Microwave absorption in $\text{YBa}_2\text{Cu}_3\text{O}_x$ granular thin films at the dc magnetic fields

S BENACKA, M MAHEL*, S GAZI and S CHROMIK

Electrotechnical Institute, Slovak Academy of Sciences, 842 39 Bratislava, Czechoslovakia.

*Present address: Department of Radiophysics, Cowenius University, Mlynská dolina, 842 15 Bratislava, Czechoslovakia

Abstract. Localization of microwave absorption in $\text{YBa}_2\text{Cu}_3\text{O}_x$ superconducting thin films in the presence of very low dc magnetic field was studied. The granular $\text{YBa}_2\text{Cu}_3\text{O}_x$ thin films of submicrometer thickness had random orientation of grains, were inserted into a microwave cavity for maximum rf magnetic field. The microwave absorption in low dc magnetic field at temperatures just below the critical temperature shows properties which may be ascribed to superconducting grains. At lower temperatures the hysteretic effects and flux-trapping occur in the intergrain regions of the film.

Keywords. Thin film; microwave properties; microwave absorption.

1. Introduction

Microwave losses in granular high temperature superconductors placed in weak dc magnetic fields, are an unpleasant factor from the radiofrequency applications point of view. Since microwave absorption is much smaller in single crystals it was natural to propose its connection with the presence of intergranular weak superconducting links rather than with superconducting grains. It is also generally accepted at present (Blazey *et al* 1989) that dissipation occurs due to the viscous motion of fluxons driven by the induced microwave currents which first enter the weak links and then through the bulk (grain) material only when the field exceeds the lower critical field H_{c1} . The absorption is assumed to be proportional to the number of free fluxons (Dulic *et al* 1989). Because the fluxons entering weak links have much lower viscosity than those in the bulk (Portis and Blazey 1988), and microwave absorption is inversely proportional to viscosity, the maximum microwave absorption change takes place at low magnetic fields. On reverse sweeping of dc magnetic field hysteretic and memory effects occur while their magnitude depending upon the strength of maximum field is attained during the sweep. The minimal absorption signal occurs in zero-field-cooled (ZFC) samples (Blazey 1989). A resonant microwave cavity perturbation (RMCP) technique used in this work is a very useful and sensitive method to study the microwave absorption properties of high temperature superconductors specially in thin superconducting films (Mahel and Benacka 1990).

The aim of this work was to localize the microwave absorption in granular superconducting thin films $\text{YBa}_2\text{Cu}_3\text{O}_x$ from temperature dependence of microwave properties in low dc magnetic fields.

2. Experimental

Superconducting thin films of $\text{YBa}_2\text{Cu}_3\text{O}_x$ were prepared by vacuum coevaporation of three components using the low temperature deposition process (Chromik *et al*

1989, 1990). The films used in these experiments were about $0.7\ \mu\text{m}$ thick, with zero resistance critical temperature $T_{ce} = 86\ \text{K}$ (measured by dc four-probe method), the onset of phase transition $T_{con} = 92\ \text{K}$, and the critical current density $J_c = 10^4\ \text{A/cm}^2$ was at $4.2\ \text{K}$ and zero magnetic field. The morphology of the films was granular with random orientation, the average grain size being typically $0.5\ \mu\text{m}$. The surface of the films was smooth without cracks or damages. The composition of the grain was 1:2:3 but excess of chemically unbounded Cu was present in our films giving an integral film composition 1:2:4. This excess of Cu creates weak links at grain boundaries between granules with $J_c(T)$ dependence characteristics of SNS connections (Strbik *et al* 1989; Benacka *et al* 1989).

The Y–Ba–Cu–O thin films deposited on single crystal Al_2O_3 substrate were cut to receive the samples of dimension of couple of square millimeters. The samples were inserted into the brass rectangular waveguide resonator of TE_{012} mode, resonating at $9.1\ \text{GHz}$, or into the cylindrical one of TE_{012} mode, resonating at $21\ \text{GHz}$. The quality factor $Q = 2000$ at $77\ \text{K}$. The samples were located in the maximum microwave field. The resonator was inserted into pair of Helmholtz coils and the orientation of dc magnetic field was allowed to vary from parallel to perpendicular direction to the surface of the film. The dc magnetic field was low frequency-modulated and the microwave absorption was detected by the phase-sensitive detection technique. In all cases the dc magnetic field was parallel to the low frequency ($170\ \text{Hz}$) modulating field and perpendicular to the microwave magnetic field. The whole cryostat was placed in permalloy double shielding with material sheets allowing measurements in magnetic fields as low as $10^{-3}\ \text{mT}$. The microwave absorption was measured as a function of temperature (4.2 to $95\ \text{K}$) and dc magnetic field ($\pm 15\ \text{mT}$) applied perpendicular to the film surface.

