Observation or Order-Parameter Enhancement by Microwave Irradiation in a Superconducting Aluminum Cylinder

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The fluxoid quantization condition for a thin superconducting cylinder causes a change in the order parameter to result in a change in the frozen-in magnetic flux. By measuring with a SQUID the change in magnetic flux for a superconducting aluminum cylinder under microwave irradiation it is found that the order parameter increases as a function of the microwave power. Order-parameter changes with changing temperature are observed also, and they are in agreement with theoretical expectations for a dirty superconductor.

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Nonequilibrium phenomena in superconductors have been the subject of much research in the last few years.[1] Microwave-induced enhanced superconductivity is one of the properties which has been investigated. Most observations concern the increase of the critical current in superconducting weak-link structures[2,3] or in thin film strips[4,5] by microwave irradiation. The existing theories[6,7] account for an increase of the energy gap of a superconductor under microwave irradiation due to the redistribution of the quasiparticles away from the gap edge.

A direct observation of gap enhancement was reported by Kommers and Clarke,[8] who measured the change in I-V characteristics in superconducting Al tunnel junctions under microwave irradiation. More recently Dahlberg, Orbach, and Schuller[9] reported on similar experiments. However, they did not observe a gap enhancement in their tunnel junctions on microwave irradiation, whereas they did simultaneously find a critical-current increase in the superconducting strips forming the tunnel contact.

In this Letter we present measurements which demonstrate the enhancement of the superconducting order parameter, which is directly related to the energy gap. In a thin Al layer evaporated on the surface of a glass tube, a magnetic flux was frozen in. Because of the fluxoid quantization condition a change in the order parameter resulted in a change in the magnetic flux in the cylinder, which was observed with a pickup coil around the cylinder. In this way we measured order-parameter variations caused by microwave irradiation and by temperature variations as well. This measuring principle had been used previously by Mercereau and Crane[10] in order to observe temperature variations in a superconducting cylinder caused by second-sound waves in the liquid helium, in which the cylinder was immersed.

The principle of the measurements relies on the well-known fluxoid quantization condition for a closed contour C through a superconductor:

$$\Phi + \frac{m}{(2e)^2}\oint_C \frac{\vec{j}\cdot d\vec{s}}{|\psi|^2} = n\Phi_0, \tag{1}$$

where $\Phi = \oint_C \vec{A}\cdot d\vec{s}$ is the magnetic flux through the surface enclosed by C, m the effective mass of an electron, e the elementary charge, j the superconducting current density, ψ the order parameter, $\Phi = h/2e$ the elementary flux quantum, and n an integer.

For a superconducting cylinder of radius r and thickness d which is small compared to the penetration depth $\lambda = m/(4e^2|\psi|^2\mu_0)$, Eq. (1) becomes

$$\Phi + 2\pi m r j/(2e)^2|\psi|^2 = n\Phi_0. \tag{2}$$

Using the relation for a long cylinder,

$$\Phi = \mu_0 j d \pi r^2, \tag{3}$$

we obtain up to first order in the small parameter $\delta\Phi/\Phi$ (see Fig. 2) the following relation between a small change in the order parameter and the resulting small change $\delta\Phi$ in the flux:

$$\frac{\delta\Phi}{\Phi} = -\frac{m}{2\mu_0 e^2 d r}\,\delta\frac{1}{|\psi|^2}. \tag{4}$$

If the temperature T is close to the critical temperature T_c a change in the order parameter caused by a temperature variation can be calculated using the relation between ψ and the superconducting energy gap Δ for a dirty superconductor[11]:

$$\psi = [\pi m v_F l N(0)/12\hbar k_B T_c]^{1/2}\Delta. \tag{5}$$

In this equation, v_F is the average Fermi velocity, l the mean free path, and $N(0)$ the density of states for one spin direction at the Fermi level. The temperature dependence of Δ follows from the BCS theory and is given, close to T_c, by

$$\Delta = \pi[8/7\zeta(3)]^{1/2} k_B T_c (1 - T/T_c)^{1/2}. \quad (6)$$

Combining Eqs. (4)–(6), we find

$$\frac{\delta\Phi}{\Phi} = -\frac{21\zeta(3)\hbar}{4\pi^3\mu_0 e^2 d r v_F l N(0) k_B T_c}\,\delta\,\frac{T_c}{T_c - T}. \quad (7)$$

