# Magnetoelectric resonance in a layered ferrite-semiconductor system

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A constant emf appears in the semiconductor component ferrite-semiconductor system when volume as well as surface magnetostatic oscillation modes are excited in the ferrite component. It is shown that the emf in the semiconductor is the result of the Hall effect in the field of the electromagnetic wave excited by the natural oscillations of the ferrite magnetization. Plots of the emf against the external magnetic field strength are presented for a layered structure consisting of a coaxial structure of *n*-type germanium disks in contact with yttrium-iron garnet disks.

One of the interesting phenomena observed in the investigation of thin metallic magnetic films and magnetic semiconductors at microwave frequencies is the appearance of a constant emf in the case of ferromagnetic resonance[1-4], the so-called magnetoelectric resonance. In principle, a constant emf can be produced in these materials by microwave oscillations for the same reason as in ordinary semiconductors, but the magnetic properties of the material introduce, naturally, a certain distinguishing feature in the mechanism of emf production[3-7] and call for a revision of the concept developed for purely semiconducting materials.

According to present-day concepts (see[3-7]), an emf can be produced in a magnetic substance by the following: 1) the Hall effect due to the nonlinearity of the carrier motion in the field of the microwave electromagnetic wave excited by the natural oscillations of the magnetization; 2) the Hall effect due to nonlinearity of the carrier motion in the field of excited microwave spin waves (dragging of the carriers by the spin waves); 3) the inhomogeneity of the carrier distribution, due to the heating of the electron gas by the microwave. However, the appearance of an emf because of the last two causes is possible only at a sufficiently large signal power acting on the investigated material. This makes it possible to differentiate in experiment the emf produced by the first of these causes from the others.

In the performed experiments[1-4] they registered the emf produced in ferromagnetic resonance under conditions of relatively low microwave power; this indicates to a certain degree that an important role is played in the production of the emf by the nonlinearity of the carrier motion in the field excited by the natural oscillations of the magnetization.

The intensity of the dc electric field ($E_0$) produced in the semiconductor by the electromagnetic wave and producing in turn the corresponding emf, takes in the classical approximation ($\omega_c\tau \ll 1$, where $\omega_c$ is the cyclotron frequency and $\tau$ is the carrier relaxation time) the form

$$\mathbf{E}_0=\mathbf{E}_{01}+\mathbf{E}_{02}\propto\omega_c\tau\left[\frac{[\mathbf{E}\times\mathbf{B}_1]}{B_0}+(\omega_c\tau)\frac{\mathbf{B}_1[\mathbf{E}\times\mathbf{B}_0]}{B_0^2}\right], \qquad (1)$$

where $\mathbf{E}$ is the ac component of the electric field and $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1$ stands for the dc and ac components of the magnetic induction. The first term in this expression, $\mathbf{E}_{01}$, describes the electric field intensity produced as a result of the carrier drift in the direction of the Poynting vector (i.e., the Hall effect due to the microwave components $\mathbf{E}$ and $\mathbf{B}$ henceforth called for brevity the microwave Hall effect). The second term describes the electric field intensity $\mathbf{E}_{02}$ due to the deviation of the current of the carriers drifting under the influence of the microwave from the direction of the Poynting vector in the presence of a constant magnetic field. Thus, depending on the ratio of $\mathbf{E}_{01}$ and $\mathbf{E}_{02}$, the direction and magnitude of the combined emf given by expression (1) can vary in a wide range. The experiments do not establish unequivocally the factors that determine the combined emf. It is stated in[6] that $\mathbf{E}_0 \approx \mathbf{E}_{02}$, and in[4] that $\mathbf{E}_0 \approx \mathbf{E}_{01}$.

The appearance of magnetoelectric resonance can be expected also in a different object, namely a layered ferrite—semiconductor structure. Indeed, the processes that occur in a magnetic semiconductor and probably in a layered structure may be identical to a considerable degree. Thus, in ferromagnetic resonance in a ferrite, the field increases not only inside the ferrite but also on its outside. To be sure, only the intrinsic quasistatic field, which is concentrated at the surface of the sample, increases strongly (the dipole field for homogeneous precession in an ellipsoidal sample and the multipole field for an inhomogeneous precession). If the semiconductor is thin and is located near the surface of a ferromagnet, then we can expect the appearance of a constant emf for all the reasons indicated above.

