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Angular dependent magnetoresistance oscillation in GaAs/AlGaAs superlattice

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Abstract

Vertical transport in GaAs/AlGaAs semiconductor superlattice has been studied as a function of magnetic field angle. A series of resistance peaks corresponding to the angular dependent magnetoresistance oscillation (ADMRO) effect were investigated. The present samples have higher carrier densities and wider well widths than previously studied. This allowed us to observe higher order ADMRO peaks. Another resistance peak is found at $\theta = 90^\circ (B \| \text{layer})$. The origin of this peak structure is discussed in terms of occurrence of closed orbits in some part of a weakly corrugated cylindrical Fermi surface for this field orientation. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The angular dependent magnetoresistance oscillation (ADMRO) effect manifests itself as a series of resistance peaks in an angular trace of magnetoresistance. The phenomenon was first found in layered organic conductors [1,2]. The salient features of ADMRO are summarized as follows. (i) The out-of-plane resistance under a magnetic field of constant strength shows oscillatory change as a function of magnetic field angle with respect to the conductive two-dimensional sheets. (ii) The angular position of resistance peaks is independent of field strength. (iii) The angular position of the resistance peaks is periodic in $\tan\theta$, where θ is measured from the direction normal to the two-dimensional sheets.

Yamaji [3] has proposed the following model to explain the ADMRO effect. The model assumes a cylindrical Fermi surface with weak modulation along the k_z direction. For a general field angle, the Fermi surface cross-section perpendicular to the field direction varies depending on the position of cut. However, provided the corrugation is sinusoidal, all the Fermi surface cross-sections collapses to a single value when the field direction

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θ satisfies the following Yamaji condition,

$$ak_F \tan\theta = \pi(n - \tfrac{1}{4}), \quad n = 1, 2, 3, \ldots, \tag{1}$$

where a is the lattice period perpendicular to the two-dimensional sheets and k_F is the radius of the Fermi cylinder in the limit of vanishing modulation. Yagi et al. [4] have calculated magnetoconductivity tensor components for such a Fermi surface using the Shockley tube-integral formula, and have shown that the calculated out-of-plane resistivity reproduces the observed ADMRO effect remarkably well.

Since the essential requirement for the occurrence of ADMRO effect is a weakly modulated cylindrical Fermi surface, the similar effect can be expected in other quasi-two-dimensional systems. Iye et al. [5] demonstrated the ADMRO effect in $SbCl_5$ intercalated graphite samples and Yagi et al. [6] observed it in GaAs/AlGaAs semiconductor superlattice samples.

The semiconductor superlattice system offers a large degree of freedom for Fermi surface tailoring by adjusting the superlattice periodicity and doping concentration. In the present study, we have extended our previous work on the ADMRO effect in semiconductor superlattices by changing such parameters.

2. Experimental

$GaAs/Al_{0.15}Ga_{0.85}As$ semiconductor superlattice samples were grown on n^+GaAs (1 0 0) substrate by molecular beam epitaxy. The relatively low Al content was chosen for the barrier layer to achieve weak potential modulation along the growth direction. The growth of superlattice was done at relatively low substrate temperature, about 540°C to prevent segregation of Si donors. The structures of two samples used in the present work were as follows. The thickness of the barrier layers was 6 nm for both samples. The width of the well layers was 10 nm for Sample #1 and 12 nm for Sample #2. Si donors were doped only in the barrier layers. Si donor concentration was $1.3 \times 10^{24}\,m^{-3}$ for Sample #1 and $2.2 \times 10^{24}\,m^{-3}$ for Sample #2. The miniband structure was calculated using a simple Kronig–Penny model neglecting non-parabolicity of the conduction band, the band bending and the slight difference in effective mass between GaAs and AlGaAs. The above-mentioned doping densities were chosen so as to make the Fermi energy lie in the first mini gap to form a weakly corrugated cylindrical Fermi surface as illustrated in Fig. 1a.

