New Hall voltages in a planar pinning potential

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Abstract

Two-dimensional vortex dynamics in a planar pinning potential (PPP) created by uniaxial or bianisotropic pinning planes in the presence of thermal fluctuations is considered on the basis of a Fokker-Planck equation. Explicit expressions for two new nonlinear anisotropic Hall voltages (longitudinal and transverse with respect to the current direction) are derived and analyzed. The physical origin of these odd (with respect to magnetic field reversal) voltages is caused by the subtle interplay between even effect of vortex guiding along the PPP and the odd Hall effect. Both new voltages are going to zero in the linear regimes of the vortex motion (i.e. in the thermoactivated flux flow (TAFF) and ohmic flux flow (FF) regimes) and have a bumplike current j or temperature θ dependence in the vicinity of highly nonlinear resistive transition from the TAFF to FF. As new odd voltages arise due to the Hall effect their characteristic scale is proportional to the Hall constant as for ordinary "steplike" odd Hall voltage, investigated earlier by Mawatari.

Key words: vortex; guiding; Hall-effect;

The influence of a planar pinning potential (PPP) on the transport properties of high temperature superconductors (HTSCs) is a topic of a great current interest [1-12]. Two main reasons stimulated this interest. First, in some HTSCs twins can easily be formed during the crystal growth. Second, in layered HTSCs the system of interlayers between parallel ab-planes can be considered as a set of unidirectional planar defects which provoke the intrinsic pinning of vortices [1].

As the pinning force in a PPP is directed perpendicular to the pinning planes [1], the vortices tend to move along these planes if the driving force has a nonzero component in any in-plane direction. Such a guided motion of vortices in a PPP leads to the appearance of a $\rho_\perp^+$-contribution to the transverse (with respect to the current direction) magnetoresistivity which is even with respect to the magnetic field reversal [2-4]. It may as well strongly modify the usual odd transverse Hall response, as it was shown recently in [3–5].

Below we outline the main points of references [3-5].

The initial Langevin equation for a vortex moving with velocity $\mathbf{v}$ in a magnetic field $\mathbf{B} = \mathbf{n}B$ ($B \equiv |\mathbf{B}|$, $\mathbf{n} = n\,\mathbf{z}$, $\mathbf{z}$ is the unit vector in the z direction, and $n = \pm 1$) has the form

$$\eta \mathbf{v} + n\,\alpha_H\,\mathbf{v} \times \mathbf{z} = \mathbf{F}_L + \mathbf{F}_p + \mathbf{F}_{th}\,, \qquad (1)$$

where $\mathbf{F}_L = n(\Phi_0/c)\,\mathbf{j} \times \mathbf{z}$ is the Lorentz force (Φ_0 is the magnetic flux quantum, c is the speed of light), $\mathbf{F}_p = -\nabla U_p$ is the pinning force (U_p is the pinning potential), $\mathbf{F}_{th}$ is the thermal fluctuation force represented by a Gaussian white noise, η is the vortex viscosity, and α_H is the Hall constant.

Our bi-anisotropic PPP is assumed to be separable and two-periodic, i.e. $U_p(x,y) = U_{pa}(x) + U_{pb}(y)$, $U_{pa}(x) = U_{pa}(x+a)$, $U_{pb}(y) = U_{pb}(y+b)$, where a and b are the periods in x and y direction, respectively. Due to the separability of $U_p(x,y)$, two-dimentional Fokker-

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Planck equation consistent with (1) can be solved. After some calculations [5] the solution of the problem can be presented as

$$\langle v_x \rangle = F_x \nu_x(F_x)/\eta, \ \langle v_y \rangle = F_y \nu_y(F_y)/\eta \qquad (2)$$

