ELECTROMAGNETIC EXCITATION OF SOUND WAVES IN TIN AND BISMUTH

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Submitted February 28, 1969

Zh. Eksp. Teor. Fiz. 57, 132–140 (July, 1969)

Excitation of sound by electromagnetic waves incident on the surface of Bi and Sn single-crystal plates in a magnetic field is investigated at frequencies between 0.4 and 10 MHz. Excitation of the sound was revealed by the sharp changes in the impedance of the plate as a function of frequency. The singularities appeared during the establishment of standing sound waves in the plate. At helium temperatures, the sound in Bi was excited only in samples with a sufficiently long mean free path, and the amplitude of the sound oscillations increased with decrease in the temperature. The lines became appreciable for $H \sim 10$ Oe; increase of the magnetic field led to an increase in the intensity proportional to H^3, up to fields $H \sim 300$ Oe, when the penetration depth became comparable with the sound wavelength. In strong fields, the intensity of the observed lines fell off, but then again increased in fields of 2–7 Oe under conditions of an electromagnetic field that was homogeneous over the thickness; the intensity oscillated with a period in the reciprocal field that was one half the de Haas–van Alphen oscillation period. The mechanism of sound excitation in Bi in strong fields is of a magnetostrictive nature. In weak fields the excitation mechanism is not clear. In Sn and also in Bi at room temperature, the sound is excited by a ponderomotive force.

THE transformation of electromagnetic energy into acoustic energy in the bulk of a metal or near its surface can take place through a variety of mechanisms. The magnetostriction transformation in ferromagnets is well known and used in practice. It is less well known that appreciable amplitude of sound oscillations can be obtained by incidence of an electromagnetic wave on the surface of a metal located in a magnetic field $H \sim 10^3-10^4$ Oe, due to the ponderomotive force $\mathbf{F} = \mathbf{j} \times \mathbf{H}/c$ ($\mathbf{j}$ is the skin current).[1-3] In addition, sound excitation was observed when the speeds of sound and of the helicon propagated in the metal were equal,[4] and also when the sound wavelength and the spatial period of the system of the bursts was equal (special communication from Grimes and Liebhaber). In principle, the sound can be excited by any electromagnetic waves in metals.[5] As shown in the work of Kaganov et al.,[6] in the anomalous skin effect, the transformation of the electromagnetic wave in a sound wave can take place as the result of the disruption of local equilibrium between the forces exerted on the lattice by the external field and by the electrons. It is possible that just such a mechanism of excitation was observed by Abeles.[7] Finally, we recall the spontaneous emission of phonons at a sufficiently large drift velocity of the electrons taking part in the current,[8] although it should be noted that the electrons in these experiments were accelerated by a constant field, and the emission took place in a wide region of the spectrum.

As we have already reported,[9] the electromagnetic excitation of sound oscillations in bismuth possesses a number of singularities and cannot be convincingly explained at the present time by any of these mechanisms. In the present research, the results are given of a more detailed investigation of sound excitation in bismuth. In addition, for a comparison, experiments were performed on sound excitation in tin.

METHOD

The experiment consisted of the study of the derivatives of the surface impedance $Z = R + iX$ of a metal plate as a function of the frequency ω. For this case, excitation of sound oscillations by an incident electromagnetic wave was manifest by the sharp change of the electric characteristics of the metal upon establishment of standing sound waves in the same. Inasmuch as the energy dissipated in the acoustic resonator—the metal plate—at the instant of resonance is $W \sim QA^2 \sim Q\alpha^2E^2$ (where Q is the quality factor and A is the amplitude of the driving force, proportional to the coefficient α of transformation of the electromagnetic wave into the sound wave), the change of the real part of the surface impedance is $\Delta R \sim \alpha^2$. We can determine the value of Q independently from the width of the resonance curve $R(\omega)$. This method has the advantage that attachment of quartz transducers to the metal is not required and therefore we can avoid deformation of the sample upon cooling to liquid helium temperatures.

