Microwave absorption by vortex cores in the high-temperature superconductor $YBa_2Cu_3O_{7-x}$

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Direct absorption measurements of microwave energy having energy less than the superconducting gap in the granular composites of the 90-K superconductor $YBa_2Cu_3O_{1-x}$ as a function of dc magnetic-field strength between 0.1 and 1.0 T reveal a nonlinearly increasing absorption of microwave energy with increasing field strength. The absorption can be detected in regions of the *T-H* phase diagram in which thermally activated flux flow does not occur. The temperature and field dependences of the absorption are different from those for low-magnetic-field absorption ($H<0.06$ T) and are shown to be consistent with the behavior expected by the absorption of microwave energy by normal carriers at the cores of vortices in type-II superconducting materials.

INTRODUCTION

Granular composities of the high-temperature copper oxide superconductors show an intense absorption of microwave energy in the superconducting state for microwave energy less than the superconducting gap.[1–5] In contrast to thin films or crystals, the absorption intensity increases as the temperature is lowered below T_c. The intensity also increases strongly with the application of low magnetic fields typically less than 100 G. This absorption is believed to be a result of flux jumps in small current loops formed in the granular composite by weak links between the grains.[6–8] Because the absorption increases nonlinearly with an increasing magnetic field, its derivative can be detected by an electron spin resonance (ESR) spectrometer which modulates the dc magnetic field with an rf *H* field and employs phase-sensitive detection. This has been the most common method used to study the low-field absorption. By measuring the absorption directly without modulation at higher fields above 0.1 T, it is observed here that the microwave absorption continues to increase with increasing magnetic field but more slowly than the low-field absorption. Because of the weaker dependence on magnetic field, this absorption is not readily observed using the ESR method and has therefore been largely overlooked. In this work the properties of the magnetic-field-dependent absorption between 0.1 and 1 T are reported. It is found that temperature and magnetic-field dependences of the absorption are quite different from those for low-field absorption, suggesting a different absorption mechanism. Analysis of the temperature and field dependences indicates the microwaves may be absorbed by normal carriers that exist at the center of vortices. Although above 70 K there may be some contribution from flux creep.

EXPERIMENTAL

Figure 1 shows the microwave bridge used to measure the microwave energy absorbed in the sample. The sample is located in a glass finger insert of an Air Products variable-temperature displex closed-cycle Dewar. The finger of the Dewar is inserted into the center of a rectangular microwave cavity operating in the TE_{102} mode, placing the sample at the center of the cavity. The cavity is located between the poles of a magnet. The klystron is tuned to the resonant frequency of the cavity. An absorption by the sample is detected by a change in the energy reflected from the cavity to the probe detector. The change in the dc current measured by the microammeter measures the microwave energy absorbed by the sample. In the range of microwave power used in these measurements the microammeter current related linearly to the incident microwave power. The measurement are made on the 90-K superconductor $YBa_2Cu_3O_{7-x}$ which was obtained from SCC Inc. Measurements were also made on samples from a number of different sources such as samples that had been subjected to shock loading. The general features of the absorption described were the same in all samples.

RESULTS

Figure 2 shows the change in the microwave power reflected from the cavity versus magnitude of the dc mag-

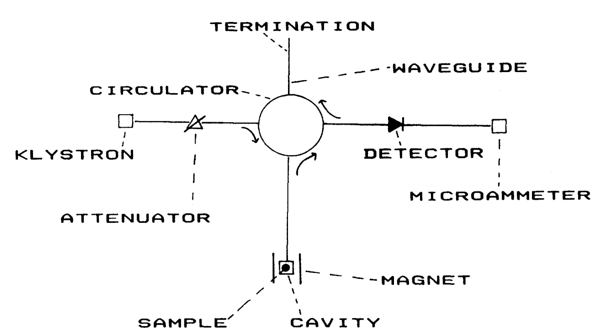

FIG. 1. Microwave bridge arrangement used to directly detect microwave energy absorbed in superconducting sample.

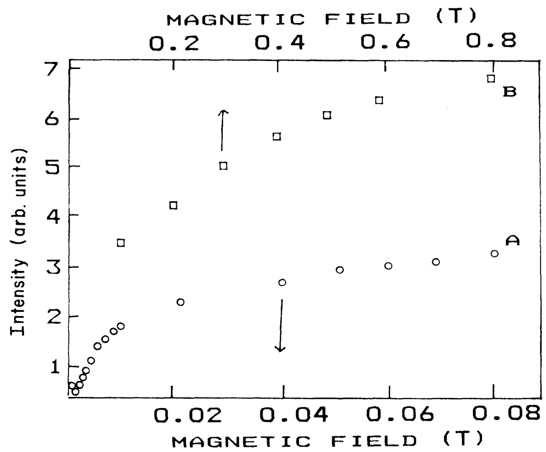

FIG. 2. Plot of the relative intensity of absorbed microwave energy at 77 K vs magnetic field up to 1.0 T. Curve (b) refers to the top axis and is absorption vs H above 0.1 T. Curve (a) refers to the bottom axis.