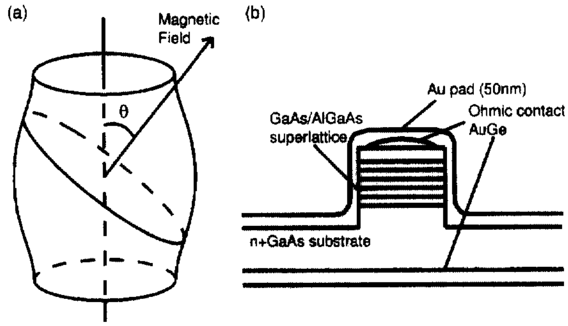

Fig. 1. (a) Weakly corrugated cylindrical Fermi surface in a quasi-two-dimensional system. (b) Schematic drawing of a square columnar mesa structure for vertical transport measurements.

In order to measure the vertical transport, a square columnar mesa was fabricated by photolithography and wet chemical etching. Four mesas of different cross-sections ranging from $50\,\mu m \times 50\,\mu m$ to $400\,\mu m \times 400\,\mu m$ were made for each sample. Electrical contact was achieved by a standard AuGe alloying technique with precaution not to let Ge diffuse into the superlattice part. The overall sample geometry is shown in Fig. 1 b. Magnetotransport measurements were done in a 15 T superconducting solenoid equipped with a variable temperature insert. A rotating sample holder with a stepping-motor-driven gear assembly enabled us to achieve angular sweep with 0.01° precision.

3. Results and discussion

Fig. 2a shows the angular dependence of the out-of-plane resistance $R_{zz}(\theta)$ of sample #1 at $T = 29.3$ K for different magnetic field strengths up to 15 T. A series of resistance peaks whose positions are almost independent of field strength are identified. Fig. 2 b is the same data set replotted as

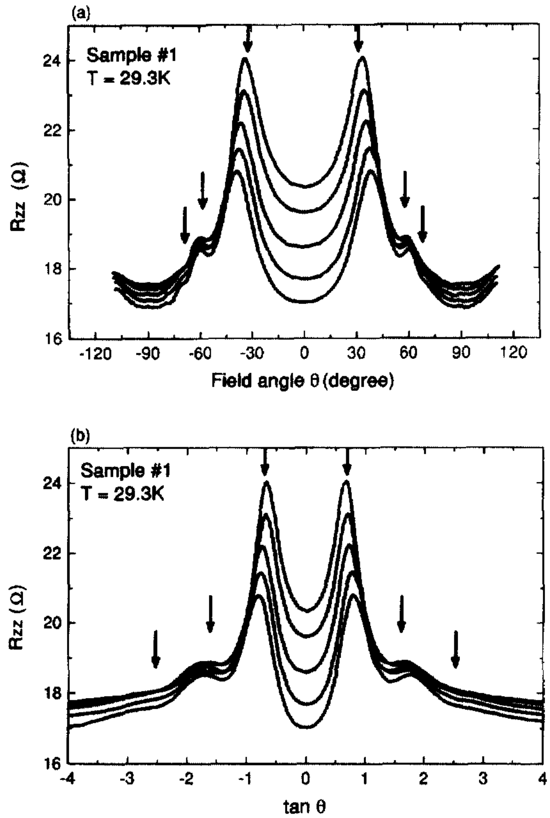

Fig. 2. (a) The angular dependence of the out-of-plane resistance of Sample #1 at $T = 29.3$ K for different magnetic field strengths. From top to bottom, $B = 15$, 14, 13, 12 and 11 T. The calculated angular positions corresponding to the Yamaji condition are marked by arrows. (b) The same data set replotted as a function of $\tan\theta$.

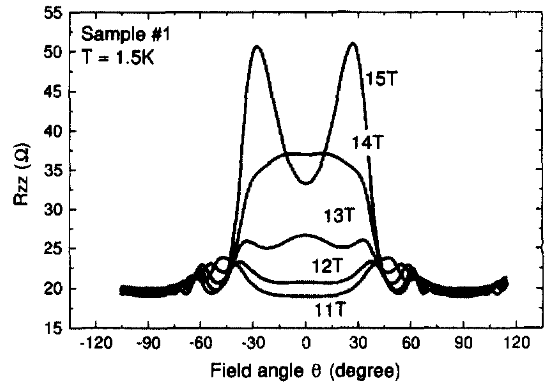

Fig. 3. The angular trace of the out-of-plane resistance of Sample #1 at $T = 1.5$ K for different magnetic field strengths.

