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Low field microwave absorption study of defects in $YBa_2Cu_3O_7$ crystals and films

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Abstract

We have studied the microwave absorption at low fields of superconducting loops made with $YBa_2Cu_3O_7$ thin film. Series of well-resolved periodic lines are observed. Angular and microwave dependences of the spectra are discussed. We have measured the microwave power dissipated within the loop. All the results show a quantitative agreement with the model of Silver and Zimmerman describing the microwave absorption of a superconducting loop closed by a junction and give a quantitative evaluation of the critical current of intrinsic junction in the film. The effect of the static field on the spectra allows us to distinguish two kinds of junction.

1. Introduction

Measurement of microwave absorption in single crystals of $YBa_2Cu_3O_7$ shows, below T_c, series of narrow, regularly spaced lines in low magnetic field. A number of qualitative observations were made on this phenomenon. For each series, the period of the lines depends on the angle between the static field and the axis of the crystals. Furthermore, lines are only observed for microwave field above a well defined threshold. Similar observations were made on other high-T_c superconductors and also on low-temperature superconductors such as indium, lead, niobium and Chevrel-phase compound $PbMo_6S_8$ [1-9].

This phenomenon is associated with the existence of an intrinsic r.f. SQUID, i.e. a superconducting loop connected by a weak link, surrounding a non superconducting surface S [3]. The modulated microwave absorption of such a system is well described by the model of Silver and Zimmerman [10]. Each line corresponds to the microwave absorption due to the motion of one flux quantum Φ_0 coherently driven by the microwave field in and out the surface $S=\Phi_0/\Delta H_0$ (where ΔH_0 is the period of the lines).

If there is no doubt on the existence of such an intrinsic r.f. SQUID, a number of questions can be raised: What is the nature of the surface S (which ranges from 10 μm^2 to 1000 μm^2 in different crystals)? What is the nature of the weak link? What is the value of the inductance L of the loop?

In order to study the weak links which are involved in the intrinsic r.f. SQUID, we realized superconducting loops using $YBa_2Cu_3O_7$ thin film of moderate quality. We rely on the possible existence of one or more intrinsic weak links along each loop. In contrast with the previous work on crystals, in such a structure, we know the value of the surface S enclosed by the loop and have a good evaluation of its inductance L.

The aim of this paper is to present experimental results on the microwave absortion of such high-T_c superconducting loop and give quantitative results on the characteristics of absorption lines series.

2. Experimental techniques

The $YBa_2Cu_3O_7$ thin films used for these studies have been prepared either by laser ablation or by sputtering. The substrates are single crystals of MgO and $LaAlO_3$. For epitaxial films with c-axis perpendicular to the substrate show typically a transition temperature around 92 K, a critical current of about 4.10^6 A/cm^2 at 77 K and a surface resistance of 0.8 mΩ at 10 GHz and at 77 K. The thickness of the films is ranging between 2000 and 3000 Å. In our studies, we used two types of films, the high quality films didn't exhibit any signal in our experiments. When deposition parameters were adjusted to lead to mixed oriented films with a-axis and c-axis grains, films exhibit lower current density due to weak links. In the following, we will discuss only on this latter films.

We made the square loops with an ion beam etching technique. The overall sample size is 1x1 mm^2. On each sample, we have 13 square loops with different areas as shown on figure 1.

The dimension of the loops ranges from 5x5 μm^2 to 900x900 μm^2. For each sample, the width of the superconducting line is 1, 2 or 5 μm. Optical microscopic observations shows that the width of the 2 or 5 μm-lines

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is very well defined and 1 μm-lines shows a dendritic structure.

