New surface magnetoacoustic waves caused by piezomagnetism

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Surface waves of new type are predicted in a semi-infinite piezomagnetic material. The best material for observing these waves is the tetragonal antiferromagnet CoF_2.

Under certain conditions the propagation of a Rayleigh wave along the free surface of a piezoelectric crystal may be accompanied by the propagation of a purely shear surface acoustic wave polarized along a high-symmetry axis of the crystal.[1,2] A purely shear surface acoustic wave may also propagate in magnetic crystals by virtue of magnetostriction.[3] Such waves are damped only slightly with distance into the interior of the material and thus hold promise for practical applications in high-frequency acoustoelectronic devices.

In a magnetically ordered crystal with a compensated magnetic moment (in antiferromagnets) there is yet another effective mechanism (in addition to magnetostriction) for magnetoelastic coupling: a piezomagnetic mechanism.[4–7] In the present paper we analyze the possibility that shear surface magnetoacoustic waves can propagate in a semi-infinite antiferromagnetic crystal by virtue of a piezomagnetic effect.

Magnetostriction and piezomagnetism should evidently lead to physically different results, since the terms in the magnetoelastic energy which are responsible for each of these effects are invariant under various symmetry elements of the crystal.[7] The magnetoelastic part of the free energy of an antiferromagnet can be written

$$F_{\rm me}=A_{ijkl}M_iM_ju_{kl}+B_{ijkl}L_iL_ju_{kl}+C_{ijkl}M_iL_ju_{kl}, \tag{1}$$

where $\mathbf{M}=\mathbf{M}_1+\mathbf{M}_2$ and $\mathbf{L}=\mathbf{M}_1-\mathbf{M}_2$ are the ferromagnetism and antiferromagnetism vectors, $\mathbf{M}_{1,2}$ are the sublattice magnetizations, $u_{kl'}$ is the strain tensor, and A, B, and C are magnetoelastic constants. The first two terms in (1), which pertain to the magnetostriction, are invariant under the interchange of the magnetic moments of the sublattices, while the last term—the piezomagnetic term—changes sign under this operation.

The system of equations describing the propagation of magnetoacoustic waves in magnetic materials consists of the equations of the theory of elasticity and magnetostatics:

$$\rho\ddot{u}_i=\partial\sigma_{ik}/\partial x_k,\quad \operatorname{div}\mathbf{B}=0. \tag{2}$$

Here $\sigma_{ik}=\partial F/\partial\sigma_{ik}$ is the stress tensor, $\mathbf{B}=\mathbf{H}+4\pi\mathbf{M}$ is the magnetic induction, ρ is the mass density, $\mathbf{H}$ is the alternating magnetic field, and the total free energy F has magnetic, elastic, magnetostrictive, and piezomagnetic components.[6,7]

For the remainder of this analysis we assume an easy-axis tetragonal antiferromagnet; examples are fluorides of transition metals, such as MnF_2 and CoF_2. A piezomagnetic effect was discovered experimentally in these materials by Borovik-Romanov.[5] For such structures the free energy describing the piezomagnetism is[4,6]

$$F_{\rm pm}=-\gamma_1(u_{xz}H_y+u_{yz}H_x)-\gamma_2u_{xy}H_z, \tag{3}$$

where γ_1 and γ_2 are piezomagnetic constants.

We assume that the crystal occupies the region $y>0$. We consider a transverse-polarized acoustic wave which is propagating along the surface of the crystal. The propagation direction is the x axis, and the displacement direction is the z axis, which is the easy axis of the antiferromagnet. System (2) can then be written

$$\rho\ddot{u}^{(z)}=\lambda\Delta u^{(z)}-2\gamma_1\psi_{x,y},\qquad \Delta\psi+4\pi\gamma_1u^{(z)}_{x,y}=0, \tag{4}$$

where $\lambda=4\lambda_{xzxz}$ is an elastic constant,[6] ψ is the magnetic potential ($\mathbf{H}=-\operatorname{grad}\psi$), Δ is the Laplacian, and the subscripts on ψ and $u^{(z)}$ mean differentiation: $a_{x,y}\equiv\partial^2a/\partial x\partial y$. These equations are to be solved under boundary conditions at the surface of the crystal:

$$\psi^{(i)}=\psi^{(e)},\quad \sigma_{zy}=0,\quad B_y^{(i)}=-\partial\psi^{(e)}/\partial y\quad \text{at}\quad y=0. \tag{5}$$

