INVESTIGATION OF DISSIPATIVE PROCESSES IN SINGLE-CRYSTAL TYPE II SUPERCONDUCTORS

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Submitted April 26, 1972

Zh. Eksp. Teor. Fiz. 63, 2144–2150 (December, 1972)

Dissipative processes are studied by means of a special nonconduction technique in single crystal samples of the type II superconductor $Ta_{70}Nb_{30}$.

DISSIPATIVE processes have been studied in Type II superconductor by many authors,[1,2] who applied a conduction method in their investigations (a large critical current is passed through a superconducting plate or wire in the mixed state and detaches the Abrikosov vortices from the centers pinning them, causing motion of the vortices with the accompanying dissipation of energy and the appearance of potential differences; it is the latter which is measured experimentally).

In 1966, we, together with É. L. Andronikashvili, S. M. Ashimov and Dzh. S. Tsakadze, employed a nonconductive technique for the study of dissipative processes and pinning processes in polycrystalline type II superconductors. In this technique a superconducting wire served as the elastic thread of an inverted torsion pendulum.[3-5]

For the study of dissipative processes in single crystal type II superconductors, we used a special nonconduction technique with the use of a direct torsion pendulum. In the process of measurement of the viscoelastic properties of vortices by this method, the sample itself is not deformed, so that there is the possibility of measuring in pure form effects connected with the motion of vortices, since in this case all other absorption mechanisms are excluded. It should also be noted that in the method previously used, different vortices (located in various parts of the wire) turned, in the course of the measurement, at different angles, which led to an indeterminacy of the amplitude of the oscillations, while, in the new method, it is the same for all vortices.

The idea of this method is as follows. We take a sample (a cylinder) from a type II superconductor, suspend it from a thin elastic thread (Fig. 1) and place it in a transverse magnetic field with magnetic field H. At $H > H_{c1}/2$, the Abrikosov vortices permeate through the cylinder (see Fig. 1b) (in what follows we shall mean by the term H_{c1} the quantity $H_{c1}/2$). Upon the rotation of the cylinder about its axis (through an angle φ) a mechanical torque acts on the pinned vortex (see Fig. 1c) and tends to return the sample to its original position. Upon increase in the amplitude of the oscillations, the force F_H exerted on the vortex by the external magnetic field increases. So long as the pinning force $F_p > F_H$, the vortex will not detach itself from the pinning center. When F_H becomes greater than F_p, the vortices will detach themselves from the pinning center and begin to move through the crystal lattice. This motion is accompanied by energy dissipation. In turn this is reflected in the logarithmic damping decrement δ, which increases with increase in the amplitude of the oscillations.

The apparatus is pictured in Fig. 2. The sample 1 is attached to a special crystal holder 2, which is connected to the molybdenum filament 3 (filament length l = 68.6 mm, diameter 50 μ). The other end of the filament is attached to the bottom of the dewar. The system is suspended by means of the glass rod 4, which carries on its upper end a disk 5 with moment of inertia J = 84.85 g-cm^2, to an elastic lead-brass filament 6 (length l = 80 mm, diameter 65 μ) that runs over a pulley with counterweight 7. This entire system was placed under the cap of the dewar. Recording of the oscillations was done by means of a spot of light reflected from mirror 8 mounted on the glass rod. Measurement of the logarithmic damping decrement and the oscillation frequency was made both visually (with the

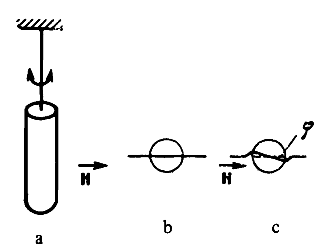

FIG. 1

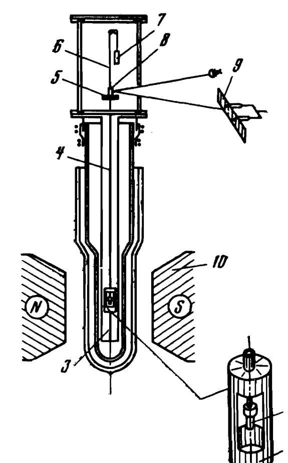

FIG. 2. Diagram of apparatus: 1—sample, 2—crystal holder made out of plexiglas to eliminate additional damping due to Eddy currents, which would be induced in a metal crystal holder, 3—molybdenum filament, 4—glass rod; 5—disc, 6—leaded brass thread, 7—counterweight, 8—mirror, 9—photomultipler and scale, 10—electromagnet.

scale 9) and by means of the electronic circuit described in[6]. That part of the dewar which contained the superconducting sample was filled with liquid helium and placed between the poles of the electromagnet 10, so that the magnetic lines of force were perpendicular to the sample.

