Anisotropic Vortex Dynamics Related to Screening Currents and Microwave Currents under Magnetic Fields on High T_C Superconductors

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Abstract

Modulated microwave absorption (MA) was measured under magnetic field sweeping at liquid nitrogen temperature on superconducting c-oriented and a-oriented YBCO thin films for various filed configurations. The both samples show strong low-field MA peaks resulted from the surface Meissner current. The MAs for the perpendicular field to the superconducting plane increase with increasing the sweep rate, indicating the stronger transient screening current due to viscous vortex motion. Anisotropic vortex dynamics were clarified on the a-YBCO.

Introduction

Microwave losses in high temperature superconductors (HTS) have been an interesting subject in the both categories of practical applications and physical fundamentals. HTS microwave filter device is one of the promising applications because its microwave loss is much less compared with normal metals [1,2]. Recently, tunable microwave filters with HTS/Ferromagnetic (FM) double-layer structure are also proposed [3,4]. In this device, the center frequency can be tuned by modifying permeability of FM layer through application of magnetic field. But it is well known that the microwave loss in HTS is quite sensitive to low magnetic fields. Therefore, it becomes an urgent topic now how to obtain the low and invariable microwave loss under magnetic field. On the other hand, the microwave loss in HTS is also a fascinating phenomenon in physics of superconductivity. It is related to some fundamental matters of superconductivity, such as screening current, Josephson junction and vortex dynamics, etc [5-7].

The physics behind the phenomenon is not fully understood yet. A few phenomenological models developed recently have helped to shed some light on the mechanisms of microwave losses in HTSs. They include nine mechanisms divided into two categories of the vortex mechanism and screening current mechanism; see Refs. [8] for review. The vortex mechanism involves the main absorption induced by viscous vortex motion driven by microwave current. The screening current mechanism involves the main absorption caused by the resultant current, vector sum of the screening currents and microwave currents, which exceeds the critical currents at weak superconducting regions and weak junctions. In the case of modulated microwave absorption (MA), we proposed that the screening current mechanism dominates over the vortex mechanism. Otherwise, the intensive main absorption signals around zero magnetic fields cannot be understood because differential vortex number due to the modulation field cannot be large [9,10]. This is obvious because the absolute vortex number is quite few around zero fields.

As for applications, high quality HTS films are essential to the microwave filters. Besides the quality of HTS films, we suppose that the orientation of film and configuration of field are two main factors to the microwave losses. At present, c-oriented HTS films are generally used in the filter devices because it is well known that propagation of microwave in the ab-plane (CuO_2 plane) parallel to the substrate plane results in lower loss. However, in a c-axis aligned a-oriented HTS film, we believe that the microwave also suffers lower loss when it propagates along b-axis, i.e. along the ab-plane. Moreover, the a-oriented film exhibits another characteristic that is a higher in-plane anisotropy. Further, when the magnetic field (H_a) is applied in the plane of film, the distinguishable two configurations of H_a//c and H_a//b can be realized.

Because of the highly anisotropic physical properties in HTS materials, the microwave loss must be affected by the magnetic field configuration. Thus it is quite valuable to investigate the anisotropic microwave absorption properties in HTS films. But as we know, few papers have been published on this topic so far. It has not been clarified which configuration of the field application is in favor of reducing the microwave losses. The aim of the present work is to investigate the field configuration dependence of the microwave losses in the a-oriented YBCO film. And we also compared the difference in nature between the c-YBCO and a-YBCO films.

Experimental

Experiments were performed on the a-oriented and c-oriented YBCO superconducting films. Using PLD technique, the a-YBCO film was grown epitaxially on $SrLaGaO_4$ substrate with 350 nm thickness and the c-YBCO on MgO substrate with 650 nm thickness, respectively. X-ray diffraction results show excellent crystallinity for both of the films. The films exhibit critical temperatures around 85 K for the a-YBCO and 87 K for the c-YBCO in a standard four-point resistance measurement.

The experimental set up consists of measuring the differential MA intensity (S) with respect to swept dc magnetic field (H_a) using the field modulation and phase sensitive detection techniques in a commercial EPR system. The modulation field (5 G and 100 kHz) was superimposed in the direction parallel to the dc field. The MA in a rectangular cavity excited in a TE_{102} mode tuned at 9.3 GHz was measured, and the microwave power was held at 0.1 mW. A sample tube was immersed in liquid nitrogen throughout the measurement.