The block diagram of the apparatus is shown in Fig. 1. The samples, having the shape of disks of diameter 18 mm and thickness 0.5–2.0 mm, were placed inside an inductance coil of the oscillator circuit of a radiofrequency oscillator. The variable condenser C allowed us to change the oscillator frequency ω smoothly and the cut-off semiconductor diode D (varicap D-901) served to modulate the frequency. The negative feedback circuit inside the generator kept it close to the oscillation threshold when ω was varied over wide limits. Inasmuch as the modulation of the characteristic frequency of the circuit leads to strong parasitic modulation of the amplitude of oscillation, the measurement apparatus was tuned to twice the modulation frequency, 2Ω. As a result, the recorder registered the signal $U_y \sim -\partial^2U_\omega/\partial\omega^2 \sim \partial^2R/\partial\omega^2$ on the y axis (U_ω is the am-

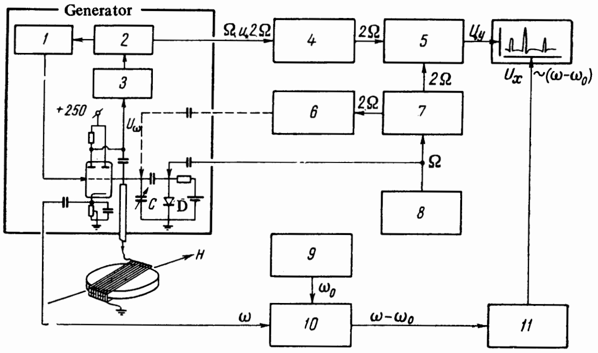

FIG. 1. Block diagram of the apparatus: 1 – dc amplifier, 2 – amplitude detector, 3 – rf amplifier, 4 – narrow band amplifier, 5 – synchronous detector with phase shifter, 6 – sensitivity calibrator, 7 – frequency doubler, 8 – sound generator, 9 – standard signal generator, 10 – mixer, 11 – frequency detector.

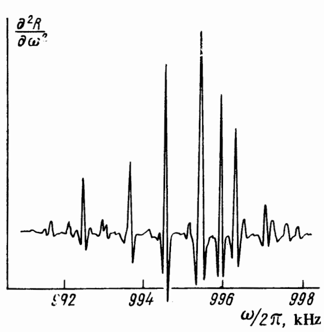

FIG. 2

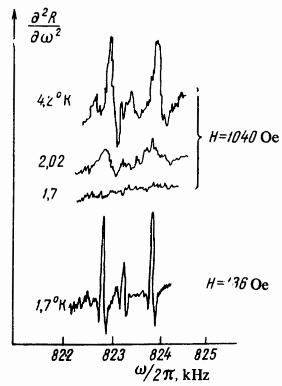

FIG. 3

FIG. 2. Record of a part of a group of resonances on a bismuth specimen with normal $n \parallel C_3$, $d = 1.01$ mm, $n \perp H \perp j$, $q = 1$, $T = 1.4°K$.

FIG. 3. Record of acoustic resonances in tin for $n \perp H \perp j$, $q = 1$.

Data on the quality factor obtained from measurement of the line width at various temperatures

Parameters of the acoustic wave	T, °K			
	77°	4.2°	1.7° normal state	1.7° superconducting state
Longitudinal, 0.82 MHz ($q=1$)	$2\cdot10^4$	$1.5\cdot10^3$	—	$6\cdot10^3$
Transverse, 1.44 MHz ($q=3$)	$5\cdot10^3$	$\sim5\cdot10^2$	$\sim3\cdot10^2$	—

plitude of the oscillation). To calibrate the sensitivity of the system, an electron tube was connected in parallel with the circuit; this tube introduced a standard damping signal into the circuit. The accuracy of the calibration was 5%.

Figure 2 shows an example of the recording of observed acoustic resonances. The resonance lines were located in dense groups on the frequency scale (up to one hundred lines in a group), separated by frequency intervals one order of magnitude greater. The location of the groups was determined by the condition of establishment of standing waves within the thickness of the sample d: $\omega_n = \pi q s d^{-1}$, where s is the speed of sound, q = 1, 3, 5, ... (see also [9]). Each separate line inside a group is related to some specific mode of oscillation. During the time of the experiment, the sample lay free in the coil on a plane support. A small displacement of the sample led to a change in the ratio of the amplitudes of the lines inside the group. The same took place also when liquid helium fell into the chamber with the measuring coil. This change in the relative intensity of excitation of the individual modes is evidently connected with an uncontrollable change in the location of the points of contact of the specimen with the support. The effect of such external factors as the value of the field H did not change the relative intensity of the resonances. Therefore, in studies of the effect of different parameters on the intensity of excitation, we traced variation of the amplitude of each individual line.

