Magnetic-field-dependent microwave absorption in the superconducting state of single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$

1992 J. Phys.: Condens. Matter 4 205

(http://iopscience.iop.org/0953-8984/4/1/030)

J. Phys.: Condens. Matter 4 (1992) 205–212. Printed in the UK

Magnetic-field-dependent microwave absorption in the superconducting state of single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$

F J Owens[†], Z Iqbal[‡] and E Wolf[§]

[†] Department of Physics, Hunter College, CUNY, 695 Park Avenue, New York, NY 10021, and Armament Research and Development Center, Picatinny, NJ 07806, USA
[‡] Allied Signal Inc. Research and Technology, Morristown, NJ 07962, USA
[§] Department of Physics, Polytechnic University, Brooklyn, NY 11201, USA

Received 22 July 1991, in final form 24 September 1991

Abstract. The derivative of the microwave absorption versus DC magnetic field strength is observed near zero field in the superconducting state of single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$. The absorption intensity decreases as the DC magnetic field is rotated away from the crystallographic c axis, which indicates preferential orientation of weak link current loops parallel to the largest crystal facet. The hysteresis of the low field absorption is also anisotropic because of the anisotropy of flux pinning barriers. Direct microwave absorption measurements at higher fields show a continued increase in absorption above 0.1 T which is associated with flux motion. The temperature, field and orientation dependence of this absorption are reported and interpreted in terms of flux motion. Barriers to flux motion in the surface regions of the crystal are estimated.

1. Introduction

It has been found that powders, thin films and single crystals of the $YBa_2Cu_3O_{7-x}$ display an increased absorption of microwave radiation having a frequency less than the superconducting gap as the temperature is lowered below T_c [1–5]. The absorption increases strongly and non-linearly with the application of small magnetic fields typically less than 50 G. The non-linearity of the magnetic field dependence enables the absorption to be readily detected using an electron paramagnetic resonance (EPR) spectrometer which has been the most commonly used method to study the absorption properties. This low magnetic-field-induced absorption has been attributed to flux jumps through small current loops having an area in the order of a square micron [1, 3, 5–7]. The flux jumps which occur as the field is increased produce a normal current which absorbs the microwaves.

At higher magnetic fields, above the typical critical current for a weak link which form the current loops, microwave absorption has been observed to continue to increase although much less strongly than that at low magnetic fields [8–11]. This high field absorption cannot readily be detected in the derivative mode requiring direct detection methods and as a result has not been widely studied in the layered copper oxide materials, and particularly in single crystals. The absorption at higher fields may be due to normal holes at the cores of vortices in the type II materials, or movement of vortices [8–11]. The absorption can be used to study flux dynamics in the materials

0953-8984/92/010205+08$03.50

and may be a particularly useful method to investigate flux dynamics in thin films as the microwave penetration depth is comparable to the film thickness.

In this work we report a study of the magnetic-field-induced microwave absorption in the superconducting state of single crystals of $N = 2$ $Bi_2Sr_2CaCu_2O_{8+x}$. The properties of the absorption are investigated in both low and high magnetic field regions, using both the derivative and the direct absorption techniques. It is shown that the properties of the low-field absorption such as intensity, field position and hysteresis depend on the orientation of the magnetic field with respect to the *c* axis of the orthorhombic unit cell. Similarly the high field absorption observed by direct absorption methods also shows anisotropic behavior. The causes of these effects will be discussed.

2. Experimental procedure

The crystals are grown at Polytechnic University following the methods previously described by Mitzi *et al* [12]. They are grown using a directional solidification approach which imposes a temperature gradient from the centre of a crucible containing the sample to the edges. As the temperature at the centre is lowered a circular zone of crystallization moves towards the edges of the crucible. Typically the crystals are in the form of 3 ml by 1 ml platelets having the large surface perpendicular to the *c* axis of the orthorhomic unit cell. X-ray diffraction measurements indicate few bulk defects such as twins or dislocations. The crystals grown in this manner have a transition temperature of 85 K as determined by four probe resistance measurements.