This apparatus was intended for the measurement of damping for not too large oscillation amplitudes (from $\sim 10^{-3}$ to $\sim 10^{-1}$ rad).

For the study of dissipative processes in type II superconductors, crystals are required with either a controlled amount of defects, or defect-free. If the polycrystalline samples are pure enough, pinning centers that are formed by impurities can exist in them; however, there are always block walls and also, if special measures are not taken, gaseous impurities and dislocations, which form dislocation nets at high concentrations, as well as point defects that form frequently so-called defect clusters. The Abrikosov vortex line can be pinned on these clusters, as is well known.[7-9] Production of a controlled number of defects in a crystal with specified dimensions and separation distances is a complicated problem (and without knowing the dimensions of the defects, their number, and the distances between them, it is difficult to interpret the results of the measurement of the dissipation processes of the vortices). Great difficulties are also encountered in the preparation of almost defect-free crystals (it has not yet been possible to obtain ideal defect-free crystals of type II superconductors).

For our investigations, we chose single crystals of $Ta_{70}Nb_{30}$, being guided by the following considerations: first, it does not have as large a variety of defects (different forms of pinning centers) as is characteristic of polycrystals; second, one can always introduce defects of the desired type in the single crystal. It must also be noted that we had at our disposal a thermodynamically reversible single crystal of $Ta_{70}Nb_{30}$, the magnetic moment of which is shown in Fig. 3 (continuous curve).

Cylindrical samples were cut from such a single crystal with a spark cutter. The spark treatment built up defects on the surface of the crystal (see Fig. 3), which were then removed by electropolishing. As con-

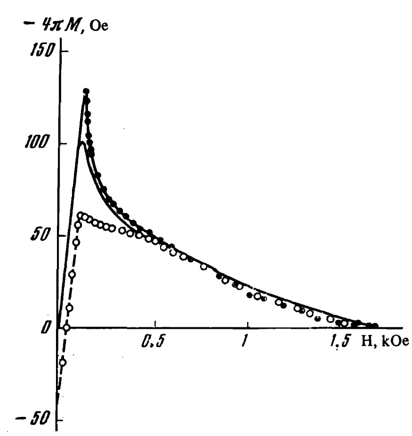

FIG. 3. Dependence of the magnetic moment on the magnetic field intensity. Solid curve—thermodynamically reversible single crystal $Ta_{70}Nb_{30}$; the points correspond to a single crystalline $Ta_{70}Nb_{30}$ with surface defects: ●—increasing field, O—decreasing field.

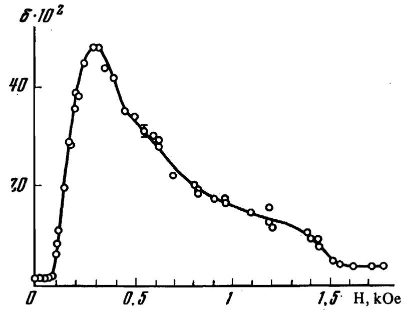

FIG. 4. Dependence of the logarithmic decrement of the damping of the oscillations on the intensity of the external magnetic field H.

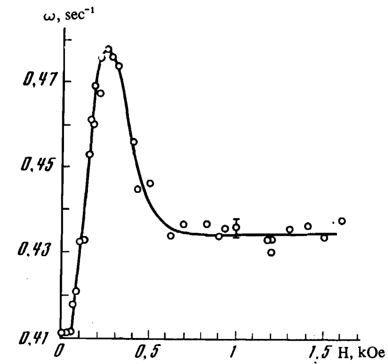

FIG. 5. Dependence of the oscillation frequency ω on the intensity of the magnetic field.

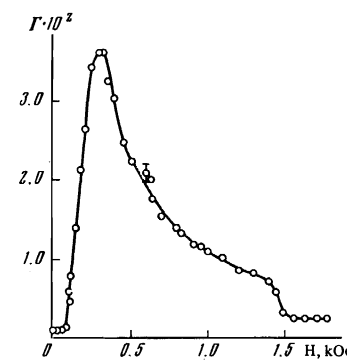

FIG. 6. Dependence of the damping coefficient on the magnetic field intensity.

