Observation of dragging of the electrons of tin by sound

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The voltage produced when sound propagates along a sample is investigated. An effect due to direct dragging of the metal electrons by the sound is separated. It is observed that the sign of the effect, depends on the acoustic-oscillation mode.

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An elastic wave propagating through a conducing crystal can interact under certain conditions with the carriers in such a way that a potential difference is produced on opposite ends of the crystal. Physically, the effect reduces to a transfer of the momentum of the elastic wave to the carriers. This effect was a first theoretically considered by Parmenter,[1] who named it the acoustoelectric effect. The acoustoelectric effect was observed in many semiconductors.[2,3]

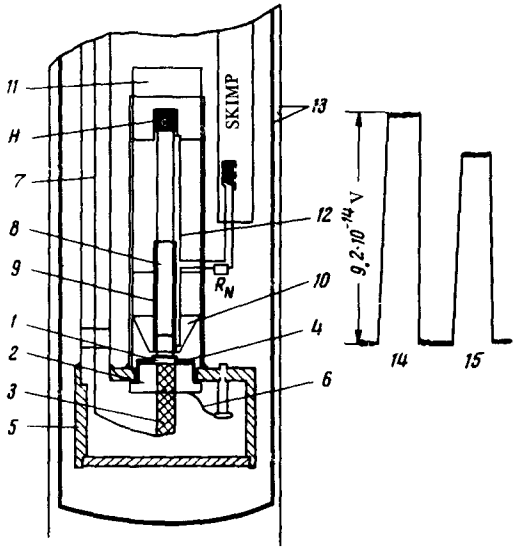

FIG. 1. Measurement setup: 1—acoustic converter, 2—glass insulator with fused-in electrode, 3—electrodes, 4—superconducting film, 5—body of holder, 6—spring clamping the insulator to the body, 7—coaxial cable to supply the converter, 8—sample, 9—remainder of glass mold, 10—guiding sleeve, 11—weight clamping the sample to the converter, 12—lead wires soldered to the sample with Wood's alloy, 13—lead and permalloy screens. Right—typical plot, 14—control signal turned on, 15—high-frequency supply to converter turned on; $T = 4$ °K.

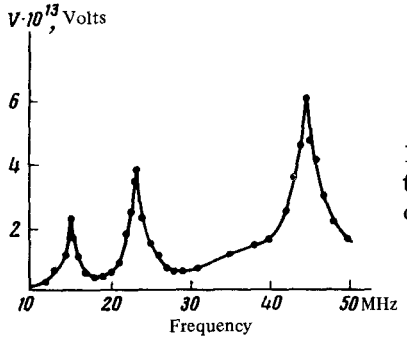

FIG. 2. Potential difference produced across the sample when the 10—50 MHz supply field of the converter is turned on. $T = 4.23$ °K.

In metals, as follows from Weinreich's calculations,[4] this effect can vanish, but this has not been verified experimentally to this day. We describe in this paper experiments aimed at observing the potential difference produced as a result of dragging of electrons by sound in tin.

A diagram of the apparatus used in the experiment is shown in Fig. 1. The converter of the electromagnetic oscillations into acoustic oscillations was a lithium niobate plate 150 μ thick. It was glued with epoxy resin to an insulator. The electromagnetic excitation was applied to the converter through an electrode (3) and a superconducting film (4). The converter supply system prevented completely the penetration of the high-frequency excitation field into the remaining part of the apparatus.

The sample was a tin single crystal with $\rho \approx 2 \times 10^{-10}$ Ω cm, 3 mm in diameter and 7 cm along. The principal measurements were made on a sample with an axis making an angle 30° with [100]. The lower end of the sample, adjacent to the converter, was electrically polished and was coated with an insulating layer of BF-2. The sample could glide freely in a sleeve (10), and a weight (11) caused it to press against the converter. The acoustic contact was through a layer of silicone oil..

To measure the potential difference we used the SKIMP installation.[5] The current leads were made of superconducting lead. The contacts were positioned 3 mm from the ends of the sample. The system made it possible to measure a voltage down to 10^{-15} V. A typical plot of the SKIMP readings during the course of the experiment is shown in Fig. 1.

The measured potential difference V produced across the sample at the different converter excitation frequencies are shown in Fig. 2. The sharp maxima at 15, 45, and 23 MHz are obviously connected with excitation of quasi-transverse and quasi-longitudinal modes. Thus, according to calculations from the data of[6], the natural frequencies of the employed converter for the quasi-transverse and quasi-longitudinal modes were 14.9 and 22.8 MHz.