EXCITATION OF SOUND IN TIN

Experiments on tin were made on single crystal samples of thickness d = 2 mm, prepared from metal with a residual resistance $\rho_0/\rho_{room} \approx 10^{-5}$. The [100] axis was directed along the normal **n** to the surface of the sample.

The acoustic oscillations were excited only in the presence of a sufficiently strong magnetic field **H**; at $\mathbf{H} \perp \mathbf{n}$, transverse oscillations were excited, and at $\mathbf{H} \perp \mathbf{n}$ longitudinal. In the latter case, the angle between the vector **H** and the direction of the high-frequency current **j** was important: the amplitude of the lines was a maximum for $\mathbf{j} \perp \mathbf{H}$, and resonances were absent for $\mathbf{j} \parallel \mathbf{H}$. The increase in the magnetic field led to an increase in the amplitude of the lines proportional to H^2 (see below, curve a in Fig. 5).

Excitation of acoustic waves occurred at room temperaure, at nitrogen temperatures, and also at helium temperatures. Upon decrease in temperature from room to nitrogen values, the amplitudes of the resonant peaks and their widths did not change appreciably. However, the amplitude decreased by a factor of 50 at 4.2°K and the lines were broadened by an order of magnitude. The effect of subsequent lowering of the temperature is demonstrated in Fig. 3. For T = 1.7°K, the critical field for tin was $H_c = 230$ Oe, so that in a field of 136 Oe the sample was in the superconducting state. The table lists data on the quality factor Q, obtained from measurement of the widths of lines at different temperatures. The whole set of results gives convincing evidence that the sound in tin is excited by a ponderomotive force. Actually, the oscillations take place along the $\mathbf{j} \times \mathbf{H}$ direction, and their amplitude grows linearly with H. Inasmuch as the skin depth δ always remains less than the sound wavelength λ, the intensity of the excitation does not depend on the temperature. At helium temperatures, because of the large mean free path of the electrons, the electron damping of the sound increases sharply,[10] which also leads to a decrease in the quality factor and a lessening of the effect. Transition to the superconducting state removes the electron damping and the lines reappear, in spite of the fact that the field H is lessened considerably. However, the quality factor in the superconducting state in our experiments remains lower than at room temperature. This is probably explained by the presence of regions of of normal phase in the sample.

EXPERIMENTS ON BISMUTH

Ponderomotive excitation of sound was also observed in bismuth at room temperature in fields greater than 5 kOe (see also [3]). This fact evidently is not of great interest, so that in what follows we shall speak only of low-temperature measurements.

At helium temperatures, the depth of the skin layer in bismuth in the absence of a magnetic field and at a frequency $\omega/2\pi \sim 10^6$ Hz is approximately equal to $\delta \sim 10^{-3}$ cm,[11] which exceeds by an order of magnitude the value of δ in ordinary metals. In our samples, the free path of the electrons l was 0.5 mm, so that an anomalous skin effect occurs at H = 0. However, even at a field H ~ 50–100 Oe, the skin effect becomes normal because of the small Larmor radius of the electrons, and at H ~ 300 Oe δ reaches the thickness of the sample d because of the large magnetoresistance.

The latter is convincingly demonstrated by the dependence on the value of the variable magnetic field in the sample on H:

$$\Phi = \mathrm{Re} \int_0^d h(z)\,dz = h(0)\delta$$

(h(z) is the variable magnetic field). The change of Φ was determined from the $\omega(H)$ dependence (see Fig. 4; we recall that $\Delta\omega/\omega = -\frac{1}{2}\Delta L/L \sim \Delta\Phi/\Phi_0$, where L is the inductance of the coil with the sample and Φ_0 the current through the coil). The absorption in the sample changes simultaneously with Φ, having a maximum in the region of the most rapid change of Φ. For $H \sim 10^3$ Oe, the electromagnetic field in the sample can already be regarded as homogeneous.

