ELECTRONIC PROPERTIES OF METALS AND ALLOYS

Static skin effect in organic metals*

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Galvanomagnetic phenomena in layered organic conductors with a multisheet Fermi surface in the form of a weakly corrugated cylinder and weakly corrugated planes are studied. It is shown that in a strong magnetic field **H** unrestricted growth of the resistivity of such conductors with increasing H is accompanied by the current lines being forced out to the surface of the specimen. The main dissipation mechanism of electron current is charge scattering by the boundaries of the sample, even in bulk conductors whose thickness is greater than the free path length l of the conduction electrons. For specular reflection at the surface the resistivity increases linearly with the magnetic field. © *2003 American Institute of Physics.*
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Unrestricted growth of the resistivity of a conductor with increasing magnetic field is usually accompanied by the current lines being forced out to the surface of the sample. In a strong magnetic field **H**, when the radius of curvature r of an electron trajectory is much less than the charge-carrier mean free path l, the electric current can be concentrated completely near the conductor surface (static skin effect).[1–6] This occurs in compensated metals, where the number of electrons equals the number of holes, and in metals with an open Fermi surface for magnetic field directions for which the resistivity increases with H. The reason is that the charge carriers colliding with the surface of the sample have a higher mobility than the electrons in the core of the conductor, because the center of an electron orbit undergoes a jump at every collision with the surface. The surface current depends strongly on the specularity of the electron reflections at the boundary of the sample. This allows us to use experimental studies of the H-dependence of the conductor resistivity under static skin-effect conditions as a method for checking the state of the surface without destroying the specimen.[7–12]

In metals the static skin effect is most pronounced when the magnetic field vector is parallel to the surface of the sample and orthogonal to the current density vector ($\mathbf{j}\perp\mathbf{H}$). This occurs when the effective free path length $l_{\rm eff}$ of the electrons which are specularly reflected from perfectly smooth defect-free surfaces is limited by electron collisions in the bulk only, i.e. $l_{\rm eff}=l$, and the conductivity $\sigma_\perp^{\rm skin}$ of a surface layer of thickness $2r$ is of the same order of magnitude as the conductivity σ_0 in the absence of a magnetic field. In compensated metals the contribution to the transverse conductivity $\sigma_\perp^{\rm vol}$ of the electrons in the interior volume is of the order of $\sigma_0(r/l)^2$ and the electric field is orthogonal to the vector **H**.

As a result, charge carriers that collide with the sample surface make the main contribution to the electric current density

$$j_i=\sigma_{ik}E_k \tag{1}$$

and the resistivity of a sample with thickness $d\ll l^2/r$ increases linearly with H.

In a magnetic field an electron deflected at an angle $\alpha > l/r$ from the surface of the sample goes into the bulk of the conductor after several collisions with the surface. The electron mean free path $l_{\rm eff}$ is much less than l and equals $r/\sin\alpha$. The result is that the transverse resistivity ($\mathbf{j}\perp\mathbf{H}$) of compensated metals increases quadratically with the magnetic field for any ratio of d and l, even if the surface of the sample is perfectly smooth and the energy and momentum projection on a plane tangent to the surface are conserved for specularly reflected electrons.

Investigations of the surface state of layered conductors with a quasi-two-dimensional electron energy spectrum by means of magnetoresistance measurements prove to be effective in magnetic fields inclined away from the surface of the sample.

We shall consider the distribution of the current lines in tetrathiafulvalene-based organic conductors $(\rm BEDT-TTF)_2X$ (where X is a radical) placed in a strong magnetic field. The organic conductors in this family consist of layered structures with a sharp metal-like anisotropy of the electric conductivity—the conductivity along the layers is much higher than the conductivity across the layers. This is probably due to the sharp anisotropy of the conduction

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electron velocity $\mathbf{v}=d\varepsilon(\mathbf{p})/d\mathbf{p}$ at the Fermi surface $\varepsilon(\mathbf{p})=\varepsilon_F$, i.e. the energy of the conduction electrons

$$\varepsilon(\mathbf{p})=\sum_{n=0}^{\infty}\varepsilon_n(p_x,p_y)\cos\left\{\frac{anp_z}{\hbar}+\alpha_n(p_x,p_y)\right\},$$

$$\alpha_n(p_x,p_y)=-\alpha_n(-p_x,-p_y), \tag{2}$$

$$\varepsilon_n(p_x,p_y)=\varepsilon_n(-p_x,-p_y)$$

depends weakly on the momentum projection $p_z=\mathbf{p}\cdot\mathbf{n}$ along the normal $\mathbf{n}$ to the layers.