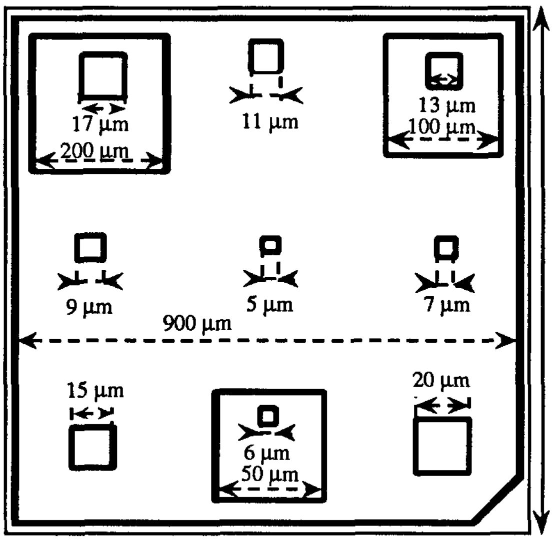

Figure 1: Geometry of the square loops of each sample.

Modulated microwave absorption measurements were carried out with a Bruker EPR spectrometer operating at frequency ν of 9.4 GHz with a rectangular TE_{102} cavity and a quality factor of 2600. We used an Oxford Instruments ESR 900 helium continuous flow cryostat and we controlled the temperature with an Au-Fe thermocouple. We essentially operated at 4 K. The microwave magnetic field h_1 and the static magnetic field H_0 are perpendicular. We can rotate the sample around the h_1 axis within a 1° accuracy and around the H_0 axis within a 5° accuracy using wedge cut sample holders. We use a range of the static field of - 1000 G to 1000 G and a microwave field in the range of 0.9 mG to 0.9 G that we measured using the Slater method [11].

3. Modulated Microwave absorption of superconducting loops

The sample is cooled in zero field with an orientation at 45° from the H_0 axis and from the h_1 axis. We study the modulated microwave absorption with a static field ranging from -10 G to 10 G and for different microwave field from 0.9 mG to 0.9 G. For each sample, we observed several series for different values of the microwave field. The main difficulty is then to isolate and study one series from an other; considerable simplifications of the spectra occured after mechanically scratching the larger loops. The first qualitative conclusion is that, within one sample, most loops behave like a r.f. SQUID.

In the following, we will focus on a series of lines with a well resolved period that we observed over a wide range of h_1 amplitude. Figure 2 shows the modulated microwave absorption spectrum dA/dH_0 attributed to the loop with a surface S of 15x15 μm^2 with a microwave field of 62 mG.

The periodicity of the lines is equal to 127 mG, value that we compare to $\Phi_0/(S.\cos(45)) = 126$ mG.

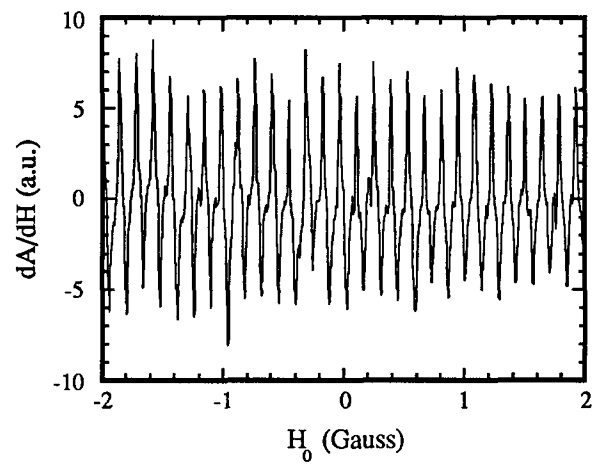

Figure 2: Modulated Microwave absorption spectrum $dA(H_0)/dH_0$ of a $YBa_2Cu_3O_7$ film square loop at 4.2 K. The dimension of the square is 15x15 μm^2. Microwave field h_1 is 62 mG.

3.1 Orientation and threshold.

The periodicity ΔH_0 of the lines varies with the angle between the surface vector S and the axis $\mathbf{H_0}$ of the static field like the inverse of the scalar product $\mathbf{S.H_0}$.

