in the oscillation extrema for the magnetoresistance of the \( \parallel \)-samples relative to the \( \perp \)-samples.

Indeed, the resonance condition (1) for the \( N \)-th Landau level for electrons in magnetic subbands with different effective masses will be satisfied in different magnetic fields

\[
\begin{align*}
\varepsilon_F &= \frac{e\hbar}{m^*_\perp} B_\perp (N + 1/2), \quad (3a) \\
\varepsilon_F &= \frac{e\hbar}{m^*_\parallel} B_\parallel (N + 1/2). \quad (3b)
\end{align*}
\]

From the latter it follows that

\[
B_\perp/B_\parallel = \frac{m^*_\parallel}{m^*_\perp}. \quad (4)
\]

The increase of the effective mass in the minibands of the lateral superlattice along the \( [110] \) direction is also the cause of the shift of the oscillation curves for \( \rho_{xx} \) in \( \perp \)-samples toward larger magnetic fields relative to oscillations of \( \rho_{xx} \) in \( \parallel \)-samples.

The anisotropy of the effective mass shows a weak (monotonic) dependence on the concentration of 2D electrons. The functional connection of the quantity \( \gamma_{m^*} = B_N[110]/B_N[110] \) with the concentration of 2D electrons for the structures studied are shown in Fig. 3.

It is natural to expect a correlation of the anisotropy \( \gamma_{m^*} \) of the effective mass with the anisotropies \( \gamma_{\sigma} \) of the conductivity and \( \gamma_{\mu} \) of the mobility. For \( n_0 < 5 \times 10^{11} \ \text{cm}^{-2} \) in heterosystems with misorientations of \( 1^\circ \) and \( 2^\circ \) with a built-in in two-dimensional channel in the AlAs layer the correlations of \( \gamma_{m^*}(n_0) \) with \( \gamma_{\sigma}(n_0) \) and \( \gamma_{\mu}(n_0) \) have been given in [4]. Unfortunately our structures with much stronger doping \( (n_0 > 5 \times 10^{11} \ \text{cm}^{-2}) \) also contain intentionally unannealed impurities (oxygen and hydrogen) on the initial substrate surface. In practice for most samples there was negative magnetoresistance involving the suppression of the weak localization by the magnetic field. Thus in experiments on measurement of the conductivity in fact one determines the effective conductivity \( \sigma = \sigma - \Delta \sigma \), where \( \Delta \sigma \) is the quantum correction to the conduc-