Electric field excited by an acoustic beam in a superconductor in the mixed state

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An electric field has been observed to be induced by an acoustic beam in tin films in the mixed state. This effect is attributed to an entrainment of magnetic fluxoids by the sound.

Superconductors in their mixed state exhibit a substantial absorption of ultrasound, as has been demonstrated in measurements on both bulk[1,2] and film[3,4] samples. According to theoretical work,[5–7] the absorption is due in large part to an interaction of the sound wave with magnetic fluxoids or vortices. The process by which the traveling sound wave loses energy (and thus momentum) as a result of its interaction with vortices is evidently accompanied by a transfer of momentum to the vortices. The system of noninteracting vortices (the simplest assumption) then starts moving along the sound propagation direction as the result of the acquired momentum. This process produces an electric field in the sample

$$E \propto -[vH], \tag{1}$$

where H is the magnetic induction in that sample, and v is the fluxoid velocity. In this letter we are reporting some experiments undertaken in an effort to observe this effect.

As the test sample we selected tin, specifically, a film deposited on an electroacoustically active substrate.

A mixed state is known[8] to arise in a superconducting film in a perpendicular magnetic field under the condition

$$d \ll \xi < \delta, \tag{2}$$

where d is the film thickness, ξ is the coherence length, and δ is the penetration depth. The coherence length in pure tin is $\xi_{T\to 0} \simeq 2\times 10^{-5}$ cm. In the case of a film (the dirty limit), in contrast, the coherent length is governed by the mean free path of the electrons and has a value $\sim (2–3)\times 10^{-6}$ cm at $T \ll T_c$, where T_c is the superconducting transition temperature of the film. As the temperature nears T_c, the coherence length ξ increases $\propto (1-T/T_c)^{-1/2}$, and at $\Delta T = T_c - T \simeq 0.01$ K it is greater than 10^{-5} cm. In this case, condition (2) holds for films less than 10^{-5} cm thick, which behave as type-II superconductors in a field perpendicular to the surface at these temperatures.

In the experiments we measured the static voltage which arises across a tin film in the mixed state as a traveling surface sound wave (a Rayleigh wave) propagates through it. The test film, the interdigital transducer,[9] and the absorbers were applied

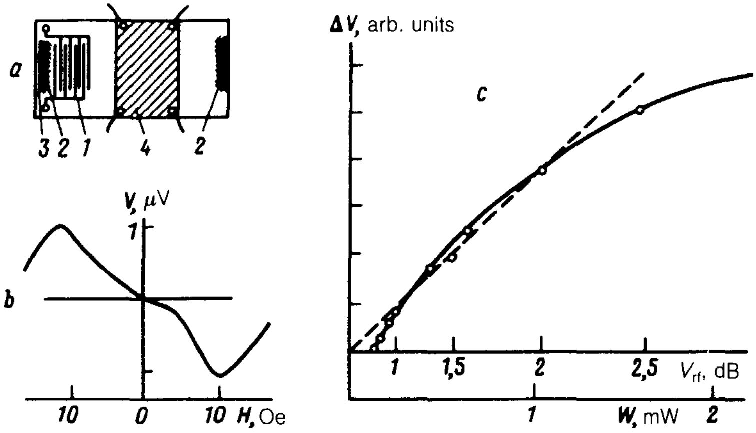

FIG. 1. a: Experimental layout. *1*—Interdigital surface-wave transducer; *2*—sound absorbers; *3*—heater; *4*—test sample. b: Voltage which arises across the sample in the sound field in various magnetic fields. c: Plot of $\Delta V = V(H^+) - V(H^-)$ versus the energy of the sound wave, which is proportional to $V_{\rm rf}^2$, where $V_{\rm rf}$ is the voltage on the transducer, and W is the power dissipated in the transducer, according to the measurements. The dashed line is a direct proportionality between ΔV and the energy of the sound wave; the solid line is an "eyeball" fit of the experimental points.

to a *YZ*-cut lithium niobate crystal, as shown in Fig. 1a. Several samples were studied, ranging in thickness from 7.7×10^{-6} to 1.5×10^{-6} cm, with widths $L \simeq 1$–6 mm.

A static electric field arose in the samples at $T < T_c$ in an acoustic flux in an external magnetic field (directed perpendicular to the plane of the film). The sign of this electric field was determined by the direction of the magnetic field (Fig. 1b). In most of the experiments we measured the quantity $\Delta V = V(H^+) - V(H^-)$ by switching the external field at a period of 2–5 min; this switching was required to establish an equilibrium value of $V(H)$. The appearance of ΔV was observed on all the test samples less than 3×10^{-6} cm thick. This effect did not occur above T_c.

In a first approximation, ΔV is proportional to the power dissipated in the transducer. Deviations from this proportionality are observed at very low power levels, where the effect apparently requires a threshold, and also at high power levels, where a saturation of the effect is observed (Fig. 1c). This saturation may be due to a change in the temperature of the sample, despite the fact that the samples were immersed in liquid helium in all the experiments.