The derivative of the low magnetic field microwave absorption is measured using a Varian E-12 electron paramagnetic resonance spectrometer operating at 9.2 GHz. The sample temperature is controlled in the the microwave cavity by placement of the sample in a double-walled glass quartz flow tube, through which cold helium or nitrogen gas flows. The tube is located inside the cavity. Direct microwave absorption measurements are made using a microwave bridge system previously described [10]. An absorption by the sample in the cavity results in a change of reflected microwave energy from the cavity to the arm of the bridge containing the diode detector. The change in the current in the detector measures the absorbed microwave energy.

3. Results

3.1. *Low-magnetic-field absorption*

Figure 1 shows the derivative of the microwave absorption versus the DC magnetic field at 77 K below 20 G in a single crystal of the $N = 2$ superconductor $Bi_2Sr_2CaCu_2O_{8+x}$ for the magnetic field perpendicular and parallel to the *c* axis. The derivative was recorded using a modulation of 5 G. and a sweep of the DC magnetic field to 20 G and back. The sample was cooled below T_c in zero magnetic field. The data in figure 1 show that the intensity and the magnetic field position of the derivative depends on the orientation of the magnetic field. Figure 2 shows a plot of the intensity of the absorption as the DC magnetic field is rotated away from the perpendicular to the crystal surface which is the c axis of the orthorhombic unit cell. These data are measured by rotating the DC magnetic field, not the crystal in the cavity. As in powdered material the derivative displays a hysteresis in magnetic field position. The centre of the derivative occurs at a higher magnetic field on the down sweep from a given field compared to the value on the up sweep. The magnitude of this hysteresis depends on the magnitude of the maximum of the sweep and the orientation of the DC magnetic field. Figure 3 is a plot of the hysteresis versus the maximum field of the sweep for the DC field parallel and perpendicular to the c axis at 77 K. The hysteresis is larger when the DC magnetic field is perpendicular to the c axis. Note that at both orientations the hystersis reaches a maximum with increasing magnetic field and then begins to decrease. The temperature dependence of the intensity of the absorption at these high modulations is quite similar to previous observations in other materials, increasing rapidly as the temperature is lowered below T_c and then eventually saturating. Because of the relative weakness of the intensity of the absorption compared to powdered material it was not possible to measure the temperature dependence of the absorption at modulations less than 1 Gauss where in films of $YBa_2Cu_3O_{7-x}$ a different temperature dependence compared to higher modulations has been reported [13]. At modulations of 1.0 Gauss it was possible, at 77 K, to observe fine structure superimposed on the broad derivative similar to that observed in $YBa_2Cu_30_{7-x}$ and $Nd_{2-x}Ce_xCuO_4$ [14,15]. Figure 4 shows the fine structure observed at 77 K for the DC magnetic field parallel to the c axis. In this orientation the separation of all the lines from their neighbours is the same and is 0.4 G.

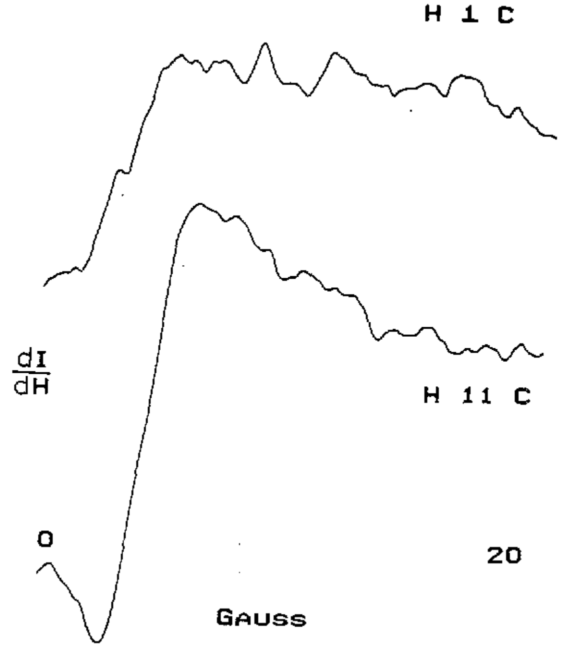

Figure 1. Derivative with respect to the magnetic field of microwave absorption at 77 K in single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$. The modulation is 5 G.