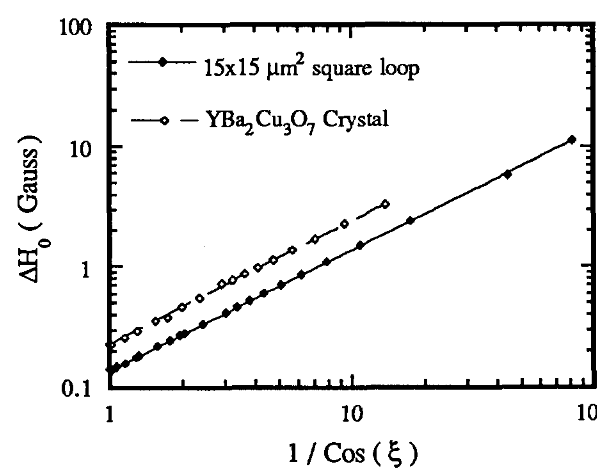

Figure 3: Dependence of the period as a function of $1/\cos(\xi)$, where ξ is the angle between the surface vector S and the H_0-axis. The white plot is the result of one of our previous experiment on crystal.

As expected and shown in figure 3, the period is minimum (ΔH_0=0.127 G) when the projection of the surface vector on the H_0 axis is maximum and diverges when the projection is null. Unlike what we observed on crystals, we measure with a very good accuracy the period when S is almost perpendicular to H_0 (ΔH_0=13G when ξ=88°).

Similarly to the results for crystals, we do not observe the absorption lines below a threshold h_{1th} in the microwave field amplitude. Above the threshold, the line shape splits as the microwave field is increased; i.e. the distance ΔH_{pp} between the positive and the negative lobes in the derivative of the absorption lines increases as shown in figure 4. The amplitude and the shape of each lobe are independent of the microwave field above threshold. For crystals, we observed that the width ΔH_{pp} is proportionnal to the microwave field h_1 [2]. The proportionnality coefficient is ranging from 3 to 100 from one series to an other. As shown in Figure 4, for superconducting square loop, we measure the same proportionnality and we get

$$\frac{\Delta H_{pp}}{h_1 - h_{1th}} = 2 \pm 0.2$$

in quantitative agreement with the Silver-Zimmerman model [10]. The microwave field measured with the Slater method is the field without the sample. The coefficient of the ratio above shows that the microwave field is unperturbated by the sample. The larger coefficient observed for crystals is thus interpreted by a locally enhanced value of h_1 at the surface of the crystal.

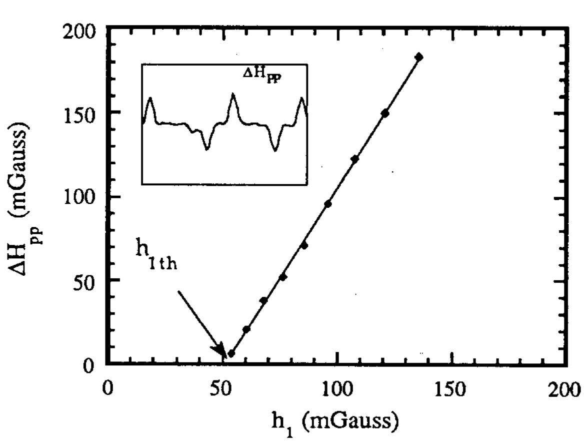

Figure 4: Linewidth ΔH_{pp} as a function of the measured microwave field. The microwave field has been measured by the Slater method [10].

Knowing the inductance of the loop, the measure of the value of the threshold provides a determination of the critical current i_c in the junction. The threshold is given by

$$\Phi_1^{th} = Li_c - \frac{\Phi_0}{4}$$

where Φ_1^{th} is the microwave flux threshold and L is the inductance of the loop. The inductance L of a square conducting loop (in the normal state) is

$$L = \mu_0 a / \pi (\ln (a/b) + C)$$

where a is the side of the square and b is the thickness of the film. C is a constant. We measured the threshold and the critical current for several series belonging to differents loops.

N°	1	2	3	4
S (μm^2)	13x13	15x15	15x15	11x11
L (10^{-11}H)	4.7	5.6	5.6	3.8
i_c (A)	3.6 10^{-5}	4.8 10^{-5}	7.8 10^{-5}	2.9 10^{-5}
j_c (10^4 A/cm^2)	0.29	0.38	3.12	0.58

Table 1

J_c is obtained assuming that the section of the junction is the section of the line. Values of j_c appear coherent with the "bad" quality of the film.