Here a is the distance between the layers, $\hbar$ is Planck's constant, the functions $\varepsilon_n(p_x,p_y)$ decrease as n increases, so that the maximum value of the function $\varepsilon(\mathbf{p})-\varepsilon_0(p_x,p_y)$, equal to $\hbar\varepsilon_F$ at the Fermi surface, is much less than the Fermi energy ε_F.

The Fermi surface of layered conductors is an open surface which is weakly corrugated along the p_z axis. Experimental observations of the Shubnikov–de Haas quantum oscillations, first in the complexes $(\mathrm{BEDT-TTF})_2\mathrm{IBr}_2$ and $(\mathrm{BEDT-TTF})_2\mathrm{I}_3$[13,14] and then in all tetrathiafulvalene-based layered conductors,[15,16] in strong magnetic fields $\mathbf{H}=(0,H\sin\theta,H\cos\theta)$ for a wide range of θ prove that at least one Fermi surface sheet is a weakly corrugated cylinder.

In a magnetic field oriented parallel to the layers many electrons with energy equal to the Fermi energy move along open orbits $\varepsilon=\text{const}$, $p_H=\mathbf{p}\cdot\mathbf{H}/H=\text{const}$ in momentum space, and the resistance for the current flowing across the layers increases without bound as H increases.

Let the sample be a plate with thickness d and boundaries $z_s=0,d$ and $y_s=0,L$, where d and L are much greater than l. At $\theta=\pi/2$ the conduction electrons near a saddle point of the Fermi surface make the main contribution to the conductivity σ_{zz} across the layers of the core of the sample.[17] Then the following formulas hold:

$$\sigma_{zz}^{\text{vol}}=\sigma_0\gamma\eta^2,\ \eta^{1/2}\ll\gamma\ll 1,$$

$$\sigma_{zz}^{\text{vol}}=\sigma_0\gamma^2\eta^{3/2},\ \gamma\leqslant\eta^{1/2}\ll 1, \tag{3}$$

where σ_0 is the conductivity in the absence of a magnetic field.[17,18] Its value is of the order of the conductivity of metals such as copper, gold, and silver. Here and below, $r=ep_F/eH$ is the radius of curvature of an electron orbit at $\theta=0$; $\gamma=r/l$; c is the velocity of light; e is the electron charge; p_F is the characteristic radius of the Fermi surface, which is a weakly corrugated cylinder. If L is not much greater than the free path length l, the contribution of σ_{zz} from charge carriers "slipping" along the boundaries $y_s=0, L$ must be taken into account. These are conduction electrons with closed orbits. Their number relative to the total number of charge carriers is not large (about $\eta^{3/2}$), but their mobility is higher than that of the electrons that do not strike the surface of the sample. For specular reflection of electrons at the boundary of the sample, electron drift along the z axis is limited by volume scattering only. The displacement of an electron along the z axis during the time between two collisions with the surface $y_s=0$ is about $r\eta^{1/2}$. If the probability w of diffuse scattering with partial erasure of the memory of the past history of the electrons is low, then the effective free path of slipping electrons can be estimated as $l_{\text{eff}}=r\eta^{1/2}/(r/l+w)$ and the conductivity of the boundary layer is

$$\sigma_{zz}^{\text{skin}}=\sigma_0\frac{l_{\text{eff}}}{l}=\sigma_0\frac{r\eta^{1/2}/l}{r/l+w}. \tag{4}$$

The fraction of electrons which form the skin layer is about $\eta^{3/2}r/L$ and the conductivity of the entire sample

$$\sigma_{zz}=\sigma_{zz}^{\text{skin}}\eta^{3/2}r/l+\sigma_{zz}^{\text{vol}} \tag{5}$$

essentially depends only on the state of the surface of the bulk specimen $(l\ll L,d)$ in very strong and perhaps currently unattainable magnetic fields such that $r/l\ll\eta^2$.