3.2. High-field absorption

When measured directly not using modulation, a continuously increasing absorption

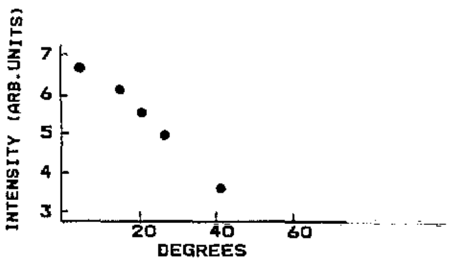

Figure 2. Intensity of the absorption versus the angle between the magnetic field and the *c* axis. The *c* axis is perpendicular to the large facet of the crystal.

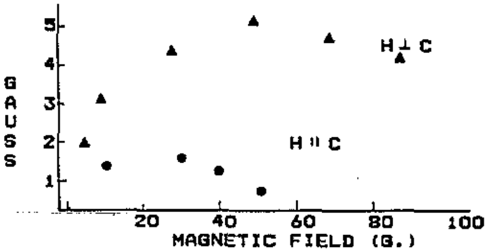

Figure 3. The hysteresis in the field position of the centre of the derivative versus the maximum magnetic field applied to the sample at 77 K for the DC magnetic field parallel and perpendicular to the *c* axis.

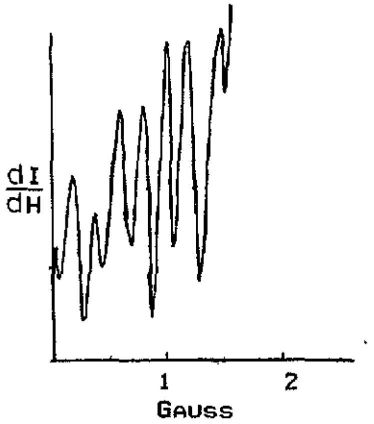

Figure 4. Derivative spectrum obtained for the field parallel to *c* at 77 K for modulations of 0.5 G.

of microwave energy is observed with increasing magnetic field above 0.01 T in the superconducting phase. In the derivative mode of detection this absorption is not observed because of the near-linear dependence of absorption on the field. Figure 5 is a plot of the microwave energy absorbed at 77 K from 0.1 T to 1.0 T versus DC magnetic field for the field parallel and perpendicular to the *c* axis. The absorption is larger for the DC field parallel to the *c* axis and shows a continuous decrease as the magnetic field is rotated away from the *c* axis. There appear to be two regions of field dependence, a strong non-linear dependence from 0.05 T to 0.5 T followed by a weaker non-linear dependence on the DC magnetic field above that. Figure 6 shows a plot of the log of the intensity of the absorption at 0.5 T versus the reciprocal of the absolute temperature indicating that the absorption increases as the temperature is raised to T_c which is opposite to that of the low-magnetic-field absorption measured at high modulations. The temperature dependence is qualitatively similar when measured at different magnetic fields.

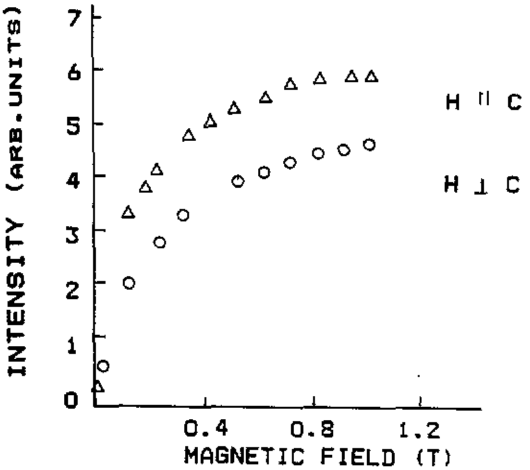

Figure 5. Direct measurement of microwave energy absorbed at 77 K for higher magnetic fields for two orientations of the DC H field.

