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Radio-Frequency Transmission in Indium Films in the Mixed State

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Radio-frequency transmission in amorphous indium films in the mixed state has been investigated experimentally. The main new result is the observation of a broad dip bounded by two discontinuities at low levels of the radio-frequency magnetic field (a few gauss). This effect has been studied as a function of the amplitude of the static perpendicular magnetic field, of the film thickness, and of the temperature. It is suggested that the experimental results may be explained as due to vortex motion in a pinning potential depending on the amplitude of the vortex oscillation.

INTRODUCTION

The study of electrodynamic properties in the radio-frequency region of superconductors in the mixed state[1] can give information on the mechanisms of interaction of flux tubes with pinning defects and, in particular, can provide information on the pinning potential.

We report measurements on the radio-frequency transmission in flat superconducting indium films in a perpendicular magnetic field $H_\perp$. Thin films of type-I material in a perpendicular magnetic field behave similarly to type-II materials. The present experiment, for low levels of the radio-frequency power, reveals new features when compared with previous measurements.[1]

EXPERIMENTAL TECHNIQUE

The experiment has been performed on 1.4×1.4-cm^2 indium films whose thickness ranged from 1500 to 11 000 Å. The films were vacuum evaporated ($\sim 1.10^{-6}$ mm Hg) on a thin mica substrate from 99.9999% pure indium. The evaporation rate was such that amorphous samples were obtained, as was checked by diffractometer studies.

The samples were placed between short transmitting and receiving coils (25 turns, 4-mm length of axis) whose axes were parallel to the film. Each of the two coils, which were crossed, was embedded in expoxy in brass housing. The specimen was electrically grounded to the coil housings in order to achieve good isolation between transmitter and receiver circuits. The current flowing in the transmitting coil could be varied up to 0.2 A and its frequency could be varied from 1 to 10 MHz. Most measurements have been done at 8 MHz. The receiving coil was at a distance of 0.1 mm from the sample surface, and 0.4 mm from the transmitting coil. At low temperatures we have obtained an attenuation of the received signal of ~ 100 dB. Both the amplitude and phase of the transmitted signal were measured. We could measure amplitude variations of ~ 0.2 dB and phase variations of ~ 0.1 deg. The lowest temperature ratio $t = T/T_c$ (T_c = critical temperature) at which measurements were taken was 0.4. The experimental set up is shown in Fig. 1.

In the following section we shall list our observations and give some explanations for the results.

EXPERIMENTAL RESULTS AND DISCUSSION

For any constant value of the perpendicular magnetic field $0 \le H_\perp < H_{\perp c}$ the transmitted signal as a function of the amplitude h_0 of the alternating magnetic field h shows a broad dip bounded by two discontinuities (Fig. 2). This effect is observed by either increasing or decreasing h_0. The amplitude of the dip, observed on 20 samples, depends on the sample quality in a way that we have not clarified experimentally.

At higher values of h_0 we have observed on certain samples two or three more steps like h_{02}. The value of h_0 at the onset of the dip h_{01} and the value of h_0 at the end of the dip h_{02} depend on the external magnetic field $H_\perp$, the temperature, and the film thickness as shown in Figs. 3 and 4. h_0 is the field at the coil axis. We suggest that the above results are due to vortex motion within a pinning potential which depends on the amplitude of the vortex oscillations induced by the magnetic field h_0.

Let us choose a reference system having the plane of the film perpendicular to the z axis. The emf induced by the flux lines per unit length and detected in our receiving coil is given by[2]

$$V = (H_\perp/c)v = (H_\perp/c)\,\dot{x}\ , \tag{1}$$

where v is the vortex velocity and c is the light velocity. $\dot{x}$ can be obtained by solving the equation of motion of a flux tube[1,3]:

$$M\ddot{x} + \eta\dot{x} + Px = \mathrm{Re}(\Phi J/c)\ ,$$

where M is the flux-tube effective mass per unit length, $\eta = \Phi H_{c2}/c^2\rho_n$ is the flow viscosity, ρ_n is

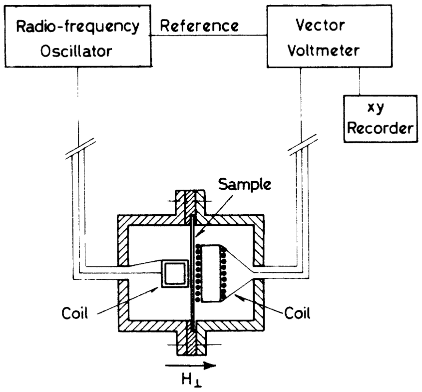

FIG. 1. Experimental setup. The low-temperature part is not shown.

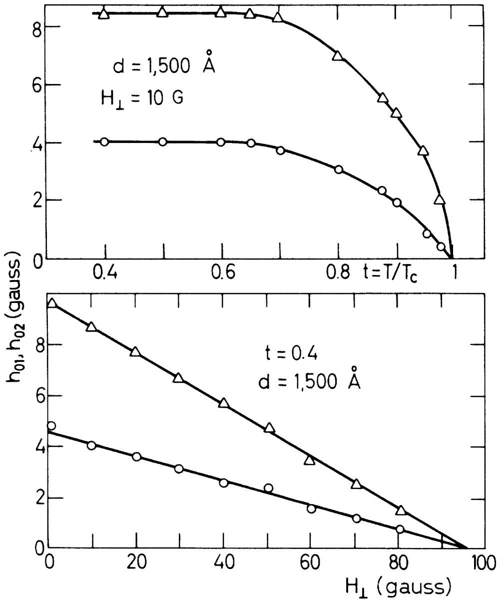

FIG. 3. Dependence of h_{01} (value of h_0 relative to the first discontinuity of Fig. 1) and of h_{02} as a function of $H_\perp, t$. ○ are the experimental points relative to h_{01}; △ are the experimental points relative to h_{02}.

