Experimental study of a superconducting layer on the surface of indium or tin in a low-frequency electromagnetic field of large amplitude

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We measured the parameters of the superconducting layer that appears periodically on the surfaces of In and Sn samples in a magnetic field $H = H_0 + H_\sim \cos\Omega t$, $100 < \Omega/2\pi < 2\times 10^5$ Hz, with amplitude $H_\sim$ given by $H_0 - H_\sim \lesssim H_c \lesssim H_0 + H_\sim$. It is shown that an electric field is present in the layer. The layer thickness is measured as a function of the frequency Ω. The minimum thickness is only three times larger than the coherence length. The surface impedance of the layer was measured at the frequency $\omega \approx 10$ MHz in a field H_0 parallel or inclined to the sample surface. In a magnetic field parallel to the surface the layer impedance does not differ from the impedance of the superconductor, accurate to 4% of the difference between the impedances of the normal and superconducting metals, and in an oblique magnetic field the dependence of the impedance on $H_\parallel$ has two well distinguishable experimental regions in which the superconducting layer has different properties.

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Current-carrying type-I superconductors can be in a two-phase intermediate state. The period of the structure and the dimension of the region occupied by the intermediate state are determined by the value of the current. When the period of the structure diminishes to a size of the order of the coherence length, the usual division of the phases into normal and superconducting becomes meaningless and a unique mixed state is produced in type-I superconductors. In the case of a solid current-carrying wire one can hope to produce a mixed-state filament inside the wire. But if the current-carrying conductor is made hollow, then the layer of the intermediate state, and in the limit the mixed state, will cover the entire inner surface of the sample.[1,2] This layer ensures a jump of the magnetic field from zero to the critical value H_c, therefore the metal outside the layer is in the normal state.

A similar layer can be produced on the outer surface of a bulky type-I superconductor immediately after an external magnetic field $H > H_c$ is rapidly turned off,[3] inasmuch as the magnetic field on the surface drops to zero, and the field in the interior exceeds the critical value until the eddy currents attenuate (Fig. 1). If the magnetic field parallel to the axis of the cylindrical sample is a sum of a dc and hf fields, $H = H_0 + H\ \cos\Omega t$, with $H_0 > H_c$ and $H_\sim > H_0 - H_c$, then the superconducting layer will be produced on the outer surface of the conductor periodically. The result can be either a solid cylindrical superconducting layer with an internal boundary moving towards the surface of the sample, or a layer of intermediate state (or two-dimensional mixed state in the limit of small periods). These two cases can be readily distinguished in experiment, since the magnetic induction flux Φ remains constant after the formation of a solid layer right up to its annihilation, whereas in the case of the intermediate state the magnetic flux is not preserved in the sample.

In an alternating field, the periodic appearance of a superconducting layer on the surface can be observed also at $H_0 < H_c$. As shown in an earlier paper,[4] the sample thickness remains normal, and the magnetic flux remains higher than critical so long as $H_c - H_0 < H_\sim$ and the skin layer is $\delta \ll r$, when r is the radius of the cylinder.

As a result of magnetic supercooling, a superconducting layer is produced in an alternating field when the field on the surface becomes lower than critical by a certain amount δH. Consequently, the sample surface region in which the magnetic field is less than H_c at the instant when the superconductivity sets in, has a size of the order of δ and at low frequencies the layer thickness can exceed significantly the coherence length ξ. Since δ_1 does not exceed the size of the skin layer, one can hope to attain, by raising the frequency, the maximum values for δ_1 and advance into the region of two-dimensional mixed state of type-I superconductors.

PROCEDURE

The experiments were performed on tin and indium single crystal in the form of plates or cylinders. Samples with flat faces were necessary for measurements in an oblique magnetic field. The sample data are listed in the table. The samples were placed in a superposition of a constant magnetic and an alternating field $H_\sim \cos\Omega t$. The constant field was in general inclined to the sample surface, whereas the ac component of the magnetic field was parallel to the surface in all the experiments. The state of the sample thickness was determined from the flux $\Phi(H_0, H_\sim)$ through the sample averaged over the period of the alternating field. To obtain the $\Phi(H_0, H_\sim)$ dependences we used the same measurement setup as before.[4]