The sample on which the measurements were performed consisted of an Al layer evaporated on a 0.8-mm-diam glass tube. Within this tube we mounted a copper wire of a thickness such that it formed, with the Al cylinder, a 50-Ω coaxial system. This system was connected to a microwave source outside the Dewar by means of a microwave cable. In this way it was possible to induce microwave currents in the Al cylinder. An advantage of the setup was the circular geometry in which edge effects could not play a complicating role. In order to be able to detect flux changes in the Al cylinder a Nb-wire coil was wound around the cylinder with 150 windings on a length of 13 mm. This coil was connected to the input of a SHE-SQUID system (input inductance 2 μH, mutual inductance to SQUID ring 20 nH). The superconducting path between the Nb pickup coil and the SQUID could be disconnected by heating a small part of the connecting wires to above the critical temperature. The sample with pickup coil was mounted in another coil with which an external magnetic field could be applied parallel to the axis of the cylinder. The whole setup was protected against external magnetic field variations by a superconducting lead shield and was immersed in a temperature-regulated helium bath.

The measurements which will be reported were made on a sample with a 50-nm-thick Al layer. The resistance ratio between the room temperature and the helium-bath temperature of this layer was measured to be 2.4. The sheet resistance at T_c turned out to be 0.15 Ω.

The measurements start with freezing in of a flux. Above T_c an external magnetic field is applied, with the pickup coil disconnected. The sample is then cooled to a temperature below T_c, the external field is switched off, and the superconducting connection between pickup coil and SQUID is reestablished.

When the temperature is now lowered further, the order-parameter change causes a flux change which results in a SQUID signal. In Fig. 1, curve a, the recorded SQUID output is given as a function of the resistance value of a temperature-calibrated Allen Bradley resistor.[12] The corresponding temperature scale is indicated. For this particular curve the magnetic flux was frozen in at 1.265 K. After the recording of curve a the temperature was again made equal to 1.265 K and now the SQUID output was recorded at a fixed temperature as a function of power delivered by the microwave source. For a frequency of 9 GHz the result is given in Fig. 1, curve b. It is clearly seen that application of a microwave power results in a SQUID output in the same direction as a temperature decrease. The microwave irradiation therefore increases the order parameter. The value of the flux Φ which was frozen in for this experiment could be determined by increasing the temperature from $T = 1.265$ K to above T_c while simultaneously recording the escaping flux with the SQUID. This is shown in curve c with the sensitivity of the SQUID reduced by a factor of 10. As soon as the critical temperature $T_c = 1.296$ K is reached the circulating current in the cylinder has become zero and the SQUID output no longer changes with increasing temperature. We have checked the microwave irradiation causes no spurious SQUID output signal above T_c. Furthermore, we have checked that a smaller value of frozen-in flux Φ results in a proportionally smaller signal when the temperature is lowered or when microwaves are applied,

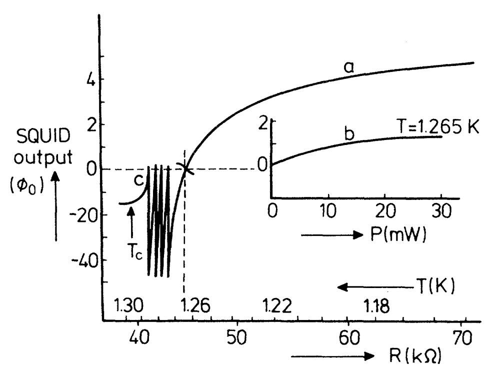

FIG. 1. Recorded output signals from the SQUID: Curve a, a function of the Allen Bradley resistance value R for decreasing temperature. Curve b, a function of 9-GHz microwave power P delivered by the source for a fixed temperature $T = 1.265$ K. Curve c, a function of T for increasing temperature. The sensitivity of the SQUID is made a factor of 10 smaller. The discontinuities are due to the automatic resetting of the SQUID. The temperature scale corresponding to the R values is indicated.