In a layered structure, the expected emf should apparently be much smaller than in a magnetic semiconductor, since the interaction of the ferromagnet's field with the carriers in the semiconductor occurs only in a small thin layer near the surface of the contact. In such a structure, however, we can use a ferromagnet and a semiconductor with arbitrary properties that are independent of one another. For example, we can take a ferromagnet with a large saturation magnetization $4\pi M_0$ and a narrow ferromagnetic-resonance line $2\Delta H$ and join it with a semiconductor having a large carrier mobility $\mu_{sc}$ or a large carrier density $n_{sc}$, and thus form a structure, of particular importance for experiments, in which the electric and magnetic properties greatly exceed the properties of the existing magnetic semiconductors. The latter circumstance gives grounds for hoping to obtain an emf at least not smaller than that observed in the experiments[1-4].

  

The observation and study of magnetoelectric resonance in a layered structure makes it possible to draw conclusions concerning its character, to separate distinctly its characteristics that are due only to the semiconducting properties and only to the magnetic properties, and also to investigate, in contrast to[1-4], the influence exerted on the semiconducting components of not only volume waves but also surface waves excited in the ferromagnetic component.

Such an experiment was performed; it is described later on.

The layered structure consisted of n-type germanium and yttrium iron garnet (YIG) disks in contact with one another. The samples were optically lapped. To exclude direct detection of the electric field of the electromagnetic oscillations of the ferrite sample by the contacts secured to the semiconductors, these contacts were made ohmic (the current-voltage characteristic of the contacts was linear, and the microwave signal detected by them did not exceed in the worst case 40 $\mu$V/W, cf. the results of[4]).

The layered structure was placed in the antinode of a microwave magnetic field (h) of a short-circuited waveguide. To excite the magnetostatic oscillations we used a transverse magnetic field (h perpendicular to the external constant magnetic field $H_0$) of frequency 3 GHz. The experiments were performed with the oscillations generated continuously, the layered structure being cooled with an air jet, and also in a pulsed regime, to prevent heating of the layered structure. The pulse duration was 50 $\mu$sec at a repetition frequency 30 Hz. In the described experiment, the field $H_0$ was applied both normally and tangentially to the plane of the layered structure, so that it was possible to excite a particular component of the natural oscillations of the ferromagnet. To limit the number of excited magnetostatic oscillations, we chose ferrite disks whose plane coincided with the crystallographic (001) plane[8].

Figure 1 shows plots of the emf and of the absorption $\alpha$ against the constant magnetic field $H_0$ for a normally magnetized layered structure consisting of coaxial YIG and germanium disks of like diameter, 7.8 mm. The YIG parameters were $4\pi M_0 = 1750$ G, $2\Delta H < 0.5$ Oe, and thickness 1.0 mm; The germanium disk had a resistivity $\rho = 12\ \Omega$-cm and a thickness 0.16 mm. The contacts on the semiconducting disks were placed in the same manner as on the ferromagnetic semiconductor in[3], i.e., one contact along the perimeter of the disk, and a second (point) contact at the center of the disk.

Plots of the emf and absorption were obtained with an automatic recorder in the continuous radiation regime at a power P = 1.2 W, the absorption spectrum consisted (see Fig. 1) of four clearly pronounced peaks. An exact interpretation of the peaks is impossible, since the corresponding electrodynamic problem for the layered structure has not yet been solved. However, on the basis of the solution of the problem for magnetostatic oscillations of an isolated ferrite disk[8], one can state with sufficient assurance, in our opinion, that the largest amplitude is apparently possessed by the peak of the homogeneous precession in the magnetic field $H_p$ (a mode analogous to that with the indices 0, 1, 1 in accordance with the classification of[8], numbered 1 in Fig. 1). In addition, in all probability, the modes excited are analogous to those with the indices 0, 5, 1; 0, 7, 1; and 0, 9, 1 (see[8]), which differ from 0, 1, 1 only