4. Discussion and analysis

The strong non-linear increase in the microwave absorption observed here in the single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$ with the application of small magnetic fields is believed to arise from the same causes as the absorption observed by many workers in the powders of the high temperature copper oxide superconductors [1–5]. The absorption has been attributed to the existence of square micron-sized current loops formed by weak links in the material. As the magnetic field is increased through the loops, flux jumps occur, producing voltage pulses which in turn cause a normal current to flow, absorbing microwave energy. The absorption occurs only at low fields because of the low critical fields of Josephson links [1–7]. In $YBa_2Cu_3O_{7-x}$ $H_{cj}(1)$ has been estimated to be 0.006 T [16]. The sharp lines observed superimposed on the broad lines further support this interpertation. Xia and Stroud [5] have calculated the derivative of the absorption spectrum versus magnetic field for an ensemble of square micron loops formed by weak links and have shown that a discrete line spectrum should be obtained with line separations equal to ϕ_0/A. where ϕ_0 is the quantum of flux and A the area of the loop. The line separation in figure 2 is 0.4 G. allowing an estimate of the loop area of 5×10^{-7} cm^2. The observation of a discrete spectrum suggests that a the majority of the loops have the same area and orientation on the crystal. In the powders there is a distribution of loop areas and orientations which gives rise to the broad spectrum washing out the discrete line structure. It was originally suggested that the junctions were formed between the grains of the powders. However since the insulating region of the junction must be smaller than the coherence length which is in the order of 30 Å in the layers of the copper oxides in the [001] plane, this seems somewhat less likely. Alternatively the junctions could be formed on the surfaces of the grains where the insulating region of the link is formed by surface defects such as crystal growth steps and twin boundaries. The observation of the low-field absorption here in single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$ in which x-ray diffraction measurements show no evidence for bulk defects such as twins or dislocations, further supports this view. The reduction of the intensity of the absorption as the DC magnetic field is rotated parallel to the large surface of the crystal points to loops lying with their area on the surface of the crystal. As the DC magnetic field is rotated parallel to the surface the amount of flux threading the loops decreases because of the $B \cdot A$ term and less flux jumps occur.

The difference of the field position of the centre of the derivative of the low field absorption on the up and down sweep to a given magnetic field is known to be a result of flux trapping in the sample [6, 7]. The difference measures the remnant field in the sample. The dependence of the magnitude of the hysteresis on the orientation of the DC field with respect to the c axis shown in figure 6 reflects the anisotropy of the sample's ability to trap flux. As the coherence length is smaller in the copper oxide planes which are perpendicular to the c axis, more flux will be trapped when the field is in this direction. These results are consistent with measurements of the effect of magnetic fields on the resistance which show that the barriers for flux motion are lower when the DC magnetic field is parallel to the c axis [17, 18]. It is interesting to note that the hysteresis versus magnetic field displays a maximum and then decreases, approaching zero at a higher field. The H–T irreversibility line is the line above which the magnetic behavior of the sample is reversible because flux cannot be trapped above this line. The field value at which the hysteresis of the microwave absorption becomes zero may measure the irreversibility point. A value of 180 G is estimated for the irreversibility field for the field parallel to the c axis, and 50 G for the field perpendicular to the c axis at 77 K.

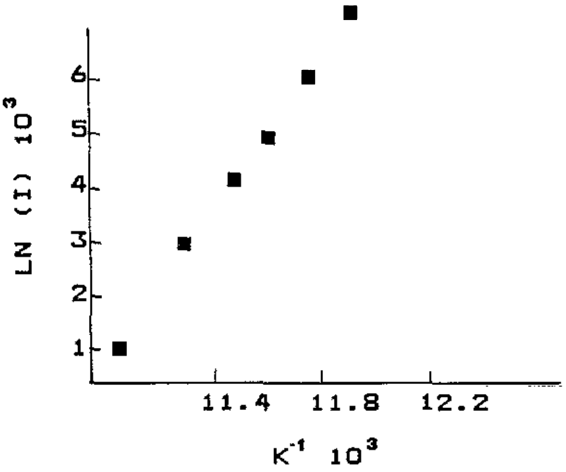

Figure 6. Log of the intensity of microwave absorption at 0.5 T versus the reciprocal of absolute temperature.