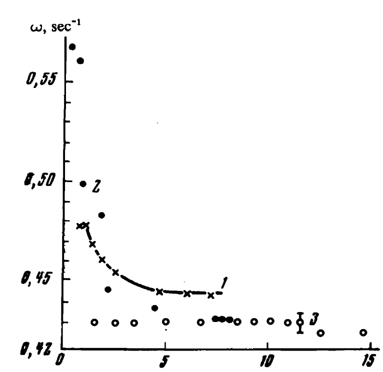

FIG. 7. Dependence of the oscillation frequency ω on the amplitude φ: curve 1 (X)–H–170 Oe, 2 (●)–H = 320 Oe, 3 (O)–H = 1450 Oe.

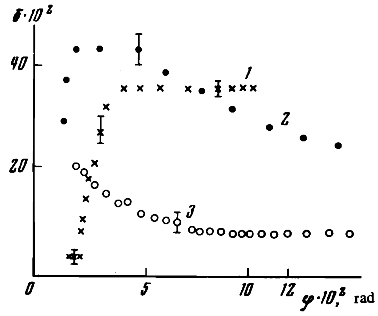

FIG. 8. Dependence of the logarithmic damping decrement δ on the amplitude of the oscillation φ: curve 1 (X)– H = 170 Oe, 2 (O)–H = 320 Oe, 3 (O)–H = 1450 Oe.

trolled experiments on the measurement of the magnetic moment have shown,[10] removal of a surface layer of thickness 50 μ completely eliminated all defects created by the spark treatment that could serve as effective pinning centers. After electropolishing of the crystal, the frozen-in flux disappears and the crystal recovers its thermodynamic reversibility, which was lost as a result of the spark treatment (see Fig. 3).

A sample cut with the spark cutter, of diameter 0.6 mm and length 5 mm, was placed in the apparatus described above and imparted axial torsional oscillations. The logarithmic damping decrement δ and the frequency of oscillation of the system ω were measured as a function of the strength of the external magnetic field H. Figure 4 shows the δ(H) dependence.

As was to be expected, upon increase of H to the first critical field H_{c1}, the logarithmic damping decrement of the oscillations does not change. On going through H_{c1}, it begins to increase approximately according to a linear law; for H = 300 Oe, it reaches a maximum and then decreases. With increase in the field intensity above the second critical value ($H > H_{c2}$), the quantity δ becomes independent of the intensity of the external magnetic field in the range of magnetic fields studied by us.

So far as the frequency of oscillation ω is concerned (see Fig. 5), it undergoes a characteristic change upon increase in the intensity of the external magnetic field. Like δ, it does not change up to a field H_{c1}; thereafter, it increases almost linearly, reaches a maximum for a smaller value of the field intensity than for δ (for H = 250 Oe), and then decreases; at H = 600 Oe, it reaches a plateau. It should be noted that the thermodynamic field of an ideal single crystal of $Ta_{70}Nb_{30}$ is H_{cM} = 640 Oe.

Knowing the dependence of δ and ω on the external magnetic field, we can construct the dependence of the damping coefficient of the oscillations Γ on the field intensity H. As is seen from Fig. 6, even in this case there exists a curve with a maximum.

Significant interest attaches to the amplitude effects observed both in the measurement of the logarithmic damping decrement and in the measurement of the oscillation frequency. First, it must be noted that the amplitude effects are not generally observed in fields with intensity $H < H_{c1}$ and $H > H_{c2}$ (at the amplitudes $\sim 10^{-3}$—10^{-1} rad of oscillation used by us).

We divide the mixed-state curve of Fig. 5 into three parts: region I—from the value of the field intensity H_{c1} to the value at which δ reaches a maximum ($H_{\delta\,max}$ = 300 Oe); region II—from $H_{\delta\,max}$ = 300 Oe to H = 600 Oe. We recall that the value of the intensity of this field corresponds to flattening of the frequency of oscillation and to the beginning of hysteresis of the magnetic moment. We also recall that the thermodynamic field of an initial "defect-free" sample is H_{cM} = 640 Oe; finally, region III—from H = 600 Oe to H_{c2}.

It should be specially noted that the amplitude effects are observed in the logarithmic damping decrement over the entire range of the mixed state from H_{c1} to H_{c2}.

Some features of behavior are inherent in the frequency of oscillation ω. It is a function of the amplitude of the oscillations in magnetic fields from H_{c1} to H = 600 Oe; for fields H > 600 Oe, it does not depend on the amplitude (see Fig. 7).

Let us now consider the behavior of the logarithmic damping decrement and the oscillation frequency in region I of magnetic fields. Typical curves for this region are shown in Figs. 7 and 8. Here the intensity of the external magnetic field H = 170 Oe.