To monitor the processes at the sample surface, two methods were used. First, we measured for this purpose the signal from a receiving coil in which the sample was placed, as a function of the phase $\varphi = \Omega t$ of the alternating field of frequency Ω. The voltage U on this coil is proportional to the derivative of the magnetic flux through the sample, $U \sim \partial\Phi/\partial t$, so that these mea-

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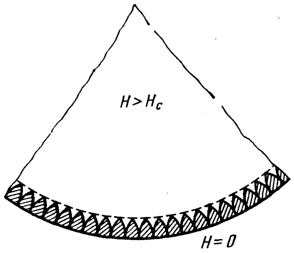

FIG. 1. Cut through a cylindrical sample by a plane perpendicular to the cylinder axis. The superconducting regions are shaded.

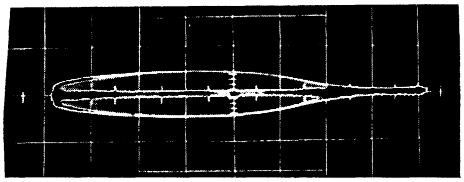

FIG. 2. Typical photograph from oscilloscope screen. The ordinates represent the bridge-unbalance voltage, and the abscissas the alternating component of the magnetic field parallel to the surface of the plate ($H=H_{\parallel}+H_{\sim}\sin\Omega t$, $H_{\parallel}=23$ Oe, $H_{\perp}=6.3$ Oe, $H_{\sim}30$ Oe, $H_c=28.5$ Oe, $\Omega/2\pi=96\times10^3$ Hz, $\omega/2\pi=10.2$ MHz. The experimental conditions correspond to plateau b on curve 2 of Fig. 10 below.

surements make it possible to separate the phase interval during which a superconducting layer exists on the surface. Inside this phase interval the voltage U, at least in the case of a cylindrical sample and a dc magnetic field parallel to the cylinder axis, is proportional to the average electric field in the layer.

The circuit used to record $U(\varphi)$ consisted of a receiving coil, a broadband amplifier, and a stroboscopic pulse-parameter meter (I4-4), which made it possible to plot the $U(\varphi)$ curves on an automatic x-y potentiometer. The signal from the gap between the inductance coil and the sample was compensated in the same manner as before.[4] To facilitate the compensation, the receiving coil was wound on the sample. As a result, the frequency band in which $U(\varphi)$ could be registered reached 200 kHz.

The second method of controlling the processes at the sample surface consisted of observing the changes of the surface impedance of the metal at a frequency $\omega \gg \Omega$. To this end, one more measuring inductance coil was clamped to the surface of the sample and was connected in one of the arms of a twin-T bridge. The bridge operated at the frequencies 10–15 MHz. It was balanced when the metal was in the normal state. The change of the surface state of the sample produced an unbalance. The unbalance signal, amplitied with a broadband amplifier, could be observed on an oscilloscope screen.

A photograph from the oscilloscope screen is shown in Fig. 2. It is seen that the impedance does not change much, with the exception at the instants when superconductivity appears on the sample surface. For a quantitative assessment we used the maximum value of the unbalance voltage.

At helium temperatures and at frequencies of the order of 10^5 Hz the depth of the skin layer in the copper wire used for the receiving coils was of the order of the wire diameter (50×10^{-4} cm). This could lead to the distortion of the alternating field under the coils. The experimental results, however, indicate that the distortion was negligible.

TABLE I.

Samples (cylinders)	Dimensions, cm r	Dimensions, cm h	$10^{-3}\frac{R_{300}}{R_0}$	Orientation of crystal axes φ,* deg.	Samples (plates)	Dimensions, cm $x\times y\times z$	$10^{-3}\frac{R_{300}}{R_0}$	Orientation of crystal axes
Sn-1	0.45	5.8	1	83	In-4	0.25×0.95×4.9	1.5	$C_4 \parallel n$**
Sn-3	0.4	6.0	1	19	In-5	0.25×0.95×4.9	1.5	$\measuredangle C_4, n=30°$
In-1	0.45	5.8	3	19				

*φ is the angle between the cylinder axis and C_4.
**n-normal to the surface.