The resistivity for the current flowing along the layers saturates in strong magnetic fields and is of the order of $1/\sigma_0$. When the magnetic field deviates from the direction along the layers all sections of the corrugated cylinder cut by the plane $p_z=\text{const}$ are closed and the resistance for the current flowing across the layers also saturates for $r\ll l$.

Thus the current lines in organic conductors whose Fermi surface is a weakly corrugated cylinder and does not contain any extra sheets are uniformly distributed over the entire cross section normal to the current. For any orientation of a magnetic field the conductivity is determined mainly by charge carriers that do not collide with the boundary.

The distribution of the current lines is substantially different in a conductor whose Fermi surface consists of elements with different topological structure. There are grounds for believing that the Fermi surface in organic complexes $(\mathrm{BEDT-TTF})_2\mathrm{MHg(SCN)}_4$ (where M is either a metal from the group (K, Rb, Tl) or NH_3) consists of a weakly corrugated cylinder and weakly corrugated planes.[19] In such conductors open sections of the Fermi surface cut by the plane $p_z=\text{const}$ occur for any orientation of a magnetic field and the resistivity saturates in a strong magnetic field for only selected directions of the current.

When the magnetic field makes an angle $\alpha=(\pi/2-\theta)\gg\eta$ with the layers, the electron trajectories in momentum space are almost indistinguishable. Magnetoresistance investigations of the interaction of charge carriers with the surface of a sample prove to be effective in a wide range of angles α.

Consider the case where the corrugated planes lie in the p_xp_y plane and the electron drift along the p_y axis in momentum space is limited. The equations of motion

$$\frac{\partial p_x}{\partial t}=\frac{eH}{c}(v_y\cos\theta-v_z\sin\theta),$$

$$\frac{\partial p_y}{\partial t}=-\frac{eHv_x}{c}\cos\theta, \tag{6}$$

$$\frac{\partial p_z}{\partial t}=\frac{eHv_x}{c}\sin\theta$$

for charge carriers that do not come into contact with the boundaries of the sample imply

$$\overline{v_x}=\frac{1}{T}\int_0^T dt\,v_x(t)=0, \tag{7}$$

where $T=2\pi m^*c/eH$ is the period of the electron motion in a magnetic field and m^* is the effective electron cyclotron mass. If the motion on an open orbit in momentum space is aperiodic, T is a time interval which is long compared to the free path time τ.

Thus the contribution to the conductivity along the x axis by volume electrons for closed and open trajectories in momentum space is inversely proportional to H^2, specifically, $\sigma_{xx}^{\text{vol}} \simeq \sigma_0 (r/l)^2$.

The drift of electrons slipping near the boundaries of the sample is different from zero along the x axis. The contribution of these electrons to the conductivity could predominate. At angles θ different from $\pi/2$ all orbits in the momentum space of the electrons whose states lie on a corrugated cylinder of the Fermi surface are closed. Their drift along the y axis is small. Colliding with the boundary $y_s = 0$ the electrons drift for a long time along the x axis and move slowly with velocity $\overline{v_y} = \overline{v_z} \tan\theta$ into the bulk of the conductor. For θ substantially different from $\pi/2$, i.e. when $\tan\theta$ is of the order of 1, their effective free path is

$$l_{\text{eff}} = \frac{r}{r/l + w + \eta \tan\theta}. \tag{8}$$

Since the quasi-two-dimensionality parameter for the electron energy spectrum in organic layered conductors is of the order of 10^{-2}, in a wide range of angles θ ($\eta \tan\theta \ll 1$) the direct electric current is almost totally concentrated near the surface of the sample if

$$L = \frac{l}{r/l + w + \eta \tan\theta}. \tag{9}$$

Charge carriers that interact with the boundaries $z_s = 0, d$ are also more mobile than electrons that are "unaware" of the existence of the sample boundaries. Electron reflection from the boundaries $z_s = 0, d$ is nearly specular because the electrons move slowly along the z axis and approach these boundaries at small angles. Therefore a large fraction of the current is concentrated not only along the boundaries $y_s = 0, L$ but also along the boundaries $z_s = 0, d$. Conduction electrons approaching the boundaries $y_s = 0, L$ at large angles are at most capable of weakening the correlations between the incident and reflected electrons. The possibility of specular reflection of charge carriers at the boundaries $y_s = 0, L$ can be easily determined by studying the resistivity of a layered conductor under static skin effect conditions.

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