netic field applied to the sample. The low-field microwave absorption is observed below 0.01 T. This absorption has been discussed previously and is believed to be a result of flux jumps through current loops formed by Josephson junctions between the grains of the composite. Above 0.01 T the absorption continues to increase in an almost linear fashion to about 0.4 T where there is some slowing of the increase of the absorbed microwave energy with increasing magnetic field. Figure 3 shows the temperature dependence of the intensity measured at a magnetic field of 0.5 T showing that the intensity of the absorption decreases as the temperature is lowered below T_c in contrast to the low-field absorption which increases with lowering temperature.

This temperature dependence is independent of the strength of the magnetic field between 0.1 and 1.0 T. Measurements have not been made above 1 T.

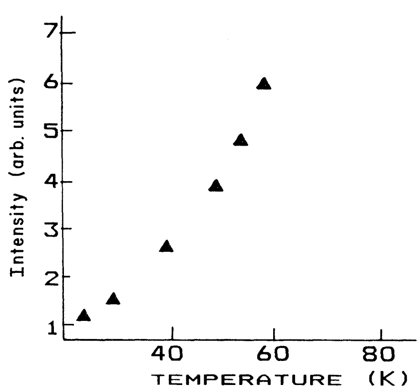

FIG. 3. Temperature dependence of the absorption at 0.5 T. The intensity units are arbitrary.

DISCUSSION

The difference in the temperature and magnetic-field dependence of the absorption below 0.01 T and above it indicates that the mechanism of absorption above 0.1 T is not due to flux jumps through current loops in the composite but has a different origin. In fact the flux-jump model cannot be operative at these higher magnetic fields because they are greater than $H_{c2}J$, the intergranular critical field of the Josephson junction, which at 77 K is in the order of 0.006 T.[9] Two possible mechanisms of magnetic field dependent absorption are considered.

Measurements of the effect of dc magnetic fields on the resistance at various temperatures below T_c in $YBa_2Cu_3O_{7-x}$ have indicated the existence of thermally activated flux flow resistance.[10–12] This nonzero resistance can cause microwave energy to be absorbed by the sample below T_c. In fact, the absorption of microwaves has been used to measure thermally activated flux flow resistance in metallic superconductors.[13] However, studies of flux creep in $YBa_2Cu_3O_{7-x}$ show that in fields less than 1.0 T there is very little creep below 77 K.[10–12] The absorption here can be detected well below T_c in temperaure and magnetic field regions where it is known that there is no flux creep. For example, absorption of microwaves is observed at 0.2 T and 40 K where there is no evidence of flux creep. It is believed therefore that the absorption observed here at fields less than a Tesla is not due to thermally activated flux flow resistance. However, close to T_c above 70 K and in fields less than one Tesla there may be some contribution from thermally activated flux flow.

In the superconducting state microwaves are absorbed not by Cooper pairs but by unpaired electrons. In a type-II superconductor, normal electrons exist at the center of the Abrikosov tubes (vortices) which are parallel to the applied magnetic field. In the lower-temperature metallic superconductors it has been shown that this core of normal carriers can absorb microwave energy and the energy absorbed is proportional to the strength of the magnetic field.[14] The number of normal carriers in a vortex will be proportional to the cross sectional area of the vortex which is approximately $\pi\xi^2$ where ξ is the coherence length given by

$$\xi=(\phi_0/2\pi H_{c2})^{1/2} , \qquad (1)$$

where ϕ_0 is the quantum of flux and H_{c2} the upper critical field. Since the absorption is proportional to the number of normal carriers, the microwave energy absorbed by one vortex is proportional to $\phi_0/2H_{c2}$. The total absorption in any sample will then be proportional to this times the total number of vortices which is the total flux threading the sample at a given applied field. The total flux at a given applied field can be deduced from the magnetization curve versus applied magnetic field above H_{c1} and should be proportional to $M(H_{c1})—M(H)$ where H is greater than H_{c1} and M is the sample magnetization. Thus at constant temperature the microwave absorption versus applied field should scale linearly as $M(H_{c2})—M(H)$. Figure 4 is a plot of the absorbed microwave energy versus the increase in the magnetization of the sam-

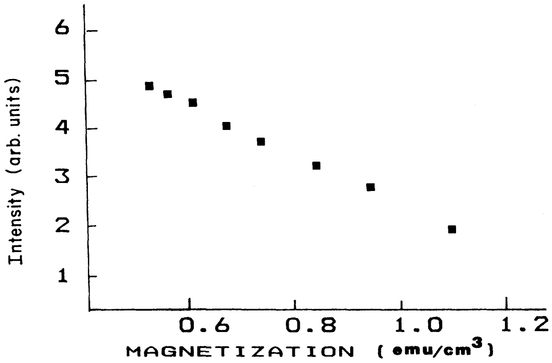

FIG. 4. Plot of the absorbed microwave energy vs the measured magnetization of the sample above H_{c1}.