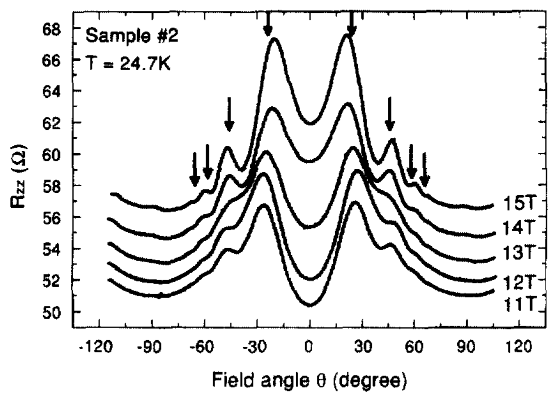

Fig. 4. The angular dependence of the out-of-plane resistance of Sample #2 at $T = 24.7$ K for different magnetic field strengths. The arrows indicate the calculated angular positions corresponding to the Yamaji condition.

a function of $\tan\theta$. Note that the measurements were done at relatively high temperature so as to suppress the Shubnikov–de Hass (SdH) effect. In Fig. 3, the angular traces of $R_{zz}(\theta)$ taken at $T = 1.5$ K are plotted. Here, the amplitude of resistance oscillation is much larger than Fig. 2, and the angular positions of resistance peaks do shift with the magnetic field strength. These oscillatory features are the SdH effect which becomes dominant at low temperatures and masks the ADMRO effect. Fig. 4 shows a similar set of data taken at $T = 24.7$ K for sample #2.

In Figs. 2 and 4, calculated angular positions corresponding to the Yamaji condition (Eq. (1)) are marked by arrows. The relevant parameters were determined from other measurements, a from growth rates and k_F from SdH oscillations at $T = 1.5$ K. Thus the angular positions of resistance peaks were in good agreement with Eq. (1) for Samples #1 and #2. Unlike the case of intercalated graphite [5], no significant deviation from Yamaji condition was seen in these GaAs/AlGaAs semiconductor superlattice systems.

In Fig. 4, resistance peaks up to the fourth order are discernible. Sample #2 has a higher carrier concentration and a wider well width than Sample #1. According to Eq. (1), this makes the resistance peaks occur at lower angles. As shown in the calculation by Yagi et al. [4], the ADMRO feature starts to become distinct above $\omega_c\tau \sim 1$, where τ is the scattering time and ω_c is the cyclotron frequency. For a given magnetic field strength, $\omega_c \sim eB\cos\theta/m^*$ diminishes as θ approaches $\frac{\pi}{2}$. The decrease of $\omega_c\tau$ tends to smear the ADMRO effect at higher angles. Thus the higher carrier concentration and the wider well width of Sample #2 constitute a favorable condition for observation of the higher-order ADMRO peaks.

Let us now turn to the behavior around $\theta = 90°$. Fig. 5a shows $R_{zz}(\theta)$ of Sample #2 at $T = 1.5$ K for a narrow angular range around $\theta = 90°$. A small broad peak is seen at $\theta = 90°$. The peak structure diminishes as the magnetic field strength is decreased. A similar peak has been observed earlier in the angular dependence of the in-plane resistance, $R_{xx}(\theta)$, and has been interpreted as a manifestation of the negative magnetoresistance due to the weak localization effect [7]. The newly found peak in $R_{zz}(\theta)$, however, is fundamentally different in nature for the reasons given below. The peak structure in $R_{xx}(\theta)$ has the following features. First, it can be observed even at low fields, and the peak structures for different field strengths can be reduced to a single curve by replotting them as a function of $B\cos\theta$, or the normal component of the magnetic field. Second, the peak height diminishes at higher temperatures. By contrast, the presently observed peak structure in $R_{zz}(\theta)$ does not obey the scaling by $B\cos\theta$, and it is relatively insensitive to temperature. Thus, the peak in $R_{zz}(\theta)$ cannot be attributed to the weak localization effect. We rather attribute it to occurrence of closed orbits for $\theta \sim 90°$.