In order to investigate the anisotropy of MA, H_a was applied to the a-YBCO film in three configurations, namely, $H_a//$a-axis, $H_a//$b-axis and $H_a//$c-axis as shown in Figure 1. In the case of $H_a//$a, $H_a$is perpendicular to the film plane and parallel to the ab-plane (CuO_2 plane). In the latter two configurations, H_a is parallel to the film plane, but it is totally different for the b- and c-axes. In $H_a//$b configuration, magnetic field is parallel to the ab-plane, whereas H_a is perpendicular to the ab-plane in $H_a//$c configuration. For comparison, the MA in c-YBCO film for $H_a//$c configuration was also investigated. In this configuration, H_a is perpendicular to the film plane.

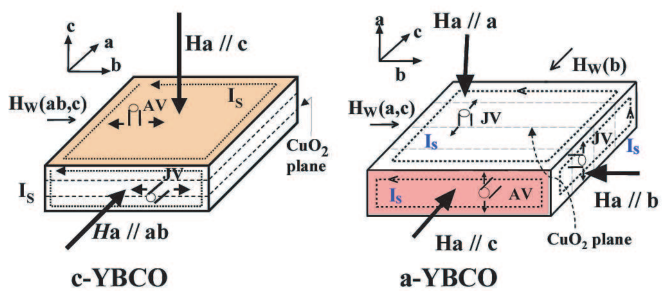

Figure 1: Various magnetic field configurations for the c- and a-YBCO films. $H_w(a, b, c)$ indicates the microwave magnetic field.

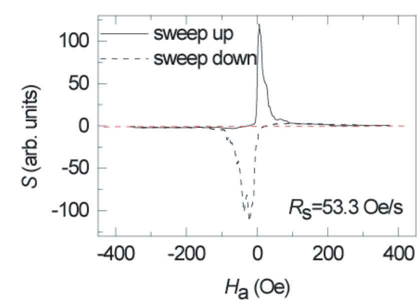

Figure 2: S vs H_a within one cycle of sweep for the c-oriented YBCO film with $H_a//$c.

Results and Discussion

1. c-YBCO film

In this part, we refer to experiments carried out on the c-YBCO film in $H_a//$c firstly. Figure 2 shows the MA signal as a function of H_a. Clearly Figure 2 displays a complete hysteresis loop of the MA. For a single sweep, such as upward sweep, a strong peak appears at a low field around 20 Oe. Then at higher field, S decreases rapidly and it is positive. Considering the signal based on the differential, this feature corresponds to a sharp increase of the MA at the low field followed by saturation of magnetic change induced by the modulation field at the higher fields.

As mentioned above, various mechanisms have been proposed to explain the MA in HTS. But they can be classified into two mechanisms, namely the screening current mechanism and vortex mechanism. The main absorption change occurs at the low field, ~20 Oe, where the system is in a Meissner state without vortex principally. So the vortex mechanism is not valid in this region. Usually HTS contains many weak links and Josephson junctions. When the external magnetic field is applied, the screening current circulates around sample edge. If the resultant current of screening current I_S and microwave current exceeds the critical current density of the weak links, these weak links are decoupled and electrical voltages appear across them. Therefore energy must be lost in these decoupled weak link areas. It is obvious that I_S increases with increasing external field (H_a), then the number of decoupled weak links and microwave losses increase also, leading to the rapid increase in S.

When H_a reaches a characteristic value, namely H_S ~50 Oe, where most of the effective weak links have been decoupled, the vortex can enter easily and the strong surface Meissner current decays. Then the MA decreases, leading to the drop of S. The result shows it decreases to a finite value, not zero. So the other mechanism, vortex motion, comes out. As we know, when a type-II superconductor is in the mixed state, a viscous vibration of vortex driven by microwave current-induced Lorentz force is the main cause of MA. Considering of our experiments carried out at liquid nitrogen temperature closed to the critical temperature of the sample, the effective lower critical field H_{C1}* must be rather low, around several tens of Oe. Therefore, just after the process of weak link decoupling, the system enters into mixed state and then the vortex mechanism begins to be valid. But the absorption difference due to the modulation field is small, then S is small in this region.

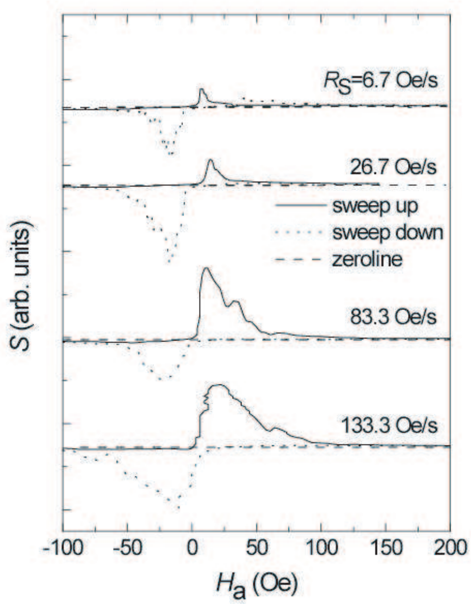

Figure 3: MA spectra at various sweep rates (R_s) for the c-YBCO with $H_a//$c.