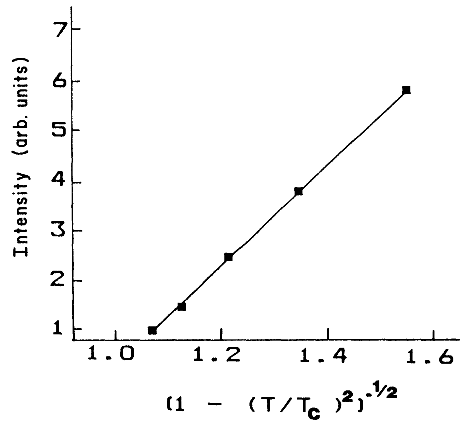

FIG. 5. Plot of the intensity of the absorption vs $[1-(T/T_c)^2]^{-1/2}$.

ple above H_{c1} showing a linear relationship, indicating that the microwave absorption is proportional to the amount of flux trapped in the sample.

Below about 70 K where the magnetization of the sample at a given magnetic field is relatively independent of temperature, the temperature dependence of core-vortex absorption should be determined by the temperature dependence of H_{c2} which is given by the Ginzburg-Landau formalism as[15]

$$H_{c2}(T)=K_1(T)[2H_c(T)]^{1/2} . \quad (2)$$

Ignoring the slight temperature dependence of K_1, the Ginzburg-Landau parameter, the temperature dependence of the microwave absorption by the core carriers of the vortices should depend on T as $[1-(T/T_c)^2]^{-1/2}$. Figure 5 shows that a straight line is obtained when the relative intensity of the absorption is plotted versus $[1-(T/T_c)^2]^{-1/2}$.

Thus the magnetic-field and temperature dependences of the intensity of the microwave energy absorbed in the field region between 0.1 and 1.0 T are consistent with absorption of microwaves by holes at the cores of the vortices. A similar conclusion has also been reached by Maniwa *et al.*[16] based on a different quantitative analysis of the magnetic-field- and temperature-dependent properties of the absorbed energy between 0.1 and 1.0 T. However, in their work the absorption intensity was observed to depend linearly on the magnetic-field strength in contrast to this work where a clear nonlinearity was observed in all the samples studied.

[1] K. W. Blazey, K. A. Müller, J. G. Bednorz, W. Berlinger, G. Amoratti, E. Buluggiu, A. Vera, and F. C. Matacotta, Phys. Rev. B **36**, 7241 (1987).
[2] K. Khachaturyan, E. R. Weber, P. Tejedor, A. W. Stacy, and A. W. Portis, Phys. Rev. B **36**, 8309 (1987).
[3] S. V. Bhatt, T. V. Ramakrishnan, and C. N. Rao, J. Phys. C **20**, L559 (1987).
[4] J. Stankowski, P. K. Kahol, N. S. Dalal, and J. S. Moodera, Phys. Rev. B **36**, 7162 (1987).
[5] C. Rettori, D. Davidov, I. Belaish, and I. Felner, Phys. Rev. B **36**, 4028 (1987).
[6] T. Xia and D. Stroud, Phys. Rev. B **39**, 4772 (1989).
[7] C. Ebner and D. Stroud, Phys. Rev. B **31**, 165 (1985).
[8] F. J. Owens, Physica C **171**, 25 (1990).
[9] A. G. Vedeshwar, Solid State Commun. **74**, 23 (1990).
[10] P. Berghuis, S. Q. Guo, A. L. F. VanDer Slot, B. Dam, G. M. Stollman, and P. H. Kes, Physica C **162**, 1169 (1989).
[11] C. W. Hagen, R. P. Griessen, and E. Salomins, Physica C **157**, 199 (1989).
[12] N. Koybashi, H. Iwaski, H. Kawabe, K. Watanabe, H. Yamane, H. Kurosawa, H. Masumotto, T. Hirai, and Y. Muto, Physica C **159**, 295 (1989).
[13] W. Hacket, E. Maxwell, and Y. B. Kim, Phys. Lett. **24A**, 663 (1967).
[14] B. Rosenblum and M. Cardonna, Phys. Rev. Lett. **12**, 657 (1964).
[15] V. L. Ginzburg and L. D. Landau, Pis'ma Zh. Eksp. Teor. Fiz. **20**, 1064 (1950).
[16] Y. Maniwa, A. Grupp, F. Hentsch, and M. Mehering, Physica C **156**, 755 (1988).