EXPERIMENTAL RESULTS

1. Measurement of the electric field intensity E as a function of the phase φ, with H_0 and $H_{\sim}$ parallel to the sample axis, has shown that in all cases, at large amplitudes of the alternating field, the electric field in the layer is different from zero (see Fig. 3). In Fig. 3 the point B corresponds to a transition to the normal state, and the point A corresponds to the reverse transition. As seen from the figure, the electric field in the layer is a noticeable fraction (on the order of 0.1) of the field in the normal state. The increase of the ac field amplitude leads to an increase of the electric field of the layer, as shown in Fig. 4.

The peak B in Fig. 3 is due to the penetration of the magnetic flux into the region previously occupied by the superconductor, and therefore it is possible to determine from the area of such peaks the value of δ_1. The

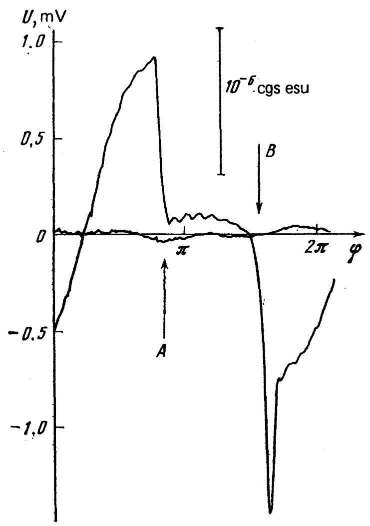

FIG. 3. Voltage on receiving coil as a function of the phase of the alternating field. Sample Sn-3, $f=\Omega/2\pi=146\times10^3$ Hz, $H_0=40$ Oe, $H_c=54$ Oe, $H_{\sim}=40$ Oe. For comparison, a plot is shown obtained under conditions when the entire sample is superconducting. The appearance of a small voltage in this case is due to insufficient cancellation of the signal from the gap between the sample and the receiving coil.

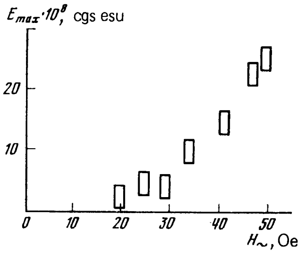

FIG. 4. Dependence of the maximum value of the electric field in the layer on the amplitude of the alternating field for Sn-3, $H_0 = 40$ Oe, $H_c = 54$ Oe, $\Omega/2\pi = 146$ kHz.

area under the peak is

$$S \sim \int E(t)\,dt = -\frac{\delta_1}{c}\left(H_c + \frac{1}{2}\frac{\partial H}{\partial t}\bigg|_{H_c}\tau\right),$$

where τ is the time required to destroy the layer. If the height of the peak is much larger than the signal in the normal state, then the second term in the round brackets

$$\frac{1}{2}\frac{\partial H}{\partial t}\tau \sim \frac{1}{2}H_\sim\Omega\tau$$

can be discarded and

$$|S| \sim \delta_1 H_c c^{-1}.$$

(This condition is not satisfied on the curve of Fig. 3. Such curves were not used to determine δ_1).

The measured dependence of δ_1 on Ω is illustrated in Figs. 5 and 6. For comparison these figures show the frequency dependence of the depth of the skin layer in the normal state $\delta(\Omega)$. As seen from the figures, in the investigated frequency band the value of δ_1 is controlled by the frequency. In indium, where under our conditions $\xi(T) \approx 6\times10^{-5}$ cm ($\xi_0 = 4.4\times10^{-5}$ cm), it is possible to raise δ_1 to $3\xi(T)$ by increasing the frequency (see Fig. 6).

The surface impedance at 10.2 MHz in fields H_0 and $H_\sim$ parallel to the sample axis, and δ_1 does not differ at $A < \varphi < B$, from the impedance of a superconductor, despite of the presence in the layer of the electric field connected with the alternating field of frequency Ω. (It was possible to discern in the experiment an impedance change amounting to 4% of the difference between the impedances of the normal and superconducting metals.)