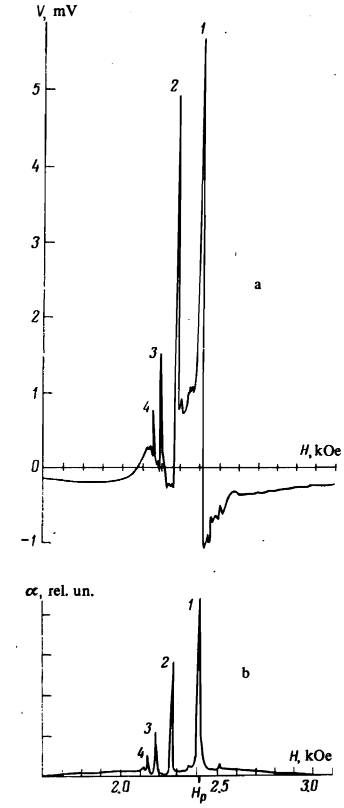


FIG. 1. Dependence of the emf (a) and of the absorption spectrum (b) on the constant magnetic field for a normally magnetized layered YIG–germanium structure at P = 1.2 W.

in a larger number of nodes of the field distribution along the radius of the disk (they are designated in Fig. 1 by the numbers 2, 3, and 4 respectively). We see that the character of the variation of the emf as a function of the constant magnetic field is analogous to the absorption spectrum, i.e., each absorption peak in the ferrite corresponds to an emf peak in a semiconductor located in exactly the same field. More careful measurements of the emf in the peaks (not with an automatic recorder, whose carriage inertia distorts the amplitude proportionality), have shown that the heights of the emf peaks have approximately the same ratio as the heights of the absorption peaks. The ratio of the four designated modes in Fig. 1 is 0 : 65 : 26 : 12 as given by magnetic measurements and 100 : 87 : 27 : 13 as given by emf measurements. The sign of the emf for all the peaks is the same and agrees with the sign of the component $E_{01}$ which is produced in the semiconductor as a result of the microwave Hall effect when homogeneous precession is excited in the ferrite, i.e., at the center of the disk the sign was positive, and at the edge negative. In fields exceeding $H_p$, a small negative emf is observed, and its value is practically independent of the field $H_0$; a similar negative emf "tail" is obtained also in weak fields $H_0$.

An analysis of the experimental data has shown that the character of the dependence of the emf on the value of the field $H_0$ depends strongly on the inhomogeneity of the constant and microwave magnetic fields, on the coaxiality of the YIG and semiconductor disks, and on the care with which the contacts were deposited on the semiconducting disk. It is necessary in the experiment to aim at a homogeneous external constant magnetic field, to prevent perturbation of the microwave magnetic field by the leads used to measure the constant emf, to place the point contact on the semiconducting disk as accurately on the center as possible, and to make the ring contact exactly circular about this center. If these requirements are not met, the ratio of the heights of the emf peaks changes, and shifting the centers of the disks relative to each other can lead even to a reversal of the sign of the emf for certain absorption peaks. The cause, in our opinion, is the existence of azimuthal currents in the plane of the structure. The emf measured between the central and the ring contacts, naturally, are identified with the radial currents in the layered structure. It is easy to understand, however, that following any violation of the electric symmetry of the structure by one of the mentioned factors (the lines of the azimuthal currents and the ring contact become non-concentric), the Hall effect due to the azimuthal current will also make a contribution to the measured emf. This contribution will be different for different disk modes. Even if the only currents present were radial, a mutual shift of the disk centers would lead, for example, to a change of the emf because the ring contact integrates the emf in azimuth.

To prevent this, it was decided to forgo the adopted experimental scheme and to produce on the semiconducting disk to ohmic point contacts, one of which is located as before at the center of the disk, and the other on its periphery (see the insert of Fig. 2a). This experimental scheme has practically reduced to zero the influence of the azimuthal Hall effect on the measured emf.

The emf and absorption plots shown in Fig. 2 are analogous to those of Fig. 1. One can see the same four absorption peaks. The emf duplicates again exactly the absorption curves. The ratio of the heights of the peaks is well maintained only for the two lowest modes of the ferromagnetic disk (with indices 1 and 2). The ratio of the heights of the peaks is 100 : 58 : 28 : 8.5 according to the magnetic measurements and 100 : 66 : 4.2 : 1.4 according to the emf measurements. The emf per unit power of the incident wave has increased sharply for homogeneous precession. In the linear regime, the system sensitivity is 6 mV/W if the ring and point contacts are used on the disk, and 150 mV/W if two point contacts are used. An emf up to 50 mV was observed directly in the experiments with two point contacts. To be sure nonlinear phenomena already made their appearance in the ferrite in this case.