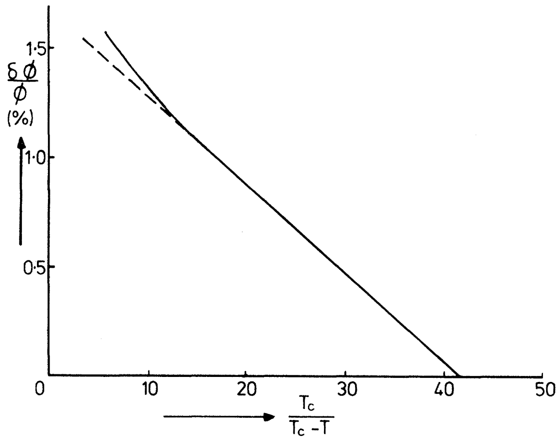

FIG. 2. The relative change in flux $\delta\Phi/\Phi$ as a function of $T_c/(T_c-T)$ corresponding to curve a in Fig. 1. The broken straight line has a slope of 4.0×10^{-4}.

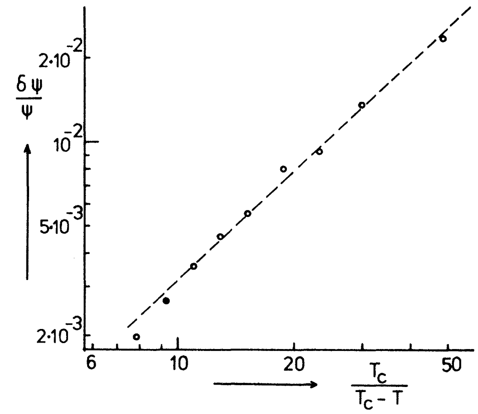

FIG. 3. Relative increase of the order parameter $\delta\psi/\psi$ as a function of $T_c/(T_c-T)$ when a 9-GHz microwave power P of 3 mW is delivered by the source.

whereas reversal of the sign of Φ results in reversal of the slope of curves a, b, and c.

In Fig. 2 we have plotted the measured flux change $\delta\Phi$ of curve a in Fig. 1 divided by the total flux Φ determined from curve c as a function of $T_c/(T_c-T)$. This results in a straight line for large values of $T_c/(T_c-T)$, in agreement with Eq. (7), which is valid for T close to T_c. Only for temperatures for which $T_c/(T_c-T)\lesssim 15$ is a small deviation from linearity seen to exist. The slope of the straight line is measured to be 4.0×10^4.

From Eq. (7) we calculate a slope of 3.5×10^4. For this calculation we used $v_F=1.29\times10^6$ m/sec,[13] $d=50$ nm, $r=0.40$ mm, $N(0)=1.1\times10^{47}$ $m^{-3}J^{-1}$ (derived from the specific-heat constant $\gamma=5.04\times10^{-2}$ $J\,kg^{-1}K^{-2}$), $l=37$ nm [derived from the resistance ratio 2.4 and the room-temperature value of $l=15.5$ nm (Ref. 13)], and $T_c=1.296$ K. The calculated and measured values of the slope in Fig. 2 are therefore in good agreement.

The experiments which we described have been repeated for a number of other temperatures and different values of frozen-in flux Φ. The behavior was always similar and the slope of the straight lines like those given in Fig. 2 was reproducible to within $\pm10\%$.