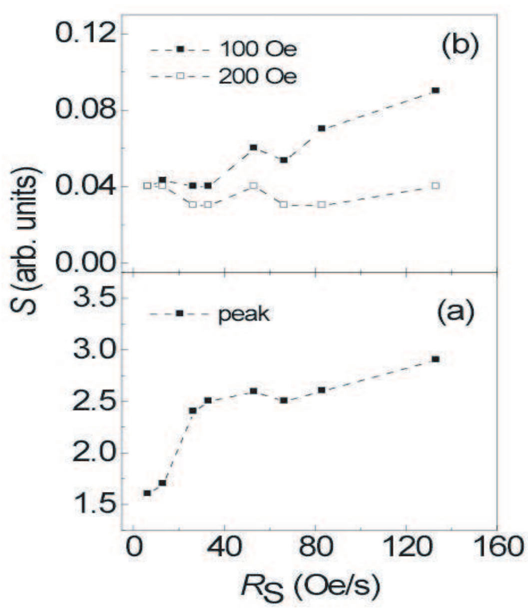

Figure 4: R_s dependence of S at (a) the peak and (b) 100 and 200 Oe for the c-YBCO with $H_a//$c.

In the vortex mechanism, the MA is proportional to the number of vortices. It is obvious that the number of the vortices increases with increasing external field. But the differential vortex numbers due to the field modulation are almost the same even with increasing field. Thus the MA intensity S is almost constant with increasing field.

The aim of present work is to obtain knowledges about the vortex dynamics following to the field and screening current. Then we investigated the MA spectra at various sweep rates (R_S) as presented in Figure 3. The spectrum changes and the intensity looks larger with increasing R_S. Figure 4 summarizes the R_S dependence of the MA peak height and signal intensities at 100 and 200 Oe. It can be seen that the MA peak height, corresponding to the weak link decoupling, and S at 100 Oe increase with increasing R_S, whereas S at 200 Oe is almost independent on R_S.

Firstly, we consider the increase of the peak height, dominated by the screening current in the Meissner state, with R_S. According to Maxwell equations, the screening current density J_S is proportional to the curl of flux density B. The B distributions at various R_S are schematically drawn in Figure 5. In this one-dimensional illustration, J_S is proportional to the slope of B distribution as $J_S \propto \mathrm{d}B/\mathrm{d}x$. The solid curve in Figure 5 denotes the equilibrium distribution under a steady magnetic field. The dashed curves denote the transient distributions under the field sweeps at various R_S. When the field is swept fast, the flux entrance into the sample must be delayed from the external field because of the viscous nature in the superconducting medium. Then, with increasing R_S, the slope of distribution near the sample surface becomes steeper. Therefore, larger J_S results in more weak links being decoupled. This is the reason why the MA peak height increases with increasing R_S, as shown in Figure 4 (a).

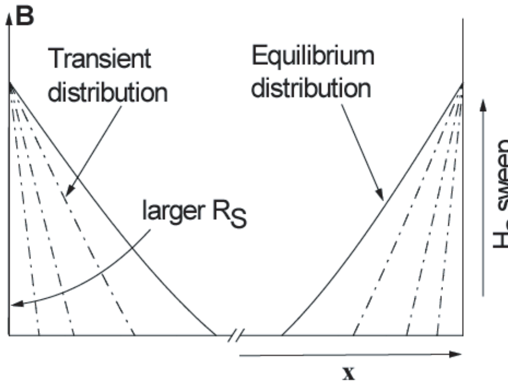

Figure 5: Illustration of transient distributions of magnetic induction B at various R_s.

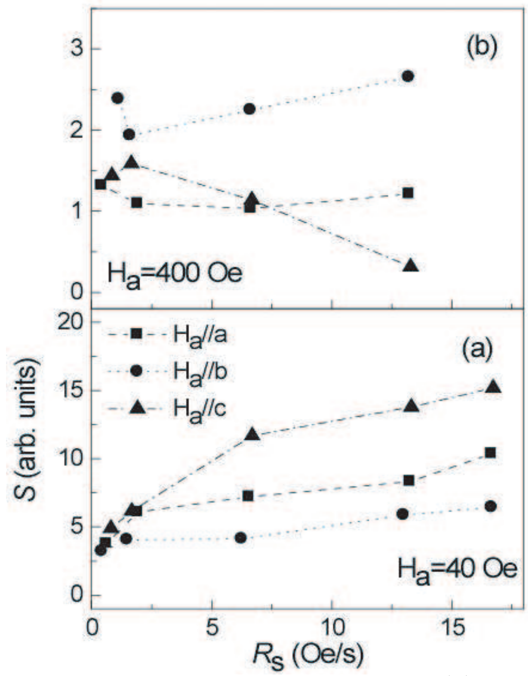

Figure 6: The R_s dependences of S at (a) low and (b) high fields for the a-YBCO film with various field configurations.