The magnetic-field-dependent microwave absorption observed above 100 G cannot be due to flux jumps in current loops formed by weak links because the fields are greater than the typical $H_{cj}(2)$ for such junctions. Further, the temperature dependence of the absorption is opposite to that of low-field absorption, increasing as the temperature approaches T_c from below. Magnetic-field-induced microwave absorption in the field regions observed here has been observed in the low-temperature metallic superconductors and attributed to absorption by normal electrons at the centres of vortices and flux motion [19, 20]—similar observations have been made in

$YBa_2Cu_3O_{7+x}$ [21]. At the temperatures and magnetic fields where the microwave absorption is observed here flux has been shown to move in $Bi_2Sr_2CaCu_2O_{8+x}$ [17, 18]. The microwave absorption is believed therefore to be due to flux motion and is therefore proportional to the flux-motion-induced resistance in the surface regions of the sample. In the case of creep (hopping of the vortices between points in the Abrikosov lattice) and flow (the viscous flow of flux above the melting point of the vortex lattice) the motion can be described by a thermally activated process. From the estimates of the irreversibility fields obtained from the low-magnetic-field absorption at 77 K it can be concluded that at 0.5 T and the range of temperatures where the temperature dependence is measured the sample is above the irreversibility line and that the flux motion consists of viscous flow. Kobayashi *et al* [17] have interpreted the field-dependent resistivity effects in terms of thermaly activated flux flow where the resistance is given by

$$R = R_0 \exp(u/kT) \tag{1}$$

where u is the pinning barrier which depends on the magnetic field and temperature. However, it should be emphasized that the interpretation of magnetic-field-dependent resistance in terms of the flux flow model is controversial as present models fail to account for many features of the measurements. The straight line in figure 6 of the plot of the log of the microwave absorption versus reciprocal of absolute temperature also supports this interpretation. In the somewhat narrow range of temperatures of this measurement the activation energy appears to be relatively independent of temperature, which has also been concluded from field-dependent resistivity studies of this material in the same temperature range. An activation energy of 0.022 eV is obtained from the data in figure 6. The value from the resistivity data in this field range is somewhat higher and is 0.06 eV. The larger microwave absorption observed when the magnetic field is parallel to c is because flux can more easily move when the DC magnetic field is in this direction. This is consistent with field-dependent resistivity measurements which show lower pinning barriers to flux motion when the field is parallel to the c axis. Note also that this is in agreement with the measurement of the hysteresis in the low-field microwave absorption which shows more flux trapped when the field is perpendicular to the c axis. The field-dependent resistivity data also indicated that the field dependence of flux motion followed an H^α dependence. Figure 7 is a plot of the log of the absorption versus the log of the magnetic field showing that the microwave absorption obeys a similar dependence. The value obtained for the field parallel to c is 0.28. The resistivity data for the same orientation yielded 2.1 at 25 K and 1.4 at 50 K. The value measured from the microwave absorption here at 77 K agrees with these values in the sense that a linear extrapolation of the resisitivity data to 77 K yields a value close to 0.28. On the other hand it is not clear that the surface resistance should scale with DC magnetic field as the bulk resistance because of the gradient of the magnetic field strength and microwave energy near the surface of the sample. In a normal metal the surface resistance is proportional to the square root of the bulk resisitivity. In conclusion, studies of magnetic-field-dependent microwave absorption in single crystals of $Bi_2Sr_2CaCu_2O_{8+x}$ show an increased absorption of microwaves as the field is increased resulting from two absorption mechanisms. At less than 20 G the absorption is a result of flux jumps through current loops formed by weak links, probably by defects on the surface of the crystal. The anisotropy of the intensity suggests that the loops are primarily parallel to the surface of the crystal.