Magnetoelectric resonance was also observed in a tangentially magnetized layered structure (the vectors h and $H_0$ lie in the plane of the disks). Figure 3 shows the dependence of the emf on the constant magnetic field in this case for a pulse-irradiated layered structure with point and ring contacts. The sign of the emf is opposite that obtained for a normally magnetized structure and its maximum value is accordingly smaller by several times. In the case of a tangentially magnetized structure, an emf due to surface modes is observed in addition to the emf due to the excitation of the volume modes. (We recall that in this type of magnetization of the ferrite the volume modes are observed in fields $H_0 > H_p$, and surface modes in fields $H_0 < H_p$.) A detailed identification of the modes for a tangentially magnetized structure is impossible, since the problem of the natural oscillations of a tangentially magnetized disk has not yet been solved.

When the direction of the external magnetic field is reversed, the character, magnitude (within the limits of experimental accuracy), and the sign of the emf, shown

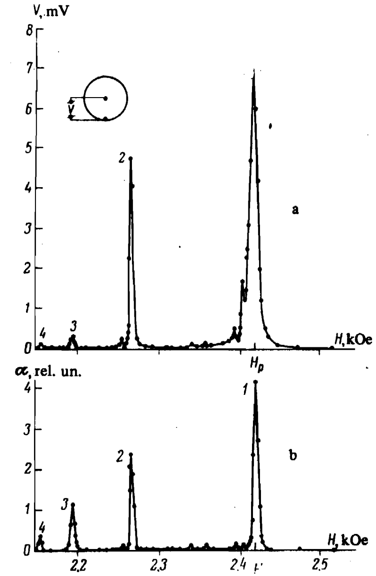


FIG. 2. Dependence of the emf (a) and of the absorption spectrum (b) on the constant magnetic field for a normally magnetized YIG–germanium structure at P = 48.5 mW. The insert shows the placement of the contacts on the germanium disk.

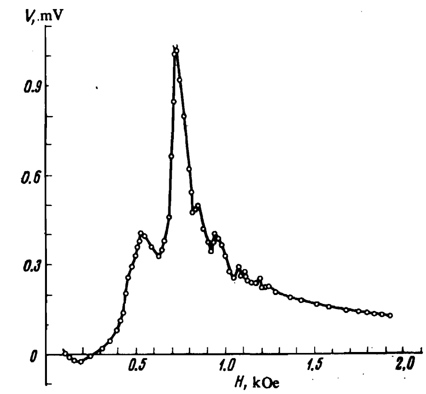


FIG. 3. Dependence of emf on the constant magnetic field for a tangentially magnetized layered YIG–germanium structure at P = 1.2 W.

in Fig. 1–3, remain unchanged. The preservation of the sign of the emf under this situation indicates that the observed emf is due mainly to the microwave Hall effect (the first term in expression (1)), as was proposed in[4]. If the emf were produced by the mechanism described by the second term of (1), as is assumed in[6], the emf would reverse sign. Thus, the effect of the mechanism described by the second term of (1) on the value of the emf is negligible.

A check on the dependence of the emf on the microwave signal power in magnetic fields $H_0$ corresponding to the resonance peaks has shown that this dependence remains linear until parametric excitation of the spin waves begins in the ferrite.

Magnetoelectric resonance occurs in all ferrite-semiconductor structures. Thus, it was observed by us in structures having different geometries (consisting of two plates, of a ferrite sphere and a semiconducting plate, etc.), different technologies (in composite structures of two contacting components, in structures where one of the components is a film deposited on the second component), varying chemical composition (with semiconducting components of indium antimonide, gallium arsenide, cadmium selenide, silicon, and tin oxide). The appearance of emf in ferromagnetic resonance in layered structures was noted between two arbitrary points of the semiconducting components: in particular, besides the longitudinal emf (described in the present article), a transverse emf (along the thickness of the semiconducting component) was also observed.

Thus, we have observed magnetoelectric resonance in a ferrite-semiconductor structure and obtained its principal characteristics. We have shown that at low levels of the signal applied to the structure it is due, to a decisive degree, to the microwave Hall effect produced in the semiconducting component of the structure by the electromagnetic fields excited by the natural oscillations of the magnetization in the ferrite component.

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