Secondly, we discuss R_S dependence of S at 200 Oe (Figure 4 (b)), which should correspond to the vortex mechanism in the mixed state. In this region, the vortex vibration motion does not depend on R_S so much. Then the resulting S does not depend on R_S.

The result at 100 Oe is interesting. The MA at 100 Oe must also be caused principally in the mixed state. Then, why its R_S dependence is totally different from that at 200 Oe? It is noteworthy that the field strength of 100 Oe is slightly above H_{C1}. When the external field reaches 100 Oe at much higher R_S, the flux entrance into the sample is much delayed and its density is lower than the equilibrium flux density corresponding to H_{C1}. In this situation, the sample behaves as it is in the Meissner state actually. Therefore, R_S dependence of S at 100 Oe is similar to that at the peak in the Meissner state. Moreover, we like to point out that this behavior is valid only at R_S higher than 40 Oe/s, as it is known from Figure 4 (b). When R_S is lower than 40 Oe/s, S does not increase because the flux is not delayed so much then it is in the mixed state. So the R_S value around 40 Oe/s is a critical value whether it is still in the Meissner or mixed states under the external field at 100 Oe. As we know, the characteristic delay time of the flux entrance is about 0.5 s. Its order of magnitude is well consistent with our explanation.

2. a-YBCO film

Next, we show experimental results of the MA on the a-YBCO film in three different magnetic configurations and discuss them. For H_a//c configuration, it shows the highest low-field S and then S decreases sharply at higher fields. For H_a//a at low fields, we see the similar behavior as that in the former configuration of H_a//c, but with lower signal intensity. With increasing H_a further, S decreases gradually and reaches a finite constant value at the high fields. But S in H_a//b configuration behaves in a quite different way, i.e. the low-field MA is very small and high-filed MA is comparatively large.

Firstly, we consider the low-field MA corresponding to the screening current mechanism as mentioned above. For H_a//c configuration, the strong screening current flows in the ab-plane. Therefore, a lot of weak links are decoupled and S is the strongest. In the case of H_a//a configuration, half of the screening current path is along the c-axis with weak superconducting-coupling. Then the current density must be reduced and the low-field MA is smaller than that in H_a//c configuration. In H_a//b configuration, the screening current flows almost along the c-axis. So in this case, only the very weak screening current flows, leading to the small low-field MA.

Secondly, we discuss the high-field MA in the a-YBCO. In this sample, the MA is rather large compared with those in the c-YBCO. The superconducting coupling between the grains is stronger in this a-YBCO, and then the surface Meissner screening current can flow even in the mixed state. Therefore the MA is dominated by the screening current mechanism even at the high fields. This is the reason why the MA is larger at the high fields in this a-YBCO.

We also investigated the R_S dependence of S on the a-YBCO film as shown in Figure 6. It can be seen in Figure 6 (a) that the low-field S, corresponding to the screening current mechanism, increases with increasing R_S for each field configuration. The reason is the same as that given in the c-oriented film. At the high field as shown in Figure 6 (b), the increasing rate of S becomes smaller for $H_a//$a and it does not change for $H_a//$b. But in $H_a//$c configuration, S decreases with increasing R_S, in a totally different way from those for $H_a//$a and $H_a//$b.

We discuss this decreasing manner. At the larger R_S the Abrikosov vortices enter into the sample very fast in the viscous medium for $H_a//$c. The generated heat is larger at the higher fields due to the larger density of vortices with increasing R_S. This induces melting of vortex, resulting in the lower viscosity. Thus the surface slope of flux distribution becomes more gradual, leading to the smaller transient screening current and smaller MA. This is the cause for decreasing manner with increasing R_S for $H_a//$c. This effect is smaller for $H_a//$a and the smallest for $H_a//$b because we have Josephson vortex in these configurations.

Conclusion

The MA spectra with the magnetic field sweeping were measured on the c- and a-oriented YBCO films. The spectra for the both films show the strong signals at the low fields closed to zero. This strong MA for $H_a//$c comes from the in-plane strong surface Meissner current, and weaker MA for$H_a//$a,b is attributed to the weaker out-of-plane screening current. At the high fields, the c-YBCO shows the very small MA due to the serious reduction of current resulted from the grain decoupling. While the a-YBCO certainly shows the small MA at the high fields but it is not so small. Probably this a-YBCO has stronger connection of the grains. With increasing R_S, the MA around the peak fields increases due to the stronger transient screening current owing to the vortex viscosity. The vortex melting is suggested by the decreasing manner of MA with R_S at the high field.

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