Helicon damping in a metal with diamagnetic domains

E. P. Vol'skiĭ

Institute of Solid State Physics, USSR Academy of Sciences
(Submitted 8 December 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 8, 585–588 (20 October 1977)

A new mechanism is proposed for the hysteretic damping of helicons and is connected with excitation of eddy currents when the walls of de Haas–van Alphen domains move under the influence of the helicon field. The results of the theory are compared with experiments on aluminum.

PACS numbers: 75.60.Ch

An experimental investigation[1] of the characteristics of helicons in highly perfect aluminum single crystals has revealed an appreciable growth of the damping of the waves at temperatures below 1 K, as well as a number of other singularities due, as shown by experiment, to the transition of the metal to a state with diamagnetic de Haas–van Alphen domains.[2] We report here an attempt to interpret at least some of the observed effect, and primarily the strong damping of the helicons.

The main idea of this paper is to calculate the losses due to the dissipative eddy currents excited by the motion of the domain walls. A similar effect exists when the magnetization of metallic ferromagnets is reversed.[3]

Before we proceed to calculate the losses in one particular example, we make a few remarks of general character concerning the electrodynamics of helicons in a situation with diamagnetic domains. We take first into account the fact that the period of the domain structure[4] should in most cases of practical interest be small in comparison both with the dimensions of the metal and with the helicon wavelength. Therefore, in analogy with the procedure used for a superconductor in the intermediate state,[5] the helicons can be described with the aid of macroscopic fields and currents averaged over the domain structure and satisfying Maxwell's equations, as well as, we assume, the linear local relations:

$$\mathbf{e} = \hat{\rho}\,\mathbf{j}\,, \tag{1}$$

$$\mathbf{h} = \hat{\mu}\,\mathbf{b} + \hat{\zeta}\,\dot{\mathbf{b}}, \tag{2}$$

where $\hat{\rho}$ is the static magnetoresistance tensor and $\hat{\mu}$ is the static tensor of the differential magnetic susceptibility.[6] The three-dimensional determinant of the latter is subject to the additional restriction

$$\det \| \hat{\mu} \| = 0 \tag{3}$$

which takes into account the transition of the metal into a state with diamagnetic domains. The additional wave-energy scattering that appears in this transition is taken into account phenomenologically by introducing in (2) the additional field proportional to $\dot{\mathbf{b}}$.[7]

The phenomenological approach, however, does not make it possible to calculate the helicon damping. We therefore determine below the microscopic intradomain distribution of the eddy currents for one particular case.

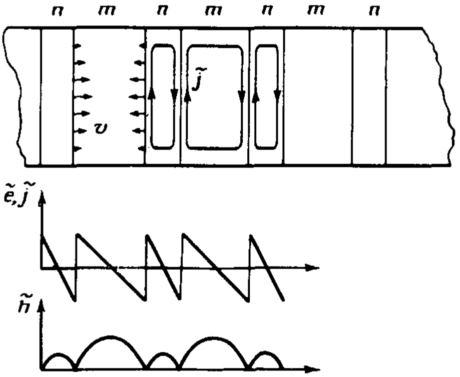

FIG. 1. Top: Section through a metallic layer by a plane perpendicular to the magnetic-field direction. The domain structure, the character of motion of the domain walls, and the eddy-current lines are shown schematically. Bottom: Amplitudes of the eddy field and currents against the coordinate in a direction perpendicular to the domain walls.

Bearing in mind the interpretation of the concrete experiments,[1] we consider a plane-parallel layer of an isotropic metal in a homogeneous external magnetic field with induction $\mathbf{B}_0$, making an angle θ with the normal to the surface of the layer. A standing helicon wave of frequency ω is excited in symmetrical fashion in such a way that the layer thickness $2d$ spans half the wavelength. We are interested in the additional energy scattering of this wave, due to the diamagnetic domains.

We assume that in the absence of the helicons an ideally periodic domain vector with period a is established in the metal, in the form of alternating plane-parallel layers of two magnetic phases, perpendicular to the metal surface (see Fig. 1). We disregard the bending of the domain walls at the surface.