3.2 Power dissipated in a superconducting loop

An important feature of the S.Z. model is that the absorbed power P does not depend on the magnitude of the microwave field, above the threshold. In order to measurate the power dissipated in the loop, we calibrated the ESR spectrometer with a known number of spins of $CuSO_4$, 5 H_2O We are then able to relate the amplitude of the absorption at the threshold to that equivalent to a given number of spins

In the S.Z. model, the dissipated power P is given by

$$P = 2\pi \nu (Li_c - \Phi_0) \frac{\Phi_0}{L}$$

It is essential to compare the measured power P_{meas} and the power calculated by the S.Z. model $P_{S.Z.}$. For the series n°1 of the table above, we find

$$P_{meas} = 1.16 \pm 0.2 \text{ nW} \quad \text{and} \quad P_{S.Z.} = 1.03 \text{ nW}.$$

showing a quantitative agreement.

3.3 Effect of the static field

Starting from zero field, the critical current i_c decreases as the magnetic flux increases. As soon as a flux quantum penetrates the junction, i_c is drastically reduced and so is the absorption threshold of the r.f. SQUID. One expects, for a fixed microwave field amplitude, that ΔH_{pp} increases with the static field, until lines disappear (the negative lobe of one line overlaps the positive lobe of the next one).

We studied two kinds of series. One, for which we observe the lines up to 500 G, with a regular periodicity and a threshold which does not vary with the static field. Another one, for which the lines dissapear above approximatly 20 G, with a period increasing and a threshold decreasing with the static field. To explain this difference, it is sufficient to suppose that the ratio between the scalar products ($\mathbf{H_0}.\sigma$) / ($\mathbf{H_0}.\mathbf{S}$), where σ is the surface vector of the junction, is strongly different from one series to an other. We estimate this ratio at 1/5000 for the first kind and at 1/100 for the second one. At present, we are not able to account for the variation of the periodicity.

It is also interesting to study the temperature dependence of the threshold, because the variations of the threshold are equivalent to the variations of the critical current of the junction.

Our experimental results raise an important question. Within the S.Z. model, the absorption lines are infinitely sharp. Experimentally, in every studies of modulated microwave absorption of crystals , the lines display an intrinsic width. The absorption of the system occurs when, a flux quantum is coherently driven in and out of the loop by the microwave field. In the S.Z. model, this transition occurs for well defined values of the static field. However, this transition can be thermally activated. Then, the probability that the transition occurs when the current is lower than the critical current is not zero [12]. This possibility could explain the broadening of the line. The same broadening is observed with the loops and might provide a method of measurement of the probability distribution of thermally excited flux quantum transitions in a superconducting loop closed by a junction.

4. Conclusions

We have shown that the differents characteristics of the modulated microwave absorption in a low magnetic field of $YBa_2Cu_3O_7$ thin film square loop can be explained in the framework of the model of Silver-Zimmerman. These loops are characterized by the existence of one or several intrinsic weak links. The one with the smallest critical current sets the conditions of the modulated microwave absorption.

We were able to make quantitative measurement on the angular dependence of the periodicity, on values of the threshold and dissipated power in the loop in a more precise way than for crystal. These measurements provide a quantitative method to study the weak links in the films. Knowing the value of the self-inductance of the loop, we have a good estimate of the critical currents of the junctions were of the order of 5.10^{-5} A and the density of 5.10^4.A/cm^2 It is interesting to note that this method could be used to study, in a quantitative and contactless manner, artificial junctions.

Studies of the angular dependence of the absorption threshold can elucidate the effect of the static field on the junction. We can determine the variation of the critical current with the static field and then the magnitude and the direction of the surface of the junction.

An investigation of the temperature dependence of the periodicity of the series for the loops can provide a method to study the temperature dependence of the London penetration depth in the film [2]. If we assume that the flux quantum penetrates the surface $S = (a + 2\lambda_L)^2$, where a is the side of the square, the variations of the period and then of the surface is directly related to the variation of λ_L.

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