Magnetic-field penetration into superconducting niobium

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Experiments reveal that the London penetration depth depends on the strength of the magnetic field in superconducting niobium samples in either the Meissner state or a mixed state.

When a superconductor is placed in a magnetic field, the wave function of the electrons changes slightly, causing the penetration depth λ to depend on the strength of the field.[1] The following expression has been derived[2] for a type I superconductor and small values of the parameter κ of the Ginzburg-Landau theory:

$$\lambda(H_e) = \lambda(0)\left\{ 1 + \frac{(\kappa + 2\sqrt{2})\kappa}{8(\kappa + \sqrt{2})^2}(H_e/H_{cm})^2 \right\}. \tag{1}$$

This expression agrees with the experimental results of Refs. 3 and 4 (H_{cm} is the thermodynamic critical field). For type II superconductors, the dependence $\lambda(H)$ has been studied neither theoretically nor experimentally, to the best of our knowledge. On the basis of general considerations we would expect a behavior at $H_e < H_{c1}$ (the right side is the lower critical field) similar to that in type I superconductors; at $\kappa \gg 1$, corresponding to London electrodynamics, the magnetic-field penetration depth should become independent of H_e. At fields $H_e > H_{c1}$ the question requires special study.

In this letter we report experimental results on the response of well-annealed and highly deformed niobium samples to a weak alternating field h_m in various static fields H_e. We derive an expression for $\lambda(H)$, and we reach the conclusion that in materials with a pronounced pinning of fluxoids the response is determined primarily by the field dependence of the penetration depth λ, even at fields $H_e > H_{c1}$.

In the measurements we use cylindrical samples (the length-to-diameter ratio is $l/D = 8$–12) with rounded ends, made from NBR-1 niobium with a resistance ratio $\gamma \sim 500$. The deformation is caused on a lathe, and then the surface is smoothed by rolling. As controls we use samples which have been deeply electropolished and then annealed at 2000 °C for 2 h in a vacuum better than 10^{-8} torr. Examination of the surface quality in an electron microscope and with a profilemeter showed that the annealed samples have only occasional pits with rounded edges; the height of the irregularities is smaller than the resolution of the profilemeter (0.01 μm). A few grooves and scuffs, with average plan dimensions $\sim 0.5 \times 5$ μm^2, separated by distances 30 μm, are seen on the surfaces of the deformed (rolled) samples. An Auger analysis reveals an elevated amount of oxygen and carbon in the surface layers of a

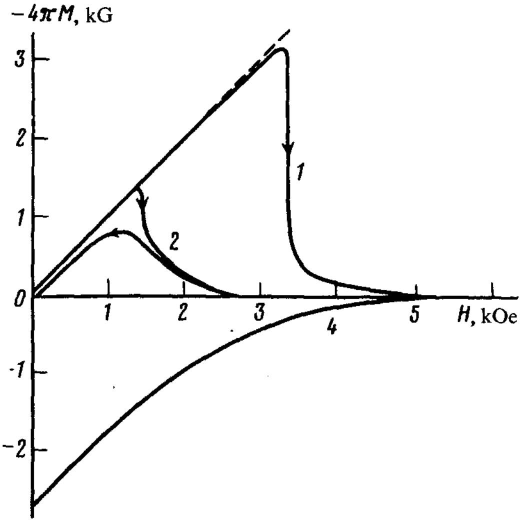

FIG. 1. Magnetization curves of (1) deformed and (2) annealed niobium samples ($T=4.2$ K).

deformed sample, in a concentration which is essentially independent of the depth according to measurements down to 800 Å.

The effective penetration depth is found from the temperature dependence of the response of the sample (the signal from a coil wound around it) to a weak sonic-frequency magnetic field ($h_m = 0.1$–1 Oe) in a zero static field; the procedure is approximately the same as that described in Refs. 5 and 6. The magnitude of the response for a rolled sample is 625 Å ($\pm 10\%$), or slightly above the value for a cold worked niobium surface.[6] The reason for the difference may be the short annealing time in our case or the prolonged exposure to air.