The appearance of V can be due not only to the effect of the dragging of the electrons by the sound (V_{ph}), but also by the change of the temperature along the sample. Obviously, the thermoelectric power (α) can produce in a circuit a voltage $V_T = \alpha \Delta T$, where ΔT is the difference between the temperatures of the contacts of the sample with the superconducting leads. Although small powers $\lesssim 10^{-3}$ W were used in the experiment, and the greater part of the sample was in liquid helium, the possibility of the appearance of ΔT could not be excluded.

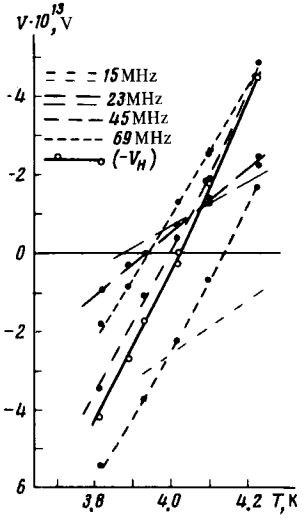

FIG. 3. Temperature dependence of the potential difference V produced across a tin sample at frequencies 15, 23, 45, and 69 MHz, and when a heater power 5.6×10^{-4} W is applied. The thin lines are the results of experiments with the end of the sample thermally insulated.

For a better understanding of the nature of V of the samples, we measured simultaneously the temperature dependence of V at the frequencies of the maxima (15 and 45 as well as 23 and 69 MHz) and for the voltage V_H produced when the sample heater H was turned on. It is obvious that V_H is proportional to V_T, accurate to effects of second order of smallness resulting from some difference between the average sample temperature when the sound and when the heater are turned on (at the employed powers, the temperature difference between the heating and the sample reached 3×10^{-2} °K, and the temperature gradient along the sample was 10^{-3} °K).

The measurement results have shown that in the investigated temperature interval 3.7—4.2 °K the character of the temperature dependence of $V(T)$ does not agree with the temperature dependence $V_T \propto V_H$, and moreover, in the normal states of the tin the $V(T)$ curves corresponding to different frequencies cross the $V=0$ axis at different temperatures (Fig. 3). (In the superconducting state $V=0$ at $T<3.71$ °K.) These data indicate that the dragging of the electrons by the sound plays a substantial role in the potential difference produced along the sample in an acoustic field. It is clear that for each frequency we have $V_{ph}=V$ at that temperature at which $V_T \propto V_H = 0$. The thin lines in Fig. 3 show the results obtained in a different experimental situation, when part of the sample above the sleeve 10 was thermally insulated by an inverted dewar. The values of V_{ph} obtained in both variants were in agreement, with a mean-squared scatter of 10% for 23 and 69 MHz, 22% for 15 MHz, and 60% for 45 MHz.

Using the temperature dependent part of V and V_{ph}, we can estimate the power of the sound field W. This makes it possible to compare $V_{ph}=V_{ph}/W$ for different frequencies. For quasi-longitudinal oscillations $v_{ph}(23\text{ MHz}) = 1.6\times10^{-11}$ V-W^{-1} cm^2 and $v_{ph}(69\text{ MHz}) = 1.0\times10^{-11}$ V-W^{-1} cm^2, while for quasi-transverse modes $v_{ph}(15\text{ MHz}) = -2.1\times10^{-11}$ V-W^{-1} cm^2 and $v_{ph}(45\text{ MHz}) = -(4.3\pm2.5)\times10^{-12}$ V-W^{-1} cm^2. The sign was chosen in accordance with the results of earlier investigations on the thermoelectric power of phonon dragging in tin.[7])

The electron dragging by sound in a metal, which was observed in the present study, cannot be regarded as a minor effect. In the case of tin, the potential difference produced when energy is transferred by the sound field is of the same order as that transferred by the thermal conductivity. We recall that tin is a complex metal with almost equal numbers of electrons and holes. In our opinion, the most important fact is that v_{ph} can have a different sign for different oscillation modes. This demonstrates how fruitless it is to attempt to estimate the magnitude of the effect only on the basis of data on sound damping in the metal. It is clear that it is hopeless to attempt to understand this effect without invoking data on the Fermi surface of the metal. We hope to return to this question in the future.

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[1)]Calculation of the effect from the radiation pressure of the sound field on the electron system yields $v_{ph}(enu)^{-1} \approx 5\times10^{-10}$ V-W^{-1} cm^2 (u is the speed of sound and n is the electron density).

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