Thus the conditions for sound excitation depend on the value of the magnetic field. In this connection, we shall call the interval 0–300 Oe the region of weak fields, and shall define fields stronger than 1 kOe as strong fields. The experiments were carried out on single crystal specimens of bismuth with the direction of the normal **n** to the surface of the disk $\mathbf{n} \parallel C_3$ (two specimens of thickness d = 1 mm and one with d = 2 mm) and $\mathbf{n} \parallel C_1$ (d = 1 mm, C_1 is the bisector axis), and also on two specimens with oblique orientations. The experimental results can be described in the following fashion.

a) Region of weak fields. The sound is excited at values of H much less than in tin, and the amplitude of the acoustic resonances increases in proportion to H^3 (see Fig. 5). The decrease in the temperature from 4.2°K to 1.7°K leads to an increase in the amplitude of the lines which, however, is not accompanied by a change in their width. The increase of amplitude is the more significant the purer the sample. On the specimens with $\mathbf{n} \parallel C_1$, on which the radio-frequency size effect was not seen (which testifies to some random contamination of the metal) the amplitude of the acoustic resonances increased by at most a factor of two, while Fig. 6 shows a 14-fold increase in the amplitude.

To explain the role of the free path of the electron in sound excitation, one of the specimens on which the lines of the acoustic resonances were very sharply observed (at 50 Oe the signal-to-noise ratio was more than 100) was deformed. After deformation, it was not possible to excite the sound in this specimen at low temperature.

The excitation of sound took place in a field parallel to the surface of the metal, with the polarization $\mathbf{H} \perp \mathbf{j}$. Here, generally speaking, we succeeded in exciting both longitudinal and transverse sound, but all the results given refer to the longitudinal case. Inclination of the field led to a sharp decrease in the amplitude of the lines and they vanished completely already at a 30° inclination. When the angle β between **H** and **j** decreased the amplitude of the lines fell approximately as $\sin^2\beta$,

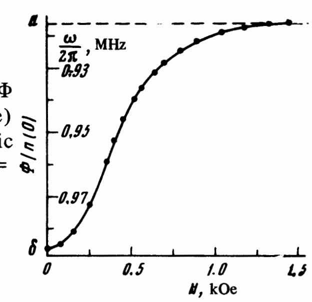

FIG. 4. Dependence of the flux Φ (normalized to unit length of sample) on the value of the constant magnetic field; $\mathbf{n} \parallel C_3$, d = 1 mm, $\mathbf{n} \perp \mathbf{H} \perp \mathbf{j}$, T = 4.2°K.

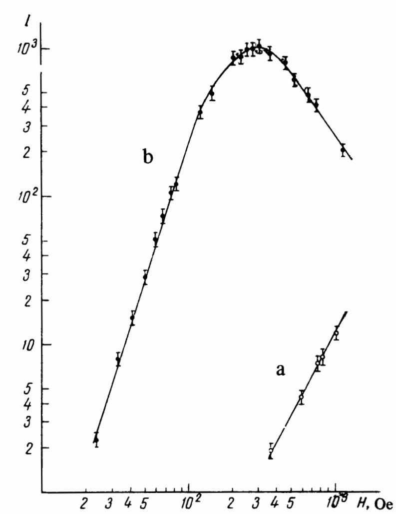

FIG. 5. Dependence of the amplitude of the lines on the value of the magnetic field: a – tin at room temperature, b – bismuth ($\mathbf{n} \parallel C_3$, d = 1 mm) at T = 4.2°K.

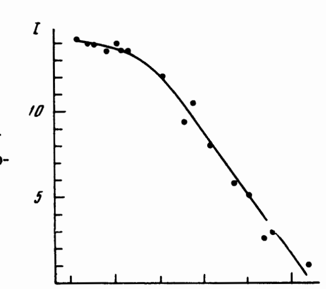

FIG. 6. Dependence of the amplitude of the lines of acoustic resonances on temperature in samples of Bi, $\mathbf{n} \parallel C_3$, d = 2 mm, $\omega/2\pi$ = 0.51 MHz, $\mathbf{n} \perp \mathbf{H} \perp \mathbf{j}$, H = 140 Oe.

although it should be noted that the accuracy of calibration was insufficient for a unique determination of the form of the functional dependence $I(\beta)$.