The width of the layers of the two phases are pa and $(1-p)a$, respectively. The coefficient p determines the relative phase concentration and ranges from zero to unity when the external magnetic field is varied within one period of the de Haas–van Alphen oscillations. The metal is therefore isotropic and the de Haas–van Alphen magnetic moment is small is comparison with the external field $\mathbf{B}_0$, while the constant magnetic field and the induction in the domains and in the transition layers between them in the domain-wall plane can be regarded as parallel to the external field $\mathbf{B}_0$.

In the described geometry, the magnetic field $\mathbf{H}$ will, naturally, be uniform throughout the interior of the metal, and the magnetic induction assumes in the two phases values B_m and B_n, respectively, so that the magnetic induction inside the metal, averaged over the domain structure, is

$$B = pB_n + (1-p)B_m. \tag{4}$$

The average helicon magnetic induction $\mathbf{b}$, which revolves in an elliptic orbit in a plane parallel to the layer surface, is added to the vector $\mathbf{B}$, and, as follows from (4), causes a change in the phase concentration p and a corresponding motion of the domain walls if the projection of the vector $\dot{\mathbf{b}}$ along $\mathbf{B}$ is not equal to zero. The amplitude of wall velocity also varies over the layer thickness like the amplitudes b and $\dot{b}$, i.e., in accordance with a cosine law, and has a maximum at the midpoint of the layer (Fig. 1).

The wall section moving with velocity v produces an electric-field discontinuity directed parallel to the wall and perpendicular to $\mathbf{B}$, of magnitude

$$2\tilde{e} = (B_n - B_m)v/c\ . \tag{5}$$

The dependence of this component of the solenoidal electric field and of the associated density of the dissipative current on the coordinates in the direction perpendicular to the walls is shown in Fig. 1.The other components of $\tilde{e}$ and $\tilde{j}$ are smaller in a ratio a/d and can be disregarded in the calculation of the losses.

The loss due to the eddy currents can now be easily expressed in terms of the velocity v, by averaging the products $\tilde{e}\tilde{j}$ over the volume and the time. Equating the eddy-current loss to the loss due to the irreversible magnetization reversal and calculated by averaging $\tilde{h}\dot{b}/8\pi$, where $\tilde{h}$ is the eddy-current field and $\dot{b}$ is the component of the helicon induction $\dot{\mathbf{b}}$ along the $\mathbf{B}$ direction, we obtain an expression for the velocity of the domain wall

$$v = (2p^2 - 2p + 1)\, a\dot{b}_1 \sin\theta / 2(B_n - B_m), \tag{6}$$

where $b_1 = b_{1m} \cos\omega t \cos kz$ is the helicon-induction component in the direction parallel to the domain walls.

For the relative resonance width connected with the losses considered here we obtain the formula

$$\Gamma \sim (2p^2 - 2p + 1)^2 (ka)^2 \sin^2\theta / \alpha , \tag{7}$$

where α is the ratio of the diagonal and Hall components of the magnetoresistance tensor. The damping (7) is of the order of unity and increases with decreasing temperature if we use for the period a of the domain structure the expression given in[4] At $p=0.5$, the damping (7) is minimal. All this agrees with experiment.[1] It should be noted, however, that the results of the present paper are valid in the frequency region where the depth of the skin layer for a wave propagating in a direction perpendicular to the magnetic field exceeds the period of the domain structure.

The authors thanks A.P. Kazantsev for interest in the work and for a discussion of the work.

[1]V.I. Bozhko and E.P. Vol'skiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 337 (1977) [JETP Lett. **26**, 223 (1977)].
[2]J.H. Condon, Phys. Rev. **145**, 526 (1966); A.A. Abrikosov, Vvedenie v teoriyu normalnykh metallov (Introduction to the Theory of Normal Metals), Moscow, 1972, p. 190.
[3]H.J. Williams, W. Shockley, and C. Kittel, Phys. Rev. **80**, 1090 (1950).
[4]I.A. Privorotskiĭ and M.Ya. Azbel', Zh. Eksp. Teor. Fiz. **56**, 388 (1969) [Sov. Phys. JETP **29**, 214 (1969)].
[5]A. Andreev, Zh. Eksp. Teor. Fiz. **51**, 1510 (1966) [Sov. Phys. JETP **24**, 1019 (1967)].
[6]E.P. Vol'skiĭ, Zh. Eksp. Teor. Fiz. **69**, 1313 (1975) [Sov. Phys. JETP **42**, 670 (1975)].
[7]A.B. Pippard, Proc. R. Soc. London Ser. A **272**, 192 (1963).