The superscripts i and e mean that the given quantity pertains to the regions $y>0$ and $y<0$, respectively. We seek a solution in the form

$$u^{(z)},\ \psi^{(i)}\propto\exp[-\varkappa y+i(kx-\omega t)],$$

$$\psi^{(e)}\propto\exp[ky+i(kx-\omega t)].$$

From system (4) we find

$$\rho\omega^2=\lambda(k^2-\bar{\varkappa}^2),\quad \bar{\varkappa}=\varkappa(1+4\Lambda)^{1/2}, \tag{6}$$

where $\Lambda=2\pi\gamma_1^2/\lambda$ is the magnetochemical coupling constant. The relationship between $\varkappa$ and k is found from boundary conditions (5): $\varkappa=\Lambda k$. Substituting the latter expression into (6), we find the dispersion relation

$$\rho\omega^2=\lambda[1-\Lambda^2(1+4\Lambda)]k^2. \tag{7}$$

Expressions for the displacement and the magnetic potential can be found within a constant factor A:

$$u^{(z)}=\exp(-\varkappa y)A\exp i(kx-\omega t)$$

$$\psi^{(i)}=2\pi i\gamma_1\exp(-\varkappa y)A\exp i(kx-\omega t),$$

$$\psi^{(e)}=2\pi i\gamma_1\exp(ky)A\exp i(kx-\omega t). \tag{8}$$

System (4) and its solutions (7) and (8) differ substantially from the initial equations (and thus the solutions) describing both shear surface acoustic waves in piezoelectric materials[1,2] and shear surface acoustic waves propagating in magnetic materials by virtue of the magnetostriction mechanism,[3] because of the different symmetry of the problem. The primary difference is in the distribution of the alternating magnetostatic field in the crystal. While either the pie-

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zoelectric field or the magnetic field in a shear surface acoustic wave has two components—a rapidly damped component ($\propto e^{-ky}$) and a slowly damped component ($\propto e^{-\varkappa y}, \varkappa \ll k$)—the wave under consideration here has only a single component: a field which is damped slowly with distance into the interior of the cryustal ($\propto e^{-\varkappa y}$). There are also differences in the dispersion relations describing these types of waves (∮17 in Ref. 6).

The antiferromagnet CoF_2 can be recommended as a material in which the effects predicted here could apparently be seen. This antiferromagnet has piezomagnetic moduli higher than those of any other unaxial crystal.[5] Working from the results of Ref. 5, we estimate a value[1)] $\gamma_1 \sim 10^4$. If we use instead Moriya's estimate,[8] which is eight times that in Ref. 5, we find values for the piezomagnetic moduli γ_1 which are comparable in magnitude to the piezoelectric moduli in piezoelectric materials ($\beta \sim 10^5$). Since the measurement in Ref. 5 were carried out under static conditions, the effects discussed here may serve as a manifestation of a piezomagnetic interaction in a dynamic situation.

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[1)]In Ref. 5 the piezomagnetic potential is written in the form $\tilde{F}_{pm} = -\gamma_{ikl} H_i u_{kl}$, so that γ_1 and $\tilde{\gamma}_1$ are related by $\gamma_1 = 4\lambda_{xzxz}\tilde{\gamma}_1$ [$\gamma_1 = 2\cdot 10^{-3}$ G(kg/cm^2)$^{-1}$, $\lambda_{xzxz} \sim 10^6$ kg/cm2].

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