Working from the formulas of Ref. 7, the values $\lambda(0) = 315$ Å (Ref. 6) and $\kappa = 0.74$ (Ref. 8), and the assumption that the value of H_{cm} for the surface layers is not greatly different from that in the interior, we find for a deformed sample an electron mean free path $l \sim 80$ Å, $\kappa = 3$, $H_{c1} = 250$ Oe. These values agree with the measurements of the magnetic moment, shown in Fig. 1. The deformed sample (curves 1) is irreversible. An appreciable magnetic moment is observed at fields up to about $H_e = 6$ kOe; this value can then be taken as an estimate of the upper critical field of the surface layers, which are the most highly deformed and impure layers. A field penetration which is noticeable at this scale occurs at $H_e = 2.45$ kOe. The curves for the annealed sample (curves 2) are of the standard shape for nearly defect-free niobium.

To determine the dependence $\lambda(H)$ at a constant temperature in static fields of various strengths, we measured the components of the response of the superconductor to a change in the modulation field. Figure 2 shows the typical behavior for a deformed sample $H_e > H_{c1}$. The signals U_1' and U'' correspond to the cases in which the voltage across the coil is in phase with (U'') and $\pi/2$ out of phase with (U_1') the

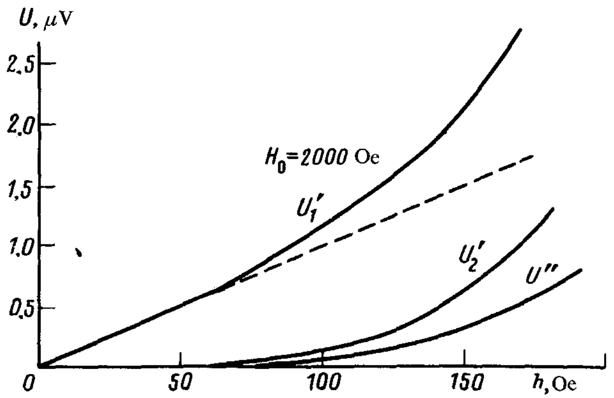

FIG. 2. Response of the annealed sample versus the amplitude of the modulation field.

modulation field. We see a nonzero slope and a linearity of $U_1'(h_m)$ in its initial region, while we have $U''(h_m) = 0$. We immediately note that an attempt to interpret these results in the model of elastic vibrations of fluxoids in pinning potential wells[9,10] runs into a contradiction in our case: A calculation of the fluxoid vibration amplitude from curves of this type measured at various values of H_e from the model of Ref. 9 yields values ranging from 4×10^3 Å at $H_e = 1060$ Oe to 3×10^4 Å at $H_e = 3000$ Oe; these values are greater than the distances between vortices in these fields, $a=\sqrt{\Phi_0/H_e}$, where Φ_0 is the quantum of flux. Since the amplitude of the elastic ($U''=0$) vibrations in the pinning potential wells cannot exceed the distance between fluxoids, this mechanism cannot explain the observed behavior $U(h_m)$. If the signal linear in h_m is due primarily to the change in the penetration depth with the field, the magnitude of the signal at $h = h_m \cos\omega t$ is

$$U \sim \frac{d\Phi}{dt} = \omega \sin \omega t \left[\lambda(H_e) - \lambda(0) + \frac{\partial\lambda}{\partial H_e} H_e\right] h_m . \qquad (2)$$

The measurements show that in fields $H_e \leqslant H_{c1}$ for the annealed sample or $H_e \leqslant 2.45$ Oe (at 4.2 K) for the deformed sample the linear response increases nearly quadratically with increasing H_e: $(\partial U/\partial h_m) \sim H_e^n$, where $n = 1.8$–2.2. In stronger fields H_e the signal increases much more extensively and becomes unstable (for the deformed sample). This behavior is attributed to a decrease in the pinning force in it and to discontinuities induced in the magnetic flux by the modulation field. The values of $\Delta\lambda(H) = \lambda(H_e) - \lambda(0)$ calculated from (2) are shown in Fig. 3. At $H = H_{cm}$ (4.2 K) = 1560 Oe, the value of $\Delta\lambda$ in the annealed sample is ~70 Å, and that in the deformed sample is ~35 Å. From (1) we find $\Delta\lambda = 35$ Å for the annealed sample ($\kappa \sim 1$) in this field and $\Delta\lambda = 70$ Å for the deformed sample ($\kappa = 3$). In other words, the agreement is quite good. The strengthening of the dependence $\Delta\lambda(H)$ with the temperature (for the annealed samples) agrees with theoretical[2,4] and experimental[3,4] data for type I superconductors.