To illustrate the temperature dependence of the microwave enhancement of the order parameter we have plotted in Fig. 3 the result of measurements of the relative increase of the order parameter when a relatively low microwave power of 3 mW is applied to the coaxial cable as a function of $T_c/(T_c-T)$. The value of $\delta\psi/\psi$ is calculated from the measured SQUID-output change when the microwaves are switched on. For calibration of the SQUID output versus change in the order parameter the temperature variation of the SQUID output and the theoretically known dependence of ψ on T as given by Eqs. (5) and (6) are used. The best-fitted straight line through the measured points of Fig. 3 has a slope 1.3. We therefore measure a steeper dependence of $\delta\psi/\psi$ on $T_c/(T_c-T)$ than the linear dependence predicted by Eliashberg's theory.[6]

We have also measured the critical current of the Al cylinder under microwave irradiation. We did observe a critical-current increase for the same microwave power range with which an order-parameter increase was observed. However, the critical-current density not being uniform due to inhomogeneities in the film prevented us from making a quantitative comparison between critical-current and order-parameter increases.

The conclusion to be drawn from the described measurements is that it is shown in a direct way that microwave irradiation increases the order parameter in a superconducting Al film. As the measurements are based on a principle different from tunnel-junction measurements they give an independent confirmation of microwave-gap enhancement, relying on the proportionality between order parameter and gap as expressed in Eq. (5).

[1]For a recent review see M. Tinkham, in *Festkörperprobleme* (Vieweg, Braunschweig, 1979), Vol. 29, p. 363.

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[11]See, for instance, D. Saint James, G. Sarma, and E. J. Thomas, *Type II Superconductivity* (Pergamon, New York, 1969), p. 150.

[12]This curve *a* gives rise to the following remark. It is seen that temperature variation causes a flux change in the SQUID of several elementary flux quanta and correspondingly a hundred times bigger change $\delta\Phi$ in the flux in the Al cylinder. This is in contrast with the result of Mercereau and Crane (Ref. 10), who found an upper limit of one flux quantum for the change in the flux through the superconducting cylinder.

[13]E. Fawcett, in *The Fermi Surface*, edited by W. A. Harrison and M. B. Webb (Wiley, New York, 1960), p. 197.

Fluxoid Pinning by Small Nitride Precipitates in Niobium

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The magnetic hysteresis of superconducting niobium single crystals containing ~80-Å-diam nitride precipitates was investigated. Introducing precipitates into the samples produced no significant change in the critical-current density J_c except near the critical fields H_{c1} and H_{c2}. The samples trapped flux below H_{c1} and exhibited dramatic peaks in J_c within 3% of H_{c2}. These observations are interpreted as clear evidence of a threshold for fluxoid pinning, and reasonable agreement with theory is obtained.

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In spite of an intense research effort since the early 1960's, the fundamental understanding of fluxoid pinning by crystal defects in type-II superconductors remains incomplete. Although a number of attempts have been made to characterize the defect structure of a material and calculate its critical-current density, in most cases the theoretical value differs from the measured one by several orders of magnitude. Moreover, in contrast to experimental evidence, the theory of the statistical summation of the elementary interactions between fluxoids and defects implies that the interaction strength must be larger than a critical value before the defect can contribute to the critical-current density. This feature of the theory is known as the threshold effect.

Recently, attempts have been made to ascertain at what stage our understanding of fluxoid pinning breaks down. The absence of an experimental observation of the threshold effect and other evidence strongly suggests that the theory of the statistical summation of the elementary interactions is at fault.[1,2] However, the presence of several types of defects in most samples investigated to date obscures the interpretation of the experimental results. Here, we report the observation of the threshold effect approximately under the conditions specified by currently available theory.

We doped several single crystals of niobium with nitrogen to concentrations up to 0.1 at.%. A portion of the interstitial nitrogen absorbed at high temperature apparently formed small Nb_2N precipitates upon cooling. Throughout most of the mixed state, dc and ac magnetization measurements showed that the critical-current density in all the samples was comparable to that of the most reversible samples which we have investigated or have seen reported, and it did not change significantly upon doping with nitrogen. However, the dc magnetization measurements revealed a large increase in magnetic hysteresis near the lower critical field H_{c1} with doping. Indeed, the more heavily doped samples trapped flux when