The presence of a maximum in the I(H) dependence (Fig. 5) was undoubtedly connected with the penetration of the alternating field into the sample. The transition to a very high number of standing waves led to a broadening of the maximum and to its shift to the region of smaller fields, evidently as the result of a decrease in the sound wavelength.

b) Region of strong fields. The excitation of sound was successfully observed in the region of strong fields, and the intensity of the excitation depended on the value of the magnetic field in a strongly non-monotonic fashion. The amplitude of the resonance lines as a function of the intensity of the magnetic field underwent in this region of fields oscillations that were periodic in the inverse field. Figure 7 shows the results of experiments at the magnetic field direction of $\mathbf{H} \parallel C_2$. It is seen that the period of oscillation of the intensity $\Delta(1/H)$ is one-half the period of the de Haas–van Alphen effect (the latter was determined from the change in the frequency of the generator upon increase in the magnetic field). The experiments were conducted only in fields parallel to the surfaces of the specimen. The sound was excited both for $\mathbf{H} \perp \mathbf{j}$ and for $\mathbf{H} \parallel \mathbf{j}$.

The value of the magnetic field also had an effect on the location of the lines; the resonance frequency ω_{res} oscillated with the usual period of the de Haas–van Alphen effect Δ_0 (the average curve in Fig. 7).

The shape of the lines was the same in weak and strong fields and corresponded to the maximum absorption at the instant of resonance. (This was proved additionally by comparison with the signal of nuclear magnetic resonance, recorded on the same apparatus. Such a line shape was observed also in tin.) In the transitional region of magnetic fields, where $\delta \sim d$, a strong change took place in the line shape, and the lines themselves remained comparatively weak. One could find an interval in the fields in which the lines had the same shape as in the weak field, but with opposite sign.

DISCUSSION

Bismuth possesses only 10^{-5} as many electrons in comparison with ordinary metals, and the Fermi surface has much smaller dimensions and the maximum value of the effective mass in bismuth is an order of magnitude smaller than the mass of a free electron.

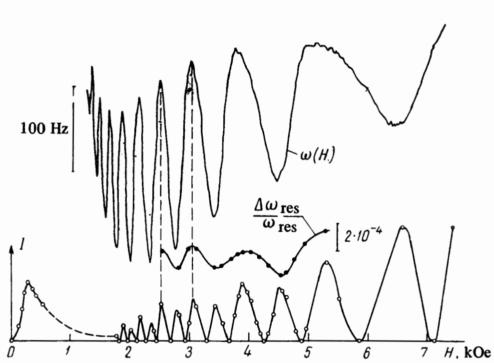

FIG. 7. Results of experiments in strong fields on a specimen of Bi, $n \parallel C_3$, d = 2 mm, $n \perp H \perp j$, $H \parallel C_2$, T = 4.2°K, $\omega/2\pi$ = 0.51 MHz.

Because of this, a whole series of effects are observed in bismuth at low temperatures over a range of substantially smaller magnetic fields. However, this is not related to sound excitation by the ponderomotive force $\mathbf{F}$, inasmuch as the integrated value of the skin current $\mathbf{j}$ is determined only by the amplitude of the incident electromagnetic wave and does not depend on the electron structure. It is seen directly from our experiments that the quality factors in tin at room and in bismuth at helium temperatures are approximately the same, and the magnetic field required for the excitation of sound of the same intensity in bismuth is an order of magnitude smaller (see Fig. 5). But the basic fact indicating that the force $\mathbf{j} \times \mathbf{H}/c$ does not determine the sound excitation in weak fields is this temperature dependence in the region of helium temperatures and the absence of excitation in the deformed specimen, inasmuch as j is one and the same in all cases, while the electron damping can only decrease with decreasing free path. In strong fields, because of the penetration of the wave, the condition $\delta \ll \lambda$ for the effectiveness of the ponderomotive force is violated, which reduces the role of this force to nothing since the current j also decreases.

The mechanism of sound excitation in strong fields, in our view, raises no doubt. As is known, the change of the dimension u of an isotropic magnet with magnetic moment M upon application of a field H is given by $u \sim H\partial M/\partial\sigma$, where σ is the stress. The oscillating part (because of the de Haas–van Alphen effect) of the magnetic moment $M \sim \cos(cS/e\hbar H)$ leads to the appearance of a term in the magnetostriction $u \sim (\partial S/\partial\sigma) \times \sin(cS/e\hbar H)$, which oscillates with the same period in the reciprocal field $\Delta_0(1/H) = 2\pi e\hbar/cS$ [12] (S is the area of the extremal cross section of the Fermi surface in momentum space). In our case, the specimen is located in a homogeneous magnetic field, modulated at a frequency ω to a depth $h/H \sim 10^{-3}$. Changes in the dimensions of the specimen lead to the appearance of a volume inertial force $P \sim \omega^2 \partial u/\partial H$. It is natural that the amplitude of the excited sound is $A \sim |\partial u/\partial H|$ and the value of $I \sim A^2$ observed experimentally oscillates with half the period $\Delta(1/H) = \Delta_0/2$. At a polarization $\mathbf{H} \parallel \mathbf{j}$, the variable field is $\mathbf{h} \perp \mathbf{H}$; therefore the modulation of the striction takes place because of the anisotropy of the extremal cross sections of the Fermi surface (compare with the method of angular modulation [13]).