In the mixed state of a superconductor, a voltage perpendicular to the magnetic field can be induced by a temperature gradient.[10] A temperature gradient arises along the substrate because of the power dissipated in the lithium niobate as it absorbs sound in a surface layer. We accordingly carried out some additional experiments to determine the thermal conditions in the substrate during the propagation of sound in it. Ten films deposited on the substrate served as sensitive resistance thermometers in the temperature range corresponding to their transition from the normal state to the superconducting state. The results of these experiments showed that the average sam-

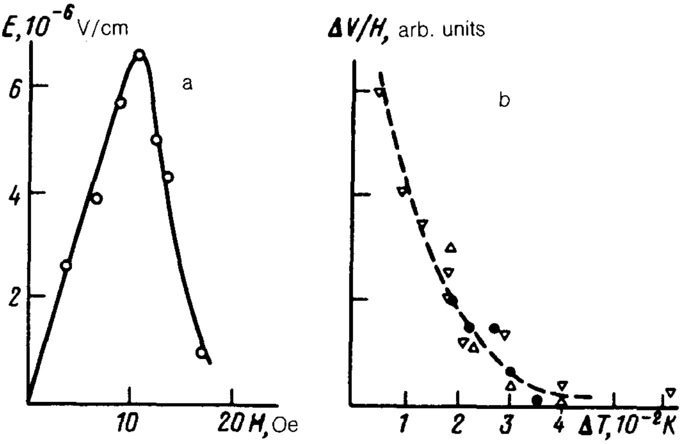

FIG. 2. *a*—Electric field excited by the sound, E, versus the static magnetic field H; *b*——magnitude of the effect, $\Delta V/H$, versus $\Delta T = T_c - T$ for three samples with a thickness $\sim 2\times10^{-6}$ cm (the symbols of different shapes correspond to the different samples).

ple temperature rises $\sim 10^{-3}$ K during the excitation of sound, and a temperature gradient $\sim 5\times10^{-4}$ K/cm arises along the substrate. These figures correspond to a power dissipation $\sim 10^{-3}$ W in the transducer; this was the power at which most of the measurements were taken. The power dissipation was determined by comparing the heating of a film thermometer caused by an auxiliary heater with the heating caused by the acoustic transducer when turned on.

According to the data of Ref. 10, the electric field excited by the temperature gradient is weak. For an excitation voltage $\sim 1 \mu$V, for example, a gradient ~ 1 K/cm is required in a field $H \sim 0.1$–1 kOe. This gradient is thousands of times the measured temperature gradient across the sample in our experiments, while the value of ΔV in our experiments was on the same order of magnitude, ~ 1 μV, although in a much weaker magnetic field (Fig. 1). This thermal effect apparently could not have any substantial influence on the results in our case.

The frequency dependence $\Delta V(\nu)$ is of a resonant nature, with a sharp peak at the frequency $\nu \sim 10$ MHz, which corresponds to the nominal frequency of the acoustic transducer. Figure 2 shows a typical plot of ΔV versus the applied field H. In weak fields, ΔV is proportional to H [cf. relation (1); we will use the ratio $\Delta V/H$ below for comparing absolute values of the effect obtained under different conditions]. As the field is increased further (Fig. 2), the effect goes through a maximum and then falls off progressively. This behavior is probably due to the onset of an interaction between individual fluxoids; this interaction would complicate their motion. The field at which the effect vanishes increases with decreasing temperature. For all temperatures studied, this field is on the order of H_{c2} of the film, which is $\sqrt{2}\kappa H_{cm}$, where $\kappa = \delta/\xi \simeq 2$–3, and H_{cm} is the thermodynamic critical magnetic field.

The effect was observed stably only near the transition temperature. As the temperature was lowered from T_c, the effect decreased sharply in magnitude (Fig. 2). This change in the effect (with increasing ΔT) seems to be due to a decrease in the value of ξ. As a result, of which condition (2) is violated. Consequently, instead of individual fluxoids, there is a more complicated magnetic structure. At $\Delta T \sim 0.1$ K we frequently observe that ΔV is not reproducible when the field is switched and that the field dependence $\Delta V(H)$ is more complex. The absolute magnitude of the effect referred to $\Delta T = 0.01$ K lies in the interval $\Delta V/H \approx 0.1$–1 μV/Oe for these test samples. The upper limit was observed for only three of the nine test samples, primarily for films with the largest thickness L condensed on a germanium sublayer.

One might suggest that the differences in the magnitude of the effect stem from the microscopic structure of the sample, which determines the viscosity for the motion of vortices and their velocity. This circumstance makes it difficult to establish a quantitative relationship between the value of ΔV and the fluxoid dynamics in the mixed state of the superconducting film during the application of sound, although all the results conform in a qualitatively satisfactory way to a picture of an entrainment of magnetic fluxons by the sound.

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