In principle, for an inhomogeneous superconductor with critical fields and temperatures which are weakened near the surface we could expect a suppression of super-

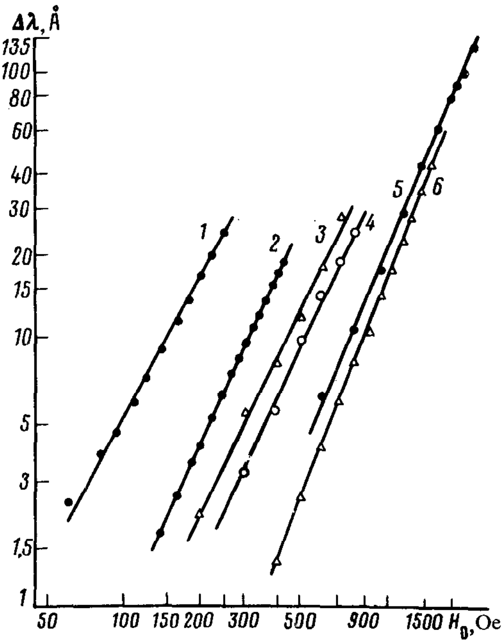

FIG. 3. Field dependence of the penetration depth. 1–4—Annealed sample; 1—$t = T/T_c = 0.91$; 2—$t = 0.86$; 3—$t = 0.76$; 4—$t = 0.67$; 5—deformed sample, $t = 0.46$; 6—the same, after the removal of ~1000-Å layer.

conductivity in the outer layers by a magnetic field[11], which should also lead to the appearance of a signal which is linear in h_m and which increases with H_e. There must, however, be a special reason for the thickness of these layers to increase quadratically with the field H_e. Further evidence against this assumption is the circumstance that the electrochemical etching of a thickness ~1000 Å from the deformed sample has essentially no effect on $\Delta\lambda(H_e)$ (Fig. 3).

The probable reason why the values of $\Delta\lambda(H)$ are smaller for the deformed sample than for the annealed sample is that the electrodynamics approaches a London electrodynamics as κ increases.

We believe that the signal from the deformed samples which is quadratic in H_e at fields above H_{c1} means that under strong-pinning conditions the Lorentz force acting on the fluxoids is incapable, at a small modulation field, of causing any significant deformation of the vortex lattice. The contribution of the motion of this lattice to the response is small, and it is possible to observe a change $\Delta\lambda(H_e)$ in a mixed state.

Evidence for strong pinning comes from not only the shape of the magnetization curve but also the high critical current ($\sim 3\times 10^7$ A/cm^2 at $H_e = 1.5$ kOe) estimated by the method described in Ref. 10, involving a cancellation of $U_2'(h_m)$ curves in the given H_e (Fig. 2).

[1]J. Bardeen, Phys. Rev. **87**, 192 (1952).
[2]V. L. Ginzburg and L. D. Landau, Zh. Eksp. Teor. Fiz. **20**, 1064 (1950).
[3]Yu. V. Sharvin and V. F. Gantmakher, Zh. Eksp. Teor. Fiz. **39**, 1242 (1960) [Sov. Phys. JETP **12**, 866 (1961)].

[4]A. B. Pippard, Proc. Roy. Soc. **A203**, 210 (1950).
[5]W. Schwartz and J. Halbritter, J. Appl. Phys. **48**, 4618 (1977).
[6]C. Varmazis and M. Strongin, Phys. Rev. B **10**, 1885 (1974).
[7]D. Saint-James, G. Sarma, and E. J. Thomas, Type II Superconductivity, Pergamon, New York, 1969 (Russ. transl. Mir, Moscow, 1970).
[8]V. A. Marchenko and G. I. Sal'nikov, Zh. Eksp. Teor. Fiz. **82**, 844 (1982) [Sov. Phys. JETP **55**, 499 (1982)].
[9]A. M. Campbell, J. Phys. C **2**, 1491 (1969).
[10]V. R. Karasik, E. V. Karyaev, V. M. Zakasarenko, M. O. Rikel', and V. I. Tsebro, Zh. Eksp. Teor. Fiz. **87**, 2114 (1984) [Sov. Phys. JETP **60**, 1221 (1984)].
[11]G. Deutscher and P. G. de Gennes, in: Superconductivity, Vol. 2 (ed. R. D. Parks), Dekker, New York, 1969.

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