Magnetoresistance oscillations in GaAs/AlGaAs superlattices subject to in-plane magnetic fields

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Abstract

The MBE-grown GaAs/AlGaAs superlattice with Si-doped barriers has been used to study a 3D→2D transition under the influence of the in-plane component of applied magnetic field. The longitudinal magnetoresistance data measured in tilted magnetic fields have been interpreted in terms of a simple tight-binding model. The data provide values of basic parameters of the model and make it possible to reconstruct the superlattice Fermi surface and to calculate the density of states for the lowest Landau subbands. Positions of van Hove singularities in the DOS agree excellently with magnetoresistance oscillations, confirming that the model describes adequately the magnetoresistance of strongly coupled semiconductor superlattices.

Key words: superlattice, Fermi surface, magnetoresistance
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1. Introduction

A superlattice (SL) is a set of regularly spaced quantum wells, coupled together via tunneling across the barriers separating them. In such a system, electrons move freely parallel to the plane of the wells, while their perpendicular motion (i.e. that in the growth direction) gives rise to the existence of energy minibands, whose widths are proportional to the strength of interwell coupling. In a short-period SL, only the lowest miniband is usually occupied.

The quasiclassical interpretation of magnetotransport experiments relies on the Onsager-Lifshitz quantization rule [1,2]. For the longitudinal magnetoresistance, it leads to Shubnikov-de Haas oscillations, which are periodic in $1/B$ and the period is given by extremal cross-sections of the Fermi surface perpendicular to the direction of the applied field $B$. There is, however, experimental evidence, that the quasiclassical interpretation of the data may fail in semiconductor SLs in tilted fields. The failure is attributed to the in-plane component of the field $B$, that suppresses electronic tunneling between wells, when their separation becomes comparable with the in-plane magnetic length $\ell_y = \sqrt{\hbar/|e|B_y}$ [3].

We have recently studied the problem theoretically [4]. The aim of this paper is to compare the longitudinal magnetoresistance $\rho_{xx}(B)$, measured on the...
GaAs/AlGaAs superlattice with rather strong interwell coupling, with the predictions of the above mentioned model calculations.

![Graph](image)

**Fig. 1.** Curves of the longitudinal magnetoresistance measured at 0.4 K for various tilt angles $\varphi$ are displayed in the upper part of the figure. To emphasize the fine structure of the curves, their second derivatives are shown in its lower part.

### 2. Experiments

The MBE-grown SL with 30 periods consists of 29 GaAs quantum wells of nominal width 5.0 nm, separated by Al$_{0.3}$Ga$_{0.7}$As barriers of total nominal width 4.0 nm. Each barrier is composed of the inner Si-doped layer 2.7 nm thick, surrounded by undoped 0.65 nm thick spacers. The dopants provide electrons for 2D electron sheets in the wells, but simultaneously limit their mobility and influence the effective height of the barriers. Taking these nominal values, we get for the SL period in the growth direction $d_z = 9.0$ nm.

We have checked the periodicity of the structure using the X-ray diffraction. It confirmed its excellent crystallographic quality, but provided the slightly smaller period $d_z = 8.5$ nm. We will use this experimental value of $d_z$ below.

Several samples in the Hall bar geometry have been etched out of this wafer and equipped with evaporated AuGeNi contacts. Both the longitudinal and Hall resistances were measured at $T = 0.4$ K in magnetic fields up to 28 T. The sample could be rotated to any angle between the perpendicular ($\varphi = 0^\circ$) and in-plane ($\varphi = 90^\circ$) orientations. The standard low-frequency ($f = 13$ Hz) lock-in technique has been used for the measurement.

Due to quasi-3D nature of the sample, it was not possible to determine the effective electron concentration and mobility from the low-field data.

In a weakly coupled system, deviating from the present one just by the width of quantum wells (nominally about 19 nm instead of 5 nm) we could observe well developed quantum Hall plateaus indicating that 27-28 2D layers of 29 were occupied with about the same electronic concentration. We assume, that the same holds for the present sample as well.

### 3. Theory

Let us shortly remind the essence of the model calculations presented in Ref.[4]. In a tight-binding model of minibands in 3D superlattices, we get an energy spectrum in the form

$$E(k) = \frac{\hbar^2}{2m} (k_x^2 + k_y^2) - 2t \cos(k_z d_z).$$

It consists of the energy of the free motion in the $xy$ plane and the approximately cosine dispersion relation of the miniband in the growth direction $z$. The parameter $t$ characterizes the effective height and width of the barriers separating individual quantum wells. The period $d_z$ of the SL determines the size of the Brillouin zone: $-\pi/d_z < k_z < \pi/d_z$. The Fermi surface of systems with the Fermi energy $E_F$ within the miniband ($-2t < E_F < 2t$) has a closed semielliptical shape. For $E_F > 2t$, it is an open corrugated cylinder.