As is seen from Fig. 8 (curve I), at small oscillation amplitudes δ does not depend on the amplitude; upon its increase, the decrement begins to grow and for comparatively high values of the amplitude it flattens. Such a dependence can be explained in the following fashion. For small oscillation amplitudes, the force F_H exerted by the external magnetic field is so small that it does not exceed the pinning force F_p and for this reason the vortices are not detached from the pinning centers; naturally, δ does not change with change of φ in this case. When φ exceeds a definite value, the force F_H increases correspondingly, which brings about an environment of comparatively weakly pinned vortices and this, in turn, is reflected in the value of δ: the larger φ the greater F_H and the larger δ. Upon subsequent increase in φ all the vortices at any moment turn out to be surrounding the pinning centers and further increase in the amplitude of the oscillations does not produce an increase in the dissipation of energy.

Such an explanation is confirmed by the dependence of of the oscillation frequency on the amplitude, shown in Fig. 7 (curve 1). The graph shows the strong dependence of ω on φ in the range of amplitudes in which the damping changes strongly; at small and comparatively high amplitudes, the frequency, as also the damping, is practically independent of the amplitude.

If we initially assume the dependence of the damping on the oscillation amplitude to start at the critical angle φ_{cr} and estimate the pinning force $\overline{F}_p$, then we obtain for our crystal the same value as the $\overline{F}_p$ determined by measurement of the magnetic moments of the crystal. This quantity is smaller by several orders of magnitude than the value of $\overline{F}_p$ measured for polycrystalline samples. Such a small value of $\overline{F}_p$ demonstrates the high quality of the samples used by us.

In region II of the magnetic field, δ and ω turn out to be dependent on φ over the entire range of amplitudes investigated by us. The value of δ as a function of the amplitude has a maximum (Fig. 8, curve 2), and the oscillation frequency φ decreases with increase in the amplitude φ (Fig. 7, curve 2). Here the intensity of the external magnetic field is H = 320 Oe.

In this range of fields, in the limits of amplitude studied by us, the phenomenon of the independence of δ and ω on φ is not observed. This can be explained by the fact that either we have not achieved the amplitudes at which pinning is observed (i.e., these amplitudes lie below the value $\varphi = 5 \times 10^{-3}$ rad), or in this region of fields there is no pinning effect as such, and only the effect of creep of the vortices takes place.

In region III of the fields, the dependences of δ and ω on φ change completely. As was noted above, in this range of fields ω does not depend on the oscillation amplitude (see Fig. 7, curve 3). So far as the logarithmic damping decrement δ is concerned, it shows a dependence on φ (see Fig. 8, curve 3). A possible explanation of this can also lead to creep phenomena, since for a field intensity $H > 600$ Oe, pinning of the vortices, which is measured by magnetic methods, disappears.[10] Evidently H = 600 Oe is that value of the field intensity for which the dissipative mechanism, due to the effect of vortex pinning, is replaced by the mechanism associated with their creep.

Summing up the foregoing, we can make the following remarks.

In the present work, we have investigated dissipative processes (by a nonconduction technique) in single crystals of type II superconductors in the mixed state. These processes are associated only with movement of the Abrikosov vortices. In magnetic field intensities from H_{c1} to $H_{\delta max} = 300$ Oe, the vortices can be assumed to be individual. In this range, pinning by the defects is observed, as indicated by the existence of a critical angle on the curve $\delta(\varphi)$. Upon increase in the values of the field intensities to $H > H_{\delta max}$, the vortices evidently begin to be collectivized and at magnetic fields with intensity $H > 600-640$ Oe the vortices can be regarded as collectivized. Beyond this limit, the characteristic changes in the oscillation frequency ω disappear.

In field intensities from H = 600 Oe to H_{c2}, the vortex pinning process has, in all probability, another character (φ_{cr} is absent); thus, the nature of the pinning in the given case is essentially different from the nature of the pinning observed in field region I, which is further indicated by the independence of the oscillation frequency on their amplitude and on the field intensity. The damping of the oscillations depends in this case both on the amplitude and on the field intensity, which can be connected with the vortex creep. The motion of the vortices observed in this case, which is estimated from our experiments, turns out to be $V_c \approx 10^{-3}-10^{-4}$ cm/sec. Such a value of the creep agrees with the data of the literature, according to which V_c can have a value from 10^{-6} to 10^{-2} sec/sec.[11]

Thus, in all probability, we have found the intensity of the external magnetic field, H = 600 Oe, at which a change in the oscillation damping mechanism takes place, namely, vortex creep is observed in place of the pinning effect.

In conclusion, the author expresses his gratitude to É. L. Andronikashvili for stimulating interest in the present work, and to A. A. Abrikosov and A. F. Andreev for their discussions and valued remarks.

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Translated by R. T. Beyer
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