Fermi Surface Topology and Generation of Chaos in Multilayer Systems under Tilted Magnetic Fields and Interlayer Electric Fields

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Interlayer magnetotransport of multilayer systems, such as semiconductor superlattices or organic layerd conductors, shows rich behaviors under tilted magnetic fields and/or interlayer electric fields.

In the case of zero electric field, it has been known that the interlayer magnetoresistance shows remarkable angular dependent effects. One is the "angular dependent magnetoresistance oscillation (AMRO)", which depends only on the field orientation and does not originate from Shubnikov-de Haas effect. Another angular effect is the "peak effect" which appears when field orientation is almost parallel to the conducting layer. These magnetoresistance angular effects have been explained by the semiclassical electron orbital motion on a warped cylindrical Fermi surface and the Boltzmann transport theory. Under the finite electric fields, the angular effects become more complicated [1]. Under the uniform interlayer electric fields, electrons carry out the Bloch oscillation along the stacking axis with Bloch frequency ω_B. When the Bloch frequency becomes an integer multiple of the cyclotron frequency $\omega_c\cos\theta$, the electron orbital motion becomes periodic causing the resonant increase of interlayer conduction (the Stark cyclotron resonance). The amplitude of Stark cyclotron resonance oscillates against the polar angle θ of the magnetic field. This is the AMRO generalized for finite electric fields.

On the other hand, Fromhold *et al.* has pointed out that electron orbital motion shows classsical chaos in semiconductor superlattices under tilted magnetic fields and interlayer electric fields [2]. They have also discussed that the system abruptly shows non-KAM chaos, which shows complex web pattern (stochastic web) in the phase space, when the Bloch frequency satisfies the condition of the Stark cyclotron resonance. They claimed that the existence of chaotic orbits increases the interlayer conduction, and the change of chaotic nature causes the oscillatory change of interlayer conduction.

In this paper, we have attempted to understand the relation between above two pictures for AMRO and chaos. For this purpose, we clarify the condition for the appearance of chaos and the mechanism for its generation in the multilayer system with a cylindrical Fermi surface.

We consider a simple multilayer system with in-plane mass m, in-plane Fermi wave number k_F, interlayer distance c, and interlayer transfer t_c. We take the stacking axis parallel to the z-axis, and assume that the electric field is applied parallel to the z-axis, and the magnetic field is rotated in the xz-plane. This system has a cylindrical Fermi surface characterized two parameters; ck_F which means the thickness and $\tan\theta_c \equiv (\hbar k_F/m)/(2t_c c/\hbar)$ which indicates the warping. Here, θ_c is the critical polar angle for the peak effect. When the polar angle θ of magnetic field $\mathbf{B}$ is larger than θ_c, small closed orbits which do not surround the Fermi cylinder appears on the Fermi cylinder, and a hyperbolic fixed point exists on the largest small closed orbit as shown in Fig. 1.

The electron orbital motion in the $\mathbf{k}$-space is described by the semiclassical equation of motion $\hbar d\mathbf{k}/dt = (-e)\mathbf{v}\times\mathbf{B} + (-e)\mathbf{E}$. This equation of motion can be deduced to that of a 1D harmonic oscillator for k_x affected by a plane-wave-type perturbation [2]. In the dimensionless form, the perturbation strength is represented by $\tan\theta / \tan\theta_c$. This means that the electron orbital motion around the Fermi level becomes unstable and shows chaos when the tilt angle θ of $\mathbf{B}$ becomes larger than θ_c, in other words, in the angle region of the peak effect. This gives the condition for appearance of chaos around the Fermi level at the weak electric field limit.

Figure 2 shows the numerically calculated stroboscopic Poincare sections for three magnetic field orientations. In-plane wave number (k_x, k_y) are plotted at discrete times separated by the Bloch oscillation period $2\pi/\omega_B$ for several electron orbits. The circle indicates the cross section of the

Fermi cylinder. As seen in Fig. 2(a), in the case of $\theta<\theta_c$, the chaotic core appears at the low energy region around the center of the Fermi cylinder. Around the Fermi level, the electron orbital motion is regular. However, as seen in Fig. 2(b), once the field orientation θ reaches θ_c, chaotic orbits appear around the Fermi level. This result supports the above condition for generation of chaos.

