Low-field AC susceptibility study of the flux motion in Bi$_2$Sr$_2$CaCu$_2$O$_y$ thin films

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Abstract. DC magnetron sputtering technique were used for the synthesis of high quality epitaxial thin films of the superconducting cuprate Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi: 2212) thin films. The structural characterization carried by X-ray diffraction indicates that the films are single phase and oriented with their c-axis perpendicular to the substrate surface. The flux motion mechanisms in the vicinity of the irreversibility line have been studied by AC susceptibility technique. The temperature dependencies of real and imaginary parts of AC susceptibility were performed, by using different values of amplitude and frequency. Temperature dependence and low field dependence of the activation energy for flux motion were obtained.

1. Introduction

High quality high temperature superconductors (HTS) thin films fabrication and multilayers are important for the fabrication of integrated junction circuits. The Bi$_2$Sr$_2$Ca$_{n-1}$Cu$_n$O$_{2+2\delta}$ (BSCCO) has high critical temperatures (T$_c$~20K for n=1, T$_c$~85K for n=2 and T$_c$~110K for n=3) and high critical current densities at low temperature and is used for the fabrication of long lengths HTS tapes.

Superconducting Bi-2212 material suitable for applications at 77 K should have high critical current densities. The films with c-axis aligned to the film plane appear to be preferably suited for the fabrication of sandwich type SNS and SIS Josephson and quasiparticle tunnel junctions [1]. The epitaxial growth of thin films of Bi: 2212 has been realized on substrates like SrTiO$_3$, LaAlO$_3$ and MgO [2-5]. The importance of Bi$_2$Sr$_2$CaCu$_2$O$_{8+d}$ HTSC is being reinvented in the light of its potential use in Terahertz nanotechnology and as a natural SQUID. Bi-2212 has a layered structure, which allows the propagation of EM waves (called Josephson plasma oscillator) [6-8] if transverse magnetic field $H_{ab}$ and longitudinal electric field $E_c$ is applied. Bi-2212 is also used as natural SQUID because there are non-superconducting layers sandwiched between superconducting CuO layers [9].
AC loss is one of the most important parameters in determining the commercial effectiveness of technological applications. In some applications, the reduction of AC loss is more important than other factors. It is well established that the largest contribution to AC losses comes from hysteresis loss, because the motion of flux lines.

The magnetic phase diagram of high-temperature superconductors (HTSC) exhibits an extraordinarily rich variety of phases [10]. Still controversial is the presence of a boundary, called the irreversibility line (IL), which separates a magnetically irreversible state, with a non-linear dissipative behavior, from a reversible region with a linear dissipative property. Some of the suggestions are based on a vortex glass formation [11] or on a flux lattice melting [12]. More recent studies investigating the irreversibility line have confirmed the presence of a predicted crossover characteristic value $H_{cr}$ [13] in the dimensionality of the vortex fluctuations [14] and [15].

Here we present the temperature dependencies of real and imaginary parts of AC susceptibility as a function of the AC driving field, the superimposed DC field and driving frequency for Bi:2212 films.

2. Experimental

Bi:2212 thin films were deposited in situ onto (100) LaAlO$_3$ heated single crystal substrate by using DC magnetron sputtering system [4]. In order to compensate the Bi loss, a bismuth enriched target with chemical composition Bi$_{2.6}$Sr$_{1.97}$Ca$_{0.97}$Cu$_{2.4}$O$_y$ has been synthesized. The optimal parameters used for fabrication of epitaxial quality Bi:2212 thin films were: sputtering gas pressure of 0.9 mbar (with a ratio 1/1 between the argon and oxygen partial pressures), the substrate temperature 790$^\circ$C and d.c. plasma power between 20W and 30W.

X-ray diffraction pattern shows only (00l) reflexions observed for thin films and the reflexions (i00) for LaAlO$_3$ substrate. The FWHM (full width for high maximum) of rocking curve is equal to 0.40$^\circ$, and confirmed the high orientation quality of sample.

In order to give an insight into the growth mechanisms of Bi:2212 films, a series of thin films with different thicknesses have been grown.

