Tunneling picture of interlayer magnetotransport in multilayer systems

Toshihito Osada [a,1], Masahiko Kuraguchi [a], Kaya Kobayashi [a], Eiji Ohmichi [a]

[a] *Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan*

Abstract

Interlayer magnetotransport of multilayer systems has been generally studied. In multilayer systems with weak interlayer coupling, interlayer conduction is mainly dominated by single tunneling process between neighboring layers. The selection rule and probability of single interlayer tunneling are controlled by orientation and strength of magnetic fields. This tunneling model gives the most general explanation of most of the magnetoresistance angular effects observed in Q2D or Q1D layered conductors. The existence of the Fermi surface is not necessary for appearance of them. This model can also be applied to the modified angular effects under strong electric fields.

Key words:
angular dependent magnetoresistance oscillations; low-dimensional conductor; incoherent transport; interlayer tunneling

It has been known that the interlayer magnetoresistance in quasi-two-dimensional (Q2D) or quasi-one-dimensional (Q1D) layered conductors show remarkable oscillatory or resonance-like structures as a function of magnetic field orientations. The interlyer magnetoresistance in Q2D conductors shows the Yamaji oscillations when the field is tilted from the normal (z-axis) of the conducting plane (xy-plane). On the other hand, in Q1D layered conductors, three fundamental angular effects (the Lebed resonance, the Danner-Chaikin oscillation, and the third angular effects) are observed corresponding to the field rotation around the most conducting axis (x-axis), the secondarily conducting axis (y-axis), and the stacking axis (z-axis), respectively. In addition, the magnetoresistance shows a sharp peak structure when the field is parallel to the conducting plane in both Q2D and Q1D conductors (the peak effect). These magnetoresistance angular effects have been explained by the semiclassical Boltzmann magnetotransport theory based on the Fermi surface topology [1]. In this model, the interlayer coherency, which allows an electron to tunnel through many layers without scattering, is tacitly assumed.

In this paper, we propose a new general quantum model (tunneling picture) of the angular effects, and show that all these angular effects except the peak effect essentially originate not from the Fermi surface topological effect but from single tunneling process between neighboring two layers. There have been a few preceding works. Yoshioka rewrote the conventional picture by the interlayer tunneling for the first time [2]. McKenzie and Moses discussed that the Yamaji oscillations and the Danner-Chaikin oscillations could appear even in the systems with no coherent interlayer coupling. They pointed out that single tunneling process causes these oscillations treating in-plane electron motion semiclassically [3].

The outline of the tunneling picture is as the followings [4]. First, we consider 2D electronic states located on each 2D layer neglecting interlayer coupling. These 2D states essentially depend only on the normal component of magnetic fields. The parallel component brings the difference of position or phase among wave functions located on different layers. Next, we introduce interlayer coupling as a perturbation. Matrix

[1] Corresponding author. E-mail: osada@issp.u-tokyo.ac.jp

elements of interlayer coupling, which give tunneling probability between neighboring two layers, are proportional to the overlap integral of 2D states located on the neighboring layers. The condition for non-zero overlap gives the selection rule, and the overlap value gives tunneling amplitude. When the magnetic field is rotated, the overlap integral might oscillates reflecting the oscillatory waveform of wave functions, if the parallel field component shift a wave function on the adjacent layer relatively. The interlayer conductivity is well described by the lowest order contribution of interlayer coupling in the incoherent limit, where in-plane scattering occurs much oftener than interlayer tunneling. Therefore, the interlayer conductivity shows resonance-like increase when the selection rule allows interlayer tunneling, and shows oscillatory structures when the tunneling probability oscillates as a function of magnetic field orientation.

Using this model, we could lead analytic formulae of the interlayer conductivity σ_{zz} in the Q2D and Q1D layered conductors.