In view of the nonstationary nature of the conditions under which the superconducting layer exist on the surface of the sample, it can be assumed that the dimension δ_1 changes substantially when the phase of the field changes from the value A to the value B indicated in Fig. 3. To check on this statement, we measured the

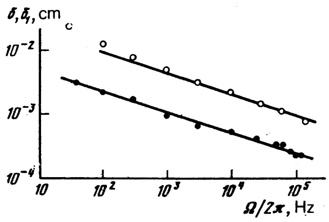

FIG. 5. Depth of skin layer δ (○) and thickness of superconducting layer δ_1(●) vs the frequency of the alternating field for Sn-3. The points for δ_1 were obtained at $H_0 = 225$ Oe, $H_c = 230$ Oe, $H_\sim = 37$ Oe. The lines are proportional to $\omega^{-1/2}$.

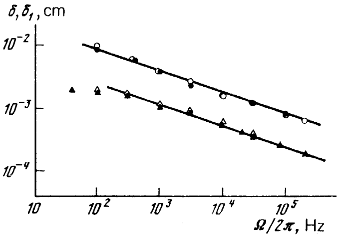

FIG. 6. Dependences of the depth of the skin layer δ (○,●) and of the thickness of the superconducting layer δ_1(△,▲) on the frequency of the alternating field: ○–In-1, ●–In-4; △ – In-1, $H_\sim = 30$ Oe, $H_c = 75$ Oe, $H_0 = 75$ Oe, ▲ – In-4, $H_\sim = 67$ Oe, $H_c = 75$ Oe, $H_0 = 75$ Oe. The lines are proportional to $\omega^{-1/2}$.

dependence of the thickness δ_1 on the phase of the alternating field at the frequency 10^2 Hz. A short rectangular current pulse, of duration 10^{-3} sec, was applied to the coil that produced the magnetic field. The field on the surface was increased thereby to the critical value within about 10^{-6} sec. The pulse could be applied at any value of the phase of the alternating field. The size δ_1 was determined, as before, from the area of the peak under the curve of the transition to the normal state. It turned out that the thickness δ_1 is independent of the phase accurate to 20%.

The time after which the regions of the superconducting phase vanish from the surface of the sample is $\tau \leqslant 2\pi/\Omega = T$, and in the range 10^3–10^5 Hz the ratio τ/T changes little with frequency (Fig. 7). The external magnetic field in which the superconducting regions appear on the surface of the sample, $H_c - \delta H$ decreases with increasing $H_\sim$ and Ω, i.e., δH increases. It appears that the dependence of δH on Ω causes the increase of the threshold amplitude $H_\sim^c$ with increasing Ω.[4]

2. On the basis of the earlier results[4] one should expect a change in the properties of the superconducting layer when the dc magnetic field is tilted relative to the sample surface. We recall that we have previously observed[4] a decrease, due to introducing the alternating field, of the magnetic field in which the sample goes over completely into the normal state, to the value $H_c - \Delta H$ (where $\Delta H \approx H_\sim$). According to Ref. 4, the value of ΔH decreased by several times when the field H_0 was deflected from the cylinder axis by an angle ψ of the order of 10°. The function $\Delta H(H_\sim)$ at $\psi = 25°$ is shown in greater detail for a cylindrical tin sample in Fig. 8. As seen from the figure, an appreciable change of ΔH is observed only when $H_\sim$ exceeds little the threshold value of the amplitude. Nonetheless, the effect of the inclination is undisputed.

It is more convenient to investigate the role of the component $H_\perp$ of the magnetic field normal to the sam-

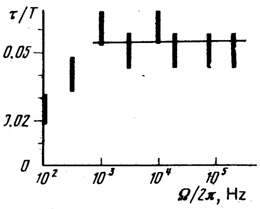

FIG. 7. Plot of τ/T against the frequency of the alternating field for In-4, $H_c = 75$ Oe, $H_0 = 75$ Oe, $H_\sim = 67$ Oe.

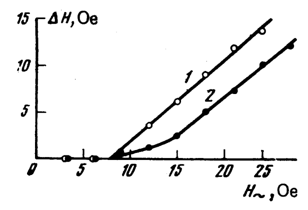

FIG. 8. Dependence of the shift of the superconducting transition on the amplitude of the alternating field in a parallel dc field and in a field inclined to the sample axis. Sample Sn-1, $H_c = 45.5$ Oe, $\Omega/2\pi = 1$ kHz. Curve 1 corresponds to an inclination angle $\psi = 0$, and curve 2 to $\psi = 25°$.