When $\theta>\theta_c$, the electron orbital motion is slowed down around the hyperbolic fixed point, and it becomes easy to be affected by the oscillatory perturbation due to Bloch oscillation. This could generate the complex chaotic orbital motions under electric fields.

[1] M. Kuraguchi, E.Ohmich, T. Osada, and Y. Shiraki, Physica **E12**, 157 (2002).
[2] T. M. Fromhold et al., Phys. Rev. Lett. **87**, 046803 (2001).

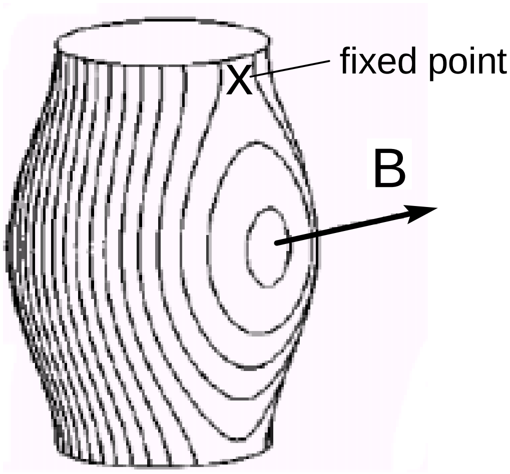

Fig. 1
Schematic drawing of a cylindrical Fermi surface of multilayer systems. For the case of $\theta>\theta_c$, several electron orbits are shown and the hyperbolic fixed point is indicated.

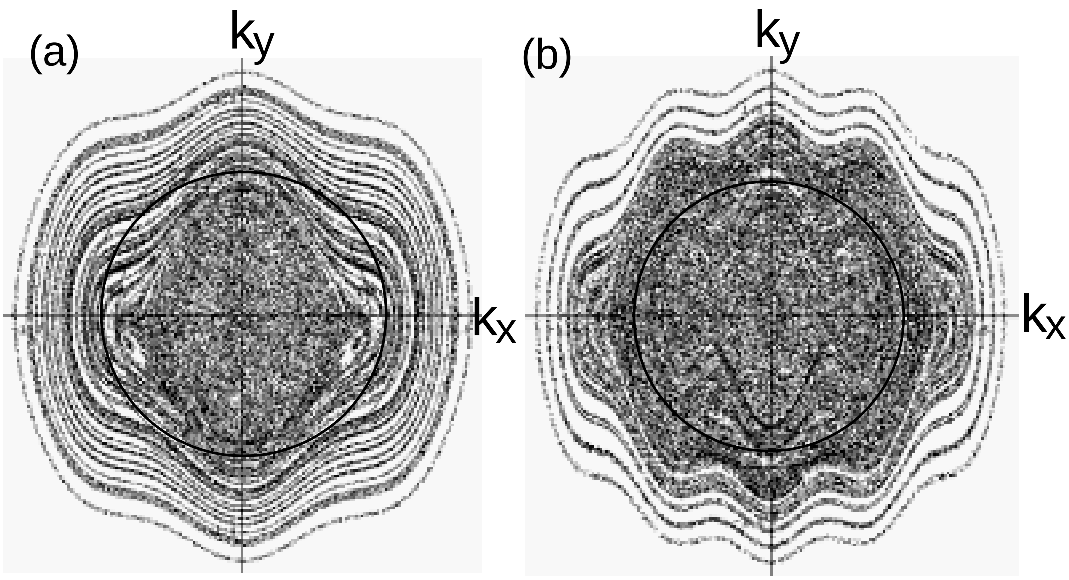

Fig. 2
Stroboscopic Pincare sections for the system with $ck_F=\pi$, θ_c=70deg, and $\omega_B/\omega_c\cos\theta=0.1\tau=0.162$. A circle indicates the cross section of the Fermi cylinder. (a) θ=60deg. (b) θ=70deg.