the normal-state resistivity, P is the constant of the pinning force, and Φ is the flux quantum. J is the current density induced within the film by h, and is given by

$$J = J_0 e^{-d/\lambda} e^{i\omega t} = \frac{c}{4\pi}\,\frac{h_0}{\lambda}\, e^{-d/\lambda} e^{i\omega t} \;,$$

where the spatial variation over z is neglected, and λ is the London penetration depth. The solution for $\dot{x}$ is

$$\dot{x} = \dot{x}_0 \cos(\omega t + \varphi) \;,$$

$$\dot{x}_0 = \frac{h_0}{4\pi\lambda}\, e^{-d/\lambda}\,\Phi\,\omega[(M\omega^2 - P)^2 + \eta^2\omega^2]^{-1/2} \;,$$

$$\tan\varphi = \frac{P - M\omega^2}{\eta\omega} \;.$$

Therefore the emf induced by the flux lines per unit length and detected in the receiving coil is

$$V = \frac{H_\perp (h_0/\lambda)\Phi e^{-d/\lambda}\omega}{4\pi c[(M\omega^2 - P)^2 + \eta^2\omega^2]^{1/2}} \cos(\omega t + \varphi) \;. \qquad (2)$$

By putting $\omega_0 = 3\times 10^8$ Hz and neglecting the term in η^2,[1] the voltages obtained from this formula agree, in order of magnitude, with the ones we have detected experimentally. Also the linear dependence of V both on h_0 and $H_\perp$ is in agreement with our observations, except at the discontinuities, for levels of the magnetic fields much below the onset of the normal-state transition. Within the experimental errors, we have observed a dependence of the re-

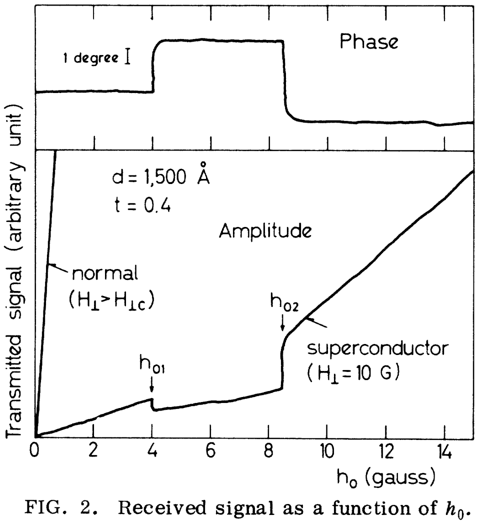

FIG. 2. Received signal as a function of h_0.

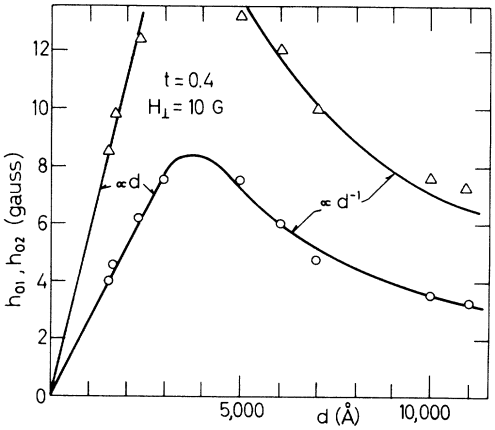

FIG. 4. Dependence of h_{01}(○) and h_{02}(△) on film thickness d.

ceived signal V, at a fixed h_0 and $H_\perp$, on film thickness d of the form $e^{-d/\lambda}$. We may notice that most of the other mechanisms one can think of might give dependence of V on $H_\perp$, h_0, and d similar to the ones given by Eq. (2); we are presenting here one of such possible mechanisms which appear to be consistent with the experimental results.

We can now comment qualitatively that this formula can exhibit discontinuities such as those shown in Fig. 2 only if the pinning constant P has discontinuous changes in value. (The possible presence of discontinuities due to the quantized values of Φ should not be significant for the present experiment because, among other reasons, we observe the same effect for values of the magnetic field $H_\perp$ near $H_{\perp c}$ where such effects should not be observable.) In a qualitative and nonrigorous manner, we can therefore argue that the observed discontinuities may be a result of a depinning mechanism depending on the amplitude h_0, that is, on the amplitude of the vortex displacements. An example of a pinning force consistent with our experimental observation may be given by a force Px, where P is a step function of x (see, e.g., Fig. 2 and the expression for $\tan\varphi$ given above). It may be interesting to recall that the dependence of h_{01} and h_{02} on t is very similar to that found by Tholfsen and Meissner for the depinning current.[4]

In addition we may notice that the dependence of h_{01} and h_{02} on d (Fig. 4) shows a maximum around 4000 Å (the coherence distance of indium is ~ 4400 Å). It is likely that this result is related to changes of vortex dimensions as a function of the film thickness. However, we have as yet no theoretical suggestion to offer on this point.

In conclusion, by performing an experiment on the radio-frequency transmission in indium films in a perpendicular magnetic field with great sensitivity in the region of low radio-frequency power, we have observed effects which can be explained as due to vortex motion in a pinning potential depending on the amplitude of the vortex oscillations. Further similar experiments might clarify the question and give information on the nature of pinning potentials for particular materials.

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