ple surface by using plates. Figure 9 shows the dependence of the magnetic flux through an indium plate on the magnetic field component $H_\parallel$ parallel to the surface for two cases: in the presence and absence of a small normal field component. It is seen from the figure that introduction of the field perpendicular to the surface deforms noticeably the $\Phi(H_\parallel)$ curve in that region where the sample layer is normal. The deformation of the $\Phi(H_\parallel)$ curve is connected with a change of the surface impedance of the layer. As shown in the upper part of Fig. 9, the surface impedance changes jumpwise when $H_\parallel$ increases, and flat sections are present both before and after the jump. The change of the surface impedance following introduction of the normal component of the magnetic field is shown in Figs. 10 and 11. The plateau marked by the letter *b* in Fig. 10 is observed in a narrow interval of angles between the external magnetic field and the plane of the sample. An increase of the normal component of the magnetic field leads to a sharp change of the impedance on the plateau *b* and changes quite little the impedance in the region *a*. According to Fig. 11, a decrease of the frequency Ω leads to an increase of the value of $H_\perp$ needed for the appearance of the plateau *b*.

Thus, in an oblique magnetic field there are two experimentally well distinguishable regions, in which the superconducting layer on the surface of the sample has different properties. Only in one of them (*a* in Fig. 1)

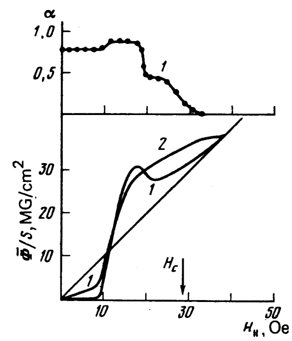

FIG. 9. The lower curves show the plot of the magnetic flux through the sample in an inclined (1) magnetic field and in a field parallel (2) to the sample surface on the value of $H_\parallel$. The upper curve shows the variation of $\alpha = (Z - Z_N)/(Z_s - Z_N)$ (Z is the projection of the surface impedance of the sample on some direction in the complex plane) as functions of $H_\parallel$ under conditions (1). Sample In-4, $H_c = 28.5$ Oe, $H_\sim = 15$ Oe, $\Omega/2\pi = 96 \times 10^3$ Hz, $\omega/2\pi = 10.2$ MHz, curves 1 correspond to $H_\perp = 5.9$ Oe.

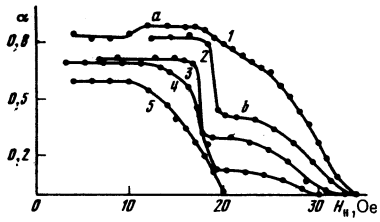

FIG. 10. Dependence of α on $H_\parallel$ at different $H_\perp$ for sample In-4, $H_c = 28.5$ Oe, $H_\sim = 21$ Oe, $f = 96$ kHz, $\omega/2\pi = 10.2$ MHz. Curves: 1) $H_\perp = 5.1$; 2) 6.3; 3) 6.6; 4) 7.8; 5) 9.8 Oe.

is the surface impedance close to the impedance of the intermediate state.

3. The most interesting is the question of the microstructure of the layer that occurs periodically in an alternating field on the surface of the sample. We have attempted to observe the structure with the aid of microcontacts, in analogy with the procedure used in Ref. 3. In an alternating field of relatively low frequency ($\Omega/2\pi \approx 100$ Hz) the signal from the microcontacts exhibited spikes corresponding to the passage of regions of the normal phase under the contact. However, no correlation of signals from different contacts could be observed. As a result, it was impossible to measure the velocity of the structure and nothing can be said concerning the dimensions of the normal and superconducting regions. There are no grounds for assuming that the emergences of the normal phase to the surface are connected with the electric field in the layer, rather with the existence of a small magnetic-field component perpendicular to the surface. With increasing frequency, the observation conditions become even worse, inasmuch as during the time of the existence of the layer an ever decreasing section of the layer passes under the microcontact. The experiments with the microcontact make it possible only to state that the layer produced in the alternating field moves along the surface.