where $F_x \equiv F_{Lx} - \delta F_{Ly} \nu_y(F_{Ly})$, $F_y \equiv F_{Ly} + \delta F_{Lx} \nu_x(F_{Lx})$, $\delta \equiv n \in$ and $\in \equiv \alpha_H/\eta \ll 1$. Here the even functions of their arguments ν_x and ν_y have the physical meaning of the probability of the vortex overcoming the potential barrier in the x or y direction under the influence of the effective motive force F_x or F_y, respectively [5]. It is of particular importance that F_x and F_y are combinations of the Lorentz and Magnus force in the corresponding directions and change their *magnitude* under the magnetic field reversal (if $\alpha \neq 0, \pi/2$) due to the factor $n = \pm 1$. It follows from this latter procedure that ν-functions should be presented as sums of the even and odd parts, i.e. $\nu = \nu^+ + \nu^-$, where $\nu^+(F) = \nu^+(-F) \approx \nu(F)$ and $\nu^-(F) = -\nu^-(-F)$. In these terms the new odd contributions to longitudinal and transverse (relative to the current direction) components of the dimensionless (in units of ρ_f) resistivities are [5]:

$$\rho_{\|}^- = \nu_y^-(F_y)\,\sin^2\alpha + \nu_x^-(F_x)\,\cos^2\alpha\,, \qquad (3)$$

$$\begin{aligned}\rho_{\perp}^- &= \epsilon\,\nu_x(F_{Lx})\,\nu_y(F_{Ly}) + \\ &+ [\nu_x^-(F_x) - \nu_y^-(F_y)]\sin\alpha\cos\alpha\end{aligned} \qquad (4)$$

where α is the angle between the $\mathbf{j}$ and the $\mathbf{y}$ vector, $\pm$ denote even and odd components of the resistivities with respect to the magnetic field reversal [3] and

$$\begin{aligned}\nu_y^-(F_y) &\approx \epsilon\,F_{Lx}\nu_y'(F_{Ly})\,\nu_x(F_{Lx})\,, \\ \nu_x^-(F_x) &\approx -\epsilon\,F_{Ly}\nu_x'(F_{Lx})\,\nu_y(F_{Ly})\,.\end{aligned} \qquad (5)$$

Eqs. (3) – (5) are accurate to the first order in $\epsilon \ll 1$ and contain a lot of new physical information which will be elaborated on elsewhere [12]. However, it is instructive to discuss in short the main physically important features of Eqs.(3)-(4). As it follows from them, Eq. (3) describes the new odd longitudinal magnetoresistivity $\rho_{||}^-$ induced by guiding of vortices along the "channels" of the washboard PPP for $\alpha \neq 0, \pi/2$. Recently, the $\rho_{||}^-$ was observed experimentally in a single crystal of $YBa_2Cu_3O_{7-\delta}$ with twins oriented at angle $\alpha = \pi/4$, i.e. in the case where $\rho_{||}^-(\alpha)$ is expected to be maximal. Eq. (4) for the odd transverse (Hall) resistivity consists of two parts. The first one is proportional to the product of ν-functions which have usual (j, θ)-steplike behavior [3,5]. whereas the second part describes new odd Hall contributions proportional to the ν^--functions, which have a bell-shape (j, θ)-dependence [3,5].

Main distinctive properties of these resistivities can be summarized as follows:

a) they are proportional to the *odd* (j, θ)-*bumblike* part of the angle-dependent probability of overcoming the potential barriers of the PPP $\nu^-(j, \theta)$ (see Eq. (5)), which is zero at $\alpha = 0, \pi/2$.

b) they change the sign with a magnetic field reversal because the appearance of ν^- is due to the Magnus force contribution to the effective motive forces F_x and F_y.

c) they are going to zero in the linear regimes of the vortex motion (TAFF and FF).

d) their angular dependence is proportional to the $\sin 2\alpha$ factor which is zero at $\alpha = 0, \pi/2$.

e) at they arise due to the Hall-effect, their characteristics scales are proportional to the Hall constant as for ordinary steplike (in (j, θ)-dependences) odd Hall voltage (first term in Eq. (4)).

f) the appearence of these new odd contributions leads to the new specific angle-dependent scaling relations for the Hall conductivity in PPP [3-5, 12].

In conclusion, the appearence of the new odd Hall voltages in a PPP follows from emergence of a certain equivalence of xy-direction for the case where a guiding of vortices along the channels of the washboard PPP is realized at $\alpha \neq 0, \pi/2$.

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