A new class of small low-field magnetoresistance oscillation in unidirectional lateral superlattice

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Abstract. A new class of small-amplitude magnetoresistance oscillation has been unveiled in unidirectional lateral superlattice (ULSL) samples in a low magnetic field regime dominated by positive magnetoresistance. The oscillation is ascribed to geometric resonance of Bragg-reflected cyclotron orbits. The predicted approximate $\propto a^{-3}k_F^{-1}$ dependence of the positions of maxima, where a and k_F represent the period and the Fermi wavenumber, respectively, has been confirmed by comparing ULSL samples with a=184 and 207 nm.

Unidirectional lateral superlattice (ULSL) samples are well known to display two types of magnetotransport characteristics: positive magnetoresistance (PMR) [1] at magnetic fields around zero, and commensurability oscillation (CO) [2] above the field range for PMR. Both PMR and CO can be basically understood by the semiclassical motion of electrons under periodic potential modulation $V_0 \cos(2\pi x/a)$ and a perpendicular magnetic field B. Very recently we have uncovered a small-amplitude magnetoresistance oscillation superposed on the slope of PMR ([3], referred to as paper I, hereafter). The new oscillation is observed for four ULSL samples with the period a ranging from 138 to 184 nm, and from the a- and the electron density n_e- dependences, is attributed to geometric resonance between a and the width $b_{j,k}$ of an open orbit resulting from the miniband structure of the superlattice. The resonant condition where magnetoresistance $\Delta\rho_{xx}/\rho_0$ takes local maximum is given by equating $b_{j,k}$ with the multiple of the period, na. The width $b_{j,k}$ of the open orbit between j-th and k-th reflection points is given by (assuming $\eta \equiv V_0/E_F \ll 1$, E_F being the Fermi energy),

$$b_{j,k} = \frac{\hbar k_F}{e|B|}\left[\sqrt{1-\left(\frac{j\pi}{ak_F}\right)^2} - \sqrt{1-\left(\frac{k\pi}{ak_F}\right)^2}\right], \quad (1)$$

where $k_F=\sqrt{2\pi n_e}$ denotes the Fermi wavenumber. The positions of local maxima (or minima in $d^2(\Delta\rho_{xx}/\rho_0)/dB^2$ to be explained later), therefore, read, up to the first order of $(\pi/ak_F)^2$,

$$|B_{\mathrm{min}}^{j,k,n}| \simeq \frac{\pi^2\hbar}{2nea^3k_F}(k^2-j^2). \quad (2)$$

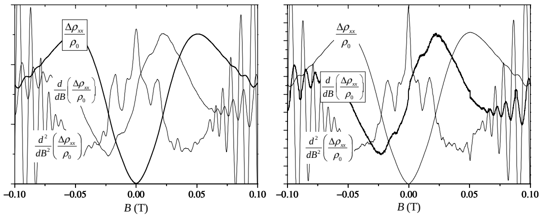

FIGURE 1. Left: Magnetoresistance with its numerical first and second derivative. Right: Directly measured first derivative with its numerical integral and derivative. Thick curves represent raw data. The data were taken on Sample A at 4.2 K.

Because of the a^{-3} dependence, $|B_{\mathrm{min}}^{j,k,n}|$ shifts rapidly with a, especially for smaller a. However, the oscillation is limited to a narrow window $|B| <\sim 0.04$ T, since the open orbits become demolished by the dominance of the magnetic breakdown at higher fields. In paper I, $|B_{\mathrm{min}}^{j,k,n}|$'s that appeared in the window belonged to different sets of parameters (j,k,n) for different samples having different a, which made the verification of the a-dependence rather unclear. In the present paper, we measure another ULSL sample with larger period, a=207 nm, and compare it with the result for the a=184 nm sample. The two samples show directly corresponding $|B_{\mathrm{min}}^{j,k}|$'s (n=1) which actually scales in accordance with Eq. (2), furnishing another support for our interpretation.