DISCUSSION

The transition from the intermediate to the two-dimensional mixed state was considered theoretically by Andreev and Dzhikaev.[5] The structure of the intermediate state in their paper is similar to that shown in Fig. 1. The interface between the normal and superconducting phases is bent, as a result of which the absolute value of the magnetic field on the boundary is less than the critical value, and the surface tension

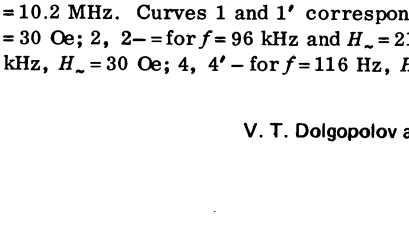

FIG. 11. Dependence of α on $H_\perp$ on plateau *a* (curves 1–4) and plateau *b* (curves 1′–4′). Sample In-4, $H_c = 28.5$ Oe, $\omega/2\pi = 10.2$ MHz. Curves 1 and 1′ correspond to $f = 114$ kHz, $H_\sim = 30$ Oe; 2, 2′ – for $f = 96$ kHz and $H_\sim = 21$ Oe; 3, 3′ – for $f = 11.6$ kHz, $H_\sim = 30$ Oe; 4, 4′ – for $f = 116$ Hz, $H_\sim = 30$ Oe.

of the separation boundary plays an important role under equilibrium conditions. The period d of the intermediate state is much less according to the theory[5] than the layer thickness δ_1. The difference between the conditions used for the calculation and the experimental condition is, first, that an immobile structure was used for the calculation while in the experiment the layer was moving. It is difficult to estimate the extent to which the structure that exists under the experimental conditions agrees with the equilibrium structure at the same field configuration. The only indication, in our opinion, that the structure is close to equilibrium is the experimental fact that the volume of the superconducting phase hardly changes during the lifetime of the layer.

The use of expression (5) of Ref. 5 allows us to connect the measured value of the electric field at a distance on the order of δ_1 from the surface with an intermediate-state structure period

$$E \approx \frac{c}{8\pi\sigma}\frac{3dH_c(T)\Delta}{16\delta_1^3},$$

where Δ is of the order of the coherence length and σ is the static conductivity. Substituting the indium parameters $\Delta \sim 4\times10^{-5}$ cm, $\sigma \sim 2\times10^{22}$ cgs esu, $\delta_1 \sim 2\times10^{-4}$ cm, $H_c(T)\approx 50$ Oe, and $E \sim 2\times10^{-7}$ cgs esu, we get $d\approx10^{-1}$ cm. This result disagrees with the assumptions made by Andreev and Dzhikaev.[5] It is possible that it precisely the motion of the structure which accounts for this contradiction.

In an inclined magnetic field the structure of the layer is determined by three factors: the electric field in the layer, the normal component of the magnetic field $H_\perp$, and the magnetic field component $H_\parallel$ parallel to the surface. In the region of the plateau a (Fig. 10) the ratio of the areas of the surfaces occupied by the normal and superconducting phases is close to $H_\perp/H_c - H_\perp$, i.e., it is determined by the normal component of the magnetic field. It is not yet clear what causes the sharp change of the surface impedance on going over to the plateau b. We note however, that this change can mean not only a change in the concentration of the normal phase on the surface, but can also be connected with the change of the microstructure of the layer. In films, for example, a transition was observed from a laminar structure typical of the intermediate state of thick plates to penetration of the magnetic field via individual islands containing several magnetic-flux quanta, at film thicknesses $(10-100)\xi$ and $H_\perp \sim 0.4H_c$.[6-8]

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Destruction of superconductivity of hollow cylindrical tin samples by current

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Results are reported of measurements made on two single-crystal tin samples. The samples were thin-wall hollow cylinder with identical dimensions but substantially different values of the residual resistance. The current-voltage characteristics of the samples and the influence of a static longitudinal magnetic field were studied and the rate of penetration of a weak longitudinal magnetic field into the bore of the sample was measured. The reduction of the measurement results leads to the conclusion that the angle between the electric field and the current in a layer of a two-dimensional mixed state is determined by the relative orientation of the electric and magnetic field on the boundary between the layer and the normal metal.

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When the superconductivity of a hollow cylindrical sample is destroyed by current flowing through the sample, a thin layer of two-dimensional mixed state (TDM) of a type-I superconductor is produced on the outer surface of the sample.[1-7] If the current I through the sample is only slightly larger than the critical value $I_c = cr_2H_c/2$ (r_2 is the radius of the outer surface of the sample and H_c is the critical magnetic field) there can

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