In Q2D conductors with the conducting layer parallel to the xy-plane), σ_{zz} is written as

$$\sigma_{zz} = N_F \left(\frac{e t_c c}{\hbar}\right)^2 \sum_{\nu} \frac{\tau J_\nu (c k_F \frac{B_\parallel}{B_z})^2}{1+\left(\nu \frac{e B_z}{m}\right)^2 \tau^2}. \quad (1)$$

Here, N_F, t_c, c, and τ are density of states, interlayer transfer energy, interlayer spacing, and in-plane scattering time, respectively. k_F and m are Fermi wave number and effective mass of each 2D layer. As seen in (1), when $B_\parallel/B_z$ is changed, σ_{zz} shows the Yamaji oscillations through the oscillations of Bessel function J_ν.

In Q1D layered conductors with the conducting axis parallel to the x-axis and the conducting layer parallel to the xy-plane, σ_{zz} is written as

$$\sigma_{zz} = N_F \left(\frac{e t_c c}{\hbar}\right)^2 \sum_{\pm,\nu} \frac{\tau J_\nu \left(\frac{2 t_b c}{\hbar v_F} \frac{B_x}{B_z}\right)^2}{1+v_F^2 \left(\nu \frac{b e B_z}{\hbar} \pm \frac{c e B_y}{\hbar}\right)^2 \tau^2}. \quad (2)$$

v_F, t_b, and b are Fermi velocity of a 1D chain, inter-chain transfer energy, and inter-chain spacing, respectively. Figure 1 shows the angular dependence of σ_{zz} described by (2). At the field orientations which satisfy $B_y/B_z = pb/c$ (p:integer), edge-like structures due to resonant interlayer tunneling are seen (the Lebed resonance). The Danner-Chaikin oscillations and the third angular effect also occur as oscillations and the maximum peak of Bessel function J_ν, respectively.

In this way, all of the magnetoresistance angular effects except the peak effect observed Q2D and Q1D conductors are well explained in the framework of the present tunneling picture considering only single tunneling process between neighboring two layers. This fact means that all of these angular effects could be observed even in the incoherent systems having no well-defined Fermi surface.

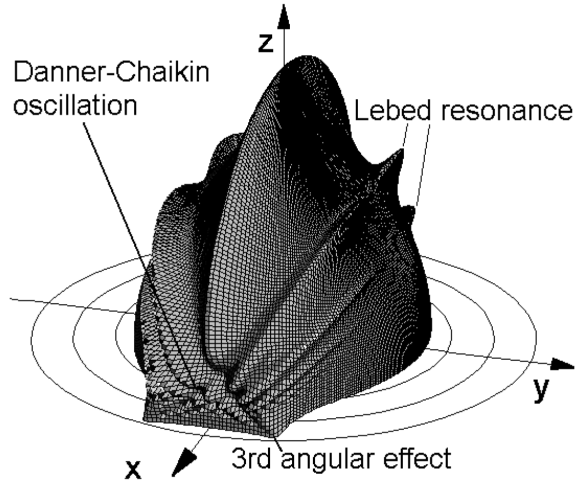

Fig. 1. Interlayer magnetoresistance as a function of magnetic field orientation in Q1D conductors.

Under electric fields parallel to the stacking axis, the 2D states located on each layer have different energy depending on the layer position. So, the magnetoresistance angular effects could be modified since the condition of interlayer tunneling changes [5][6]. Especially in Q2D conductors, the Yamaji oscillation of the interlayer current is modified:

$$\frac{j_z}{E_z} = N_F \left(\frac{e t_c c}{\hbar}\right)^2 \sum_{\nu} \frac{\tau J_\nu (c k_F \frac{B_\parallel}{B_z})^2}{1+\left(\nu \frac{e B_z}{m} - \frac{c e E_z}{\hbar}\right)^2 \tau^2}. \quad (3)$$

The interlayer current shows resonance-like increase when the Bloch frequency $ceE_z/\hbar$ equals to the integer times of the cyclotron frequency eB_z/m. This resonance corresponds to the Stark cyclotron resonance caused by the interlayer tunneling between 2D Landau states with different Landau indices. The generalized Yamaji oscillations occur as a result of change of tunneling probability depending on B_x/B_z. The fact that (3) and (2) have the same form suggests that the angular effects in Q2D systems under electric fields correspond to those in Q1D systems.

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