If we apply an external magnetic field $B$, the energy spectrum converts to a set of Landau subbands. Let us suppose, that $B \equiv (0, B \sin \varphi, B \cos \varphi)$, and that
it changes its orientation between perpendicular ($\varphi = 0^\circ$, $B = B_z$) and in-plane ($\varphi = 90^\circ$, $B = B_y$) configurations. Magneto-oscillations are determined by extremal cross-sections of the Fermi surface and a plane perpendicular to $B$. These oscillations are periodic in $1/B$ with a period determined by the cross-section area $A_0$:

$$ A_0 = \frac{2\pi|e|}{\hbar} \frac{1}{\Delta(1/B)}.$$  \hspace{1cm} (2) \hspace{1cm}

This quasiclassical approach works well at low magnetic fields.

The above outlined description becomes completely inadequate for strong in-plane fields ($B_z = 0$). Matrix elements of the one-electron Hamiltonian are then given in the tight-binding approximation by

$$ H_{j,j} = \frac{\hbar^2}{2m} (k_x + k_j)^2 + \frac{\hbar^2 k^2_j}{2m}, \quad H_{j,j+\pm 1} = -t, \hspace{1cm} (3) $$

where $k_j = jK_0$ is the magnetic-field-dependent wave-vector with $K_0 = |e|B_y d_z/\hbar = d_z/\ell_y$. The energy spectrum consists of Landau subbands periodic in $k_x$ with the period $K_0$:

$$ E_n(k_x,k_y) = E_0(k_x) + \frac{\hbar^2 k_y^2}{2m}. \hspace{1cm} (4) $$

The subbands $E_n(k_x)$ are flat and separated by wide gaps at low $B_y$, at high fields the subbands become wide and the gaps narrow. Therefore, the strong in-plane field $B_y$ changes the topology of the equienergetic lines $E_F = E_n(k_x,k_y)$. For large $B_y$, $K_0$ becomes larger than the diameter of the free-electron Fermi circles $2\kappa_F$. Fermi contours do not cross anymore and inter-well tunneling becomes impossible. This is the meaning of the statement, that strong in-plane fields suppress inter-layer coupling and facilitate the 3D$\rightarrow$2D transition in SLs.

Upon lowering $B_y$, Fermi contours first touch at the Brillouin zone boundaries, when $E_F$ reaches the top of the lowest Landau subband. Then they merge into an open contour and new closed Fermi ovals belonging to the next higher subband appear, when $E_F$ reaches its bottom. These events correspond to two types of critical fields $B_{c1}$ and $B_{c2}$. At $B = B_{c1}$, $E_F$ touches the bottom of a Landau subband. $E_n(k_x,k_y)$ has a minimum there and a step-like singularity appears in the DOS. At $B = B_{c2}$, $E_F$ coincides with the top of the subband, which corresponds to a saddle point in $E_n(k_x,k_y)$ and to a logarithmic singularity in the DOS.

Fig. 2. The reconstruction of the Fermi surface from the low-field-magnetoresistance data. The parameters $t = 4.7$ meV and $E_F = 5.2$ meV lead to good agreement between the experimental and theoretical curves. The inset shows two cross-sections of the Fermi surface, the $k_\alpha$ on the horizontal axis denotes either $k_y$ or $k_z$.

4. Results and discussion

Experimental curves of the longitudinal magnetoresistance $\rho_{xx}(B)$ for various tilt angles $\varphi$ are displayed in the upper part of Fig. 1. To emphasize the fine structure of the curves, their second derivatives are shown in its lower part. The oscillations can be seen on all the curves, including that obtained in strictly in-plane fields. The oscillations of the magnetoresistance in lower fields are found to be periodic in $1/B$ and the periods have been employed to characterize the sample in terms of the model described above. Fitting the parameters of equation (2) to the experimental data, we were able to get the values of the coupling constant $t = 4.7$ meV and of the Fermi energy $E_F = 5.2$ meV. The fit quality is illustrated by Fig. 2. Experimental points stem from the periods of oscillations. The parameters $t$ and $E_F$ have been calculated from the data for two extreme tilt angles $\varphi = 0^\circ$ and $\varphi = 90^\circ$ and inserted to equation (2) to get the theoretical interpolation curve drawn in Fig. 2. The fit is quite good,
5. Conclusions

The periods of oscillations of low-field magnetoresistance were used to construct the Fermi surface of the SL. The good fit of the theoretical curve confirms that the two-parameter cosine model of the miniband is appropriate to describe the experimental data.

The strong in-plane magnetic field suppresses interwell coupling and finally converts the 3D electronic system of the SL to an multiple 2D layer system. The description of this process requires a fully quantum-mechanical approach. The oscillations of the calculated DOS are in excellent agreement with oscillations of experimental magnetoresistance curves. It proves, that the model is consistent and can be used to explain qualitatively the magnetoresistance data on strongly coupled semiconductor superlattices.

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