Thus we have succeeded in observing in bismuth magnetostriction that oscillates with the field—a phenomenon which has already been observed by a different method by Green and Chandrasekhar.[14] Evidently our method is simpler than the direct dilatometric measurements,[14] and gives a basis for hoping that the magnetostriction can be used for the study of the derivatives $\partial S/\partial\sigma$ in different metals, since one can generally estimate the absolute value of the oscillating striction from the amplitude of the effect and the quality factor of the resonance. However, absolute calibration of the sensitivity of the circuit is necessary for this; such was not achieved in our experiments. It follows from a comparison of the data of [14] and [15] that the changes of the resonance frequencies $\Delta\omega_{res}$ were determined basically by the oscillations of the sound velocity and not of the dimensions of the specimen. Here the amplitude of the quantum oscillations of the sound velocity observed by us was approximately an order of magnitude larger than in [15]. Oscillations of sound attenuation were not seen by us, if we do not consider the very clearly expressed modulation of the intensity of the maxima in the curve I(H) in Fig. 7.

To explain sound excitation in weak fields, it is necessary to find an excitation mechanism in which the magnetic field and the free path of the electrons are appreciable. Magnetostriction is virtually absent in weak fields. In bismuth in this range of frequencies and fields, there are no electromagnetic waves. The assumption that sound emission is the result of a large drift velocity of the electrons[9] is also not confirmed; first, the effect does not depend on the amplitude of the incident electromagnetic wave, at any rate in the amplitude interval where we could test it (our method required that the generator be set close to the generation threshold, which did not allow us to increase the amplitude of the oscillations in the circuit substantially); in the second place, the effect is undoubtedly present in this region of magnetic fields where $\delta \sim d$ and the skin current density is known beforehand to be insufficient for the excitation of Cerenkov radiation.

Inasmuch as sound excitation is not observed in ordinary metals at fields of 10–100 Oe, one can assume that the effect is connected in some fashion with the specifics of bismuth. The bismuth spectrum has a structure that is characteristic for semiconductors; it consists of four Fermi-ellipsoids ("valleys"), located far from one another in momentum space. At the same time the current carriers in bismuth possess a path length that is characteristic for a pure metal and reaches 10^{-1} cm at helium temperatures, so that the relation $l \gtrsim \lambda$ holds. Therefore, the establishment of an equilibrium distribution of carriers relative to the spectrum in periodic fashion by a sound wave deformed in space and time can result not only from "intervalley" transitions, but from direct transfer of carriers of one valley or another into a region of minimum potential energy (cf., for example, with germanium,[16] where the intervalley transitions play the fundamental role). In a magnetic field H ~ 10 Oe in bismuth, the relation $r/\lambda \ll 1$ holds (r is the Larmor radius of the electrons). Therefore, a field perpendicular to the wave vector **k**, by eliminating the possibility of transfer of electrons along **k**, can effect the deformation interaction of the electrons with the wave. On the other hand, as shown by Kravchenko and Rashba,[17] under conditions of comparatively rare intervalley transitions in semimetals, the principal role is played by collisions of the electrons with the surface, and the electron distribution near the surface can differ from the distribution inside the metal.

For the explanation of the role of all these factors, further experiments are necessary. In particular, it would be interesting to attempt to excite sound in semiconductors.

In conclusion, a small note on the shape of the resonance lines. Line inversion was observed in the range of fields where the derivative $\partial R/\partial \rho$ was negative and large in absolute value (the region $\delta \gtrsim d$). Here ΔR was determined not only by the transfer of energy into the sound wave but also by the redistribution of high-frequency currents in the specimen, which is associated with the decrease in the conductivity because of sound excitation.

The authors are grateful to V. Ya. Kravchenko, É. I. Rashba and G. I. Babkin for numerous useful discussions.

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Translated by R. T. Beyer
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