The anisotropy of the hysteresis is due to the difference in flux pinning barriers parallel and perpendicular to the *c* axis. At higher fields the field-dependent microwave absorption is a result of flux motion in the crystal. Its dependence on field orientation is also a result of differences in pinning barriers parallel and perpendicular to the *c* axis.

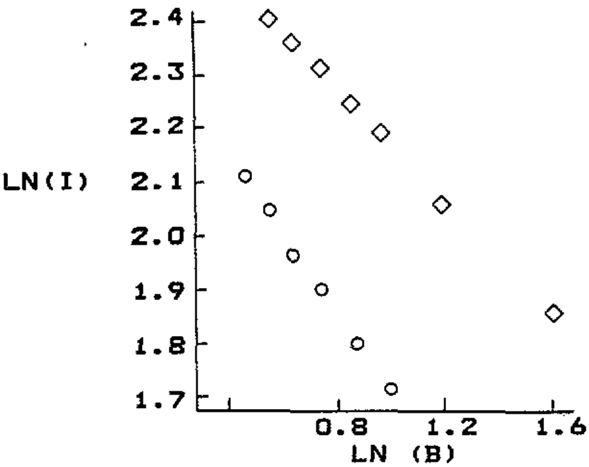

Figure 7. Log of the intensity of the microwave absorption versus the log of the magnetic field at 77 K.

References

[1] Blazey K W, Muller K A, Bednorz J G, Berlinger W, Amoretti W, Buluggio G, Vera E and Matacotta F C 1987 *Phys. Rev.* B 36 7241
[2] Khachaturyan K, Weber E R, Tejedor P, Stacey A W and Portis A M 1987 *Phys. Rev.* B 36 8390
[3] Stankowski J, Kahol P K, Dalal N S and Moodera J S 1987 *Phys. Rev.* B 36 7126
[4] Rettori C, Davidov D, Belaish I and Felner I 1987 *Phys. Rev.* B 36 4028
[5] Xia T and Stroud D 1989 *Phys. Rev.* B 29 4772
[6] Owens F J 1990 *Physica* C 171 25
[7] Owens F J 1990 *J. Phys.: Condens. Matter* 2 8345
[8] Maniwa Y, Grupp A, Hentsch F and Mehering M 1988 *Physica* C 156 755
[9] Owens F J 1991 *Phys. Rev.* B 43 8631
[10] Owens F J 1990 *Phys. Lett.* 151A 349
[11] Nishida A and Hori K 1990 *Solid State Commun.* 74 947
[12] Mitzi D B, Lombardo L W, Kapitulnik A Laderman S S and Jacowitz R D 1990 *Phys. Rev.* B 141 6564
[13] Blazey K W and Huler A 1989 *Solid State Commun.* 72 1199
[14] Dulcic A, Creepeau R H and Freed J H 1989 *Physica* C 160 223
[15] Blazey K W and Mangelschots I 1990 Physica C 170 267
[16] Vedeshwar A G 1990 *Solid State Commun.* 74 23
[17] Kobayashi N, Iwasaki H, Kawabe H, Watanabe K, Yamane H, Kurosawa H, Masumoto H, Hirai T and Muto Y 1989 *Physica* C 159 293
[18] Palestra T M, Batlogg B, Schneemeyer L F and Waszczak J V 1988 *Phys. Rev.* B 61 1662
[19] Hackett W, Maxwell E and Kim Y B 1967 *Phys. Rev. Lett.* 24 663
[20] Rosenblum B and Cardona M 1964 *Phys. Rev. Lett.* 12 657
[21] Tomasch W J, Blackstead H A, Ruggiero S T, McGinn P J, Clem J R, Shen K, Weber J W and Boyne D 1988 *Phys. Rev.* B 37 9864