Two ULSL samples with periods a=184 nm (Sample A) and 207 nm (Sample B) were prepared from the same GaAs/AlGaAs wafer and had the same Hall-bar pattern (64×37 μm^2). Potential modulation was introduced by strain-induced piezoelectric effect [4] from a surface grating. Modulation amplitudes were measured from the amplitude of CO [5] and were $V_0 \sim 0.25$ and

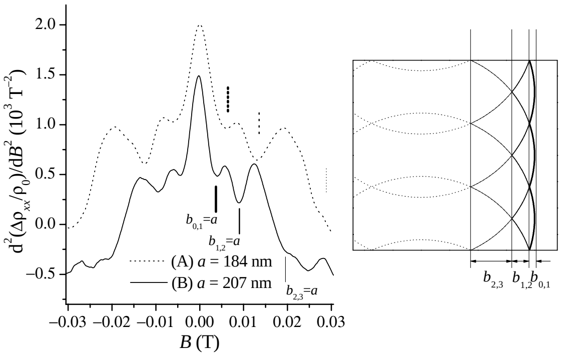

FIGURE 2. Left: $d^2(\Delta\rho_{xx}/\rho_0)/dB^2$ traces for Samples A and B for similar n_e; n_e=2.38×10^{15} m^{-2} and 2.33×10^{15} m^{-2} for dotted (A) and solid (B) curves, respectively. The former is vertically offset for clarity. Vertical lines mark the positions of minima. Right: Sketch of the open orbits (Bragg-reflected cyclotron orbits).

0.22 meV for Samples A and B, respectively, and did not vary much with n_e. The measurement of ρ_{xx} was done by standard low-frequency lock-in technique. In order to pick out the small-amplitude oscillation from much larger PMR background, we numerically differentiated magnetoresistance with respect to B. Alternatively, $d\rho_{xx}/dB$ was directly measured by picking up the resistance that follows a small-amplitude (rms 1 mT) ac component of magnetic fields superposed on an ordinary dc sweep. Fig. 1 demonstrates the consistency of both types of measurements. We use the data obtained by standard measurements in the following. Close inspection of the traces in Fig. 1 reveals that minima in $d^2\rho_{xx}/dB^2$ correspond to local maxima in ρ_{xx}. To see the dependence of the oscillation on k_F, n_e was varied by employing persistent photoconductivity effect.

Fig. 2 compares second derivative traces for the two samples at nearly the same n_e. Straightforward correspondence of the minima positions (marked by dotted and solid vertical lines) can be observed between the two traces. The minima are identified as the condition that the width $b_{j,k}$ (right panel in Fig. 2) satisfies $b_{j,k}$=a (n=1). It can readily be seen that the minima for Sample B appears at smaller $|B|$. In the left panel of Fig. 3, positions of minima are plotted as a function of n_e. The figure clearly shows the trend of smaller $B_{\min}$ for Sample B having larger a, in the ranges of n_e. To be more quantitative, $B_{\min}$ is normalized by the prefactor $\pi^2\hbar/2ea^3k_F$ of Eq. (2) and plotted in the right panel of Fig. 3. The normalized values coincide between the two samples, unambiguously confirming the a^{-3} dependence. Moreover, the normalized value is expected from Eq. (2) to be equal to k^2-j^2 (shown as horizontal dashed line), which is also evident in the figure, at least for the two smaller $B_{\min}$'s. The deviation from 3^2-2^2=5 for the largest $B_{\min}$ will partly be explained by the lesser applicability of the first order approximation in Eq. (2) for larger j and k. Owing to rather narrow n_e range, k_F^{-1} dependence is less evident, which has been unequivocally shown in paper I.

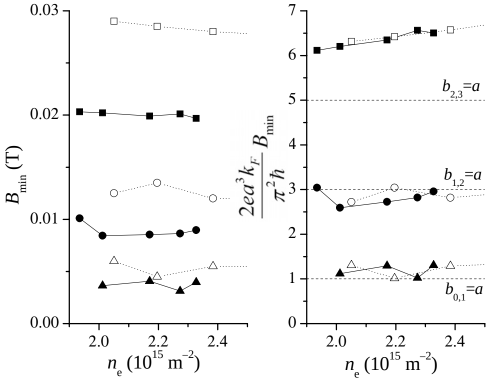

FIGURE 3. Left: Plot of minima position $B_{\min}$(>0) versus n_e. Open and solid symbols represent Samples A and B, respectively. Right: $B_{\min}$ normalized by $\pi^2\hbar/2ea^3k_F$ [see Eq. (2)].

To summarize, we have confirmed the expected a-dependence of the new low-field magnetoresistance oscillation we have found in ULSL, supporting our interpretation that the oscillation originates from the geometric resonance of open orbits. This provides another piece of evidence of the formation of miniband structure in ULSL [6].

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