3. Results and discussion

The RMCP technique is a useful method to get information about the superconducting state below the critical temperature of samples, at which the dc resistance vanishes. Because the microwave skin depth in the normal state of $\text{YBa}_2\text{Cu}_3\text{O}_x$ films is of several micrometers, i.e. much more than both the average grain size and the film thickness, by this method we could expect to receive information about the properties of whole sample. It was recognized that the onset critical temperature T_{con} , measured by the microwave method (without any dc or ac modulated field applied) using frequency modulation of klystron is in excellent agreement with the zero resistance critical temperature received by four-probe dc measurements (Gazi and Benacka 1990). We attribute the temperature $T_g < T_{con}$, observed by microwave measurements to the critical temperature of grains, and the temperature width $\Delta T_g = T_{con} - T_g$ ($\sim 1\ \text{K}$) for the transition is caused mainly by oxygen inhomogeneity and disordered grain orientation. Lowering the sample temperature further, a quality factor of microwave cavity gradually increases and saturates at $20\ \text{K}$ or lower, at temperature T_i depending on the method of the sample preparation. The temperature T_i is ascribed to the critical temperature of intercrystalline weak connections created by proximity effect (Strbik *et al* 1989), and the width of this transition $\Delta T_i = T_g - T_i$ to dimensional dispersion of weak links. In our thin films ΔT_i represents the values of 20 to $40\ \text{K}$. The application of small dc magnetic field ($\sim 10\ \text{mT}$) at arbitrary temperature $T < T_g$ depresses the

quality factor of cavity to a value received at temperature T_g . It means that a majority of superconducting weak links created by proximity effect is destroyed but the superconducting state of grains remains unaffected. By further lowering the temperature, the hysteresis and memory effects become more and more pronounced due to flux-trapping in intercrystalline regions. The original state may be restored by heating the sample to temperature $T > T_g$. Thus, the temperature dependence of microwave absorption allows characterization of superconducting properties of thin films in the whole measured temperature range.

To receive more detailed information about the localization of microwave losses, we used the technique of dc magnetic field modulation. The maximum of modulated microwave signal was received just after the sample was zero field cooled (ZFC). Increasing the dc magnetic field B , perpendicular to the film surface, in both directions increases losses and after changing the direction of sweep some hysteresis and signal amplitude depression occur. As long as the magnitude of field modulation B_m is small, compared to the critical field B_{c1} ($B_m/B_{c1} \ll 1$) the signal changes the sign only on changing the sweep direction, but at higher modulation amplitudes ($B_m/B_{c1} \gtrsim 1$) the signal changes the sign even during one sweep direction. The effect is related to the temperature dependence of B_{c1} .

The microwave losses are also strongly affected by maximal amplitude $B_{\max}$ of swept dc magnetic field. On the downward sweep, at relatively low temperature, the flux is trapped in the sample, hysteresis increases proportional to $B_{\max}$ and the absorption peak, near zero magnetic field, is much depressed. The original state may be restored again by heating the sample to a temperature higher than T_g .

In the narrow temperature range below $T_{c\text{on}}$ the signal shows some hysteresis (figure 1 curve c) even for fields which are larger than B_{c1} . At lower temperatures hysteric signals were again observed (figure 1, curves a, b) showing the larger magnetic flux-trapping (hysteresis). As the temperature is lowered below 40 K a new effect appears with small hysteresis, which again increases with further decreasing of

Figure 1. Microwave absorption in high temperature range is characterized mainly by properties of grains (intergrain connections are in the normal state).

Figure 2. Microwave absorption in low temperature range is characterized by intergrain weak connections.

temperature (figure 2). These results show that flux-penetration and flux-trapping effects at temperature $T > T_g$, where an overwhelming majority of intergrain connections are in the normal state, may be associated with granular properties. At temperature $T < T_i$ where the intergranular regions are in the superconducting state, they play a major role in microwave absorption.

Thus the temperature dependence of microwave absorption in granular $\text{YBa}_2\text{Cu}_3\text{O}_x$ thin films shows two distinct temperature regions, in which the microwave absorption may be ascribed to the grains or to intercrystalline connections.

4. Conclusions

The microwave absorption effects were investigated in granular $\text{YBa}_2\text{Cu}_3\text{O}_x$ superconducting thin film. The results show that the main absorption effect, at temperature sufficiently lower than the critical temperature of grains, arises from magnetic flux penetration and its interaction with microwave field into the intergranular regions. The absorption is dominated by resistive losses and is minimal at the zero field. At temperatures closer to the critical temperature of grains, where a considerable part of intercrystalline connections is in the normal state, the microwave losses and hysteretic effects in low magnetic field characterize the granular properties. In conclusion, it is inferred that for application of thin superconducting films of high temperature superconductors in high frequency cryoelectronic circuits, epitaxial films with smallest possible defects are necessary.

References

- Benacka S, Suistunov V M, Plecenik A, Chromik S, Gazi S, Levarsky J, Strbik V and Takacs S 1989 *IEEE Trans. Magn.* **25** 2583

- Blazey K W, Portis A M and Holtzberg F H 1989 *Physica* **C157** 18
- Blazey K W 1989 *Phys. Scr.* **T29** 92
- Chromik S, Sith J, Strbik V, Schilder J, Swatko V and Benacka S 1989 *J. Appl. Phys.* **66** 1477
- Chromik S, Strbik V, Adam R, Smatko V and Benacka S 1990 *Proc. Int. Conf. on Superconductivity, Bangalore, India.*
- Dulcic A, Rakvin B and Pozek M 1989 *Europhys. Lett.* **10** 593
- Gazi S and Benacka S 1990 (in preparation)
- Mahel M and Benacka S 1990 *Proc. 5th Czechoslovak Symp. on Weak Superconductivity, Smolenice* (Nova Sci. Publ.) p. 97
- Portis A M and Blazey K W 1988 *Solid State Commun.* **68** 1097
- Strbik V, Benacka S, Gazi S, Chromik S, Levarsky J and Sith J 1989 *Mod. Phys. Lett.* **B3** 729