The Fermi surface of the present system is a weakly corrugated cylinder. When a magnetic field is applied parallel to the two-dimensional sheets, there occur small closed orbits in the belly part of the Fermi surface as shown in Fig. 5 b. As the magnetic field is tilted away from the parallel direction, these closed orbits disappear, leaving only the elongated orbits extending over many Brillouin zones. With a finite scattering time, those orbits are similar in character to open orbits. It is tempting to attribute the peak structure in $R_{zz}(\theta)$ to the occurrence of closed orbits for a narrow angular range around $\theta = 90°$.

In fact, a phenomenon which has a similar physical origin is discussed in some quasi-one-dimensional organic conductors [8,9]. It is a kink structure in the angular trace of the interlayer magnetoresistance when a magnetic field is rotated in the most conductive plane. This kink structure is attributed to the appearance of the closed orbits on the sheetlike Fermi surface. The critical angle where

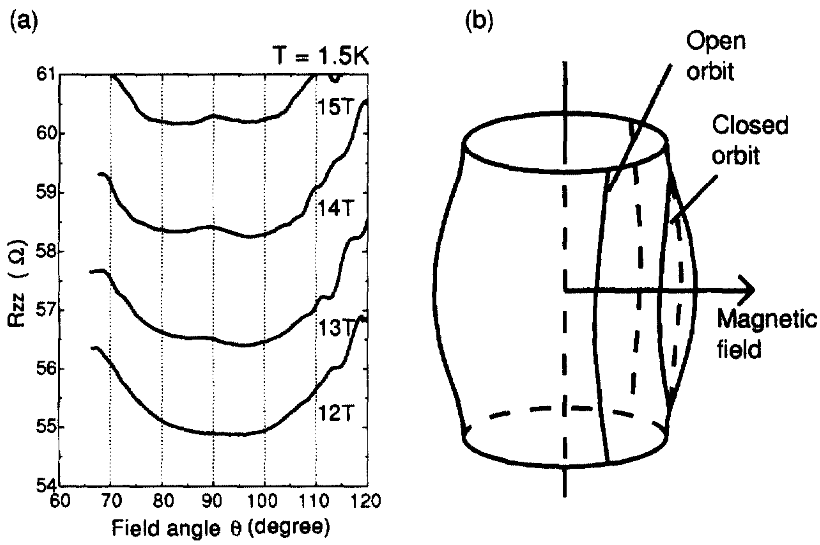

Fig. 5. (a) The angular traces of the resistance of Sample #2 taken at $T = 1.5$ K for different magnetic field strengths. (b) Small closed orbits occur in the belly part of the Fermi surface when the magnetic field is applied parallel to the two-dimensional sheets.

the small closed orbits vanish is estimated as $\theta = 87°$ for the Fermi surface of Sample #2. Although there is some ambiguity in determining the critical angle experimentally, it should be around the minimum in $R_{zz}(\theta)$ which is located at several degrees away from $\theta = 90°$ as seen in Fig. 5a. The critical angle for disappearance of small closed orbits depends critically on the amplitude of corrugation of the cylindrical Fermi surface, which is governed by the interlayer transfer integral. Thus, we may utilize the resistance peak structure around $\theta = 90°$ to gain information on the interlayer transfer.

4. Summary

The ADMRO effect was observed in the vertical transport of GaAs/AlGaAs semiconductor superlattices. The angular positions of the resistance peaks were found to agree with the Yamaji condition. Adjusting the superlattice periodicity and doping concentration enabled us to observe the higher order ADMRO peaks. A peak structure in the angular dependence of the resistance was found for the field parallel to the layer plane. The peak structure is attributed to the occurrence of closed orbits on the weakly corrugated cylindrical Fermi surface when the magnetic field is nearly parallel to the two-dimensional sheets.

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