AC susceptibility measurements were performed by means of a Lakeshore AC susceptometer, equipped with a superconducting coil providing a background DC field of maximum 1 Tesla. The frequencies used may vary from 10 to 1000Hz, while the field amplitude from (0.005-10 Oe)10 to 800 A/m. Superconducting thin film was carefully placed in the centre of one of the secondary coils with its c-axis parallel to the direction of both AC and DC magnetic fields.

3. Results and discussions

Figure 1 shows the real $\chi'$ and imaginary $\chi''$ components of AC susceptibility for $f=1000$Hz and $H_{ac}=0.02$ Oe, at different DC values up to 1 Tesla. The real part of susceptibility extrapolates at low temperature to a field independent value, which suggests completing magnetic screening. The increase of $B_{dc}$ leads to a slight broadening of the transition width in $\chi'$ susceptibility transition. The peak in imaginary part of AC susceptibility, $\chi''$, occurs at a temperature $T_p$ (Fig.1). Many authors assimilate the $T_p(B_{dc},f)$ values measured for different DC fields, $B_{dc}=B_{irr}$, at a given frequency $f$, as the irreversibility line (IL). In order to avoid nonlinear effects the exciting AC field amplitude $H_{ac}$ was kept below the value 4 A/m.

To analyse the shift of the $\chi''$ intergranular peak we use a linear TAFF model in which vortex displacements are thermally activated and the hopping rate is given by:

$$f = f_0 \exp [-U(B_{dc}, T_p)/(k_B T)]$$

where $f_0$ is a typical attempt frequency and $U(B_{dc}, T_p)$ the activation energy. On the basis of this equation we obtain:

$$U(B_{dc}, T_p) = -k_B T_p \ln (f - \ln f_0) \quad (1).$$

For a proper interpretation of data, we assume that:

$$U(B_{dc}, T_p) = U(B_{dc})^*U(T_p).$$
These approximations are valid close to $T_c$ and contain the specific dependencies predicted by some models [16,17].

Fig. 1. The temperature dependence of AC susceptibilities, $\chi'$ and $\chi''$ in Bi:2212 film for $B_{dc}$ fields up to 1 Tesla, for $f=1000$ Hz and $H_{ac}=4$ A/m.

Fig. 2. shows the temperature and frequency dependence of imaginary part $\chi''$ of a.c. susceptibility in the presence of a d.c. field $H_d = 200$/m superposed over the a.c. field $H_{ac}=400$ A/m. For a fixed value of $B_{dc}$ the temperature $T_p$ increases with increasing frequency.
Fig. 2. Temperature dependence of the imaginary part $\chi''(T)$ of the complex susceptibility for frequencies $f=110, 220, 300, 600$ and $1000$ Hz. The d.c. and a.c magnetic fields were $B_{dc}=0.5, 1, 5$ and $10$ mT and $H_{ac}=10$ A/m, respectively.

Equation (1) indicates that, in linear regime, $U(T_p)/T_p = [U(H_d)]^{-1} \ln(f_0/f)$ depend on the driving frequency in a logarithmic way. This was checked by representing the Arrhenius plot for $U(T_p)/T_p$ versus $(\ln f)$, for different $B_{dc}$ values. As shown in fig. 3, we obtain a linear dependence for $n=1$ in $U(T_p) = (1-T_p/T_c)^n$.

Fig. 4. The plot of $U(T_p)/T_p = [1-(T_p/T_c)]/T_p$ versus $\ln f$ in different $B_{dc}$ fields.

This result indicates the presence of the ohmic TAFF regime, where the activation barrier is independent of the driving force.
The field dependence of the activation energy was determined by using the slopes of the linear fits determined for each field in fig.4. From the best fit (full line in fig.4) we find that the activation energy is:
\[ U = 2920 - 2088 \ln B \text{ [K]} \]

An explanation for the \( \ln B \) dependence of activation energy may be obtained from the shape of the pinning potential and from the pinning energy distribution. At small magnetic fields, in the individually pinned vortex regime, the motion of individual vortices in the field of unperturbed pinning centers is present. By using for the pinning energies a distribution \( f(U) = f_0 \exp \left[ -(U-U_0)/\sigma \right] \) and assuming that vortices “fill” the strongest pinning sites first, the activation energy can be written as [18, 19]:
\[ U(B) = U_0 + \sigma \ln \left( B_0/B \right) \]

Where \( U_0 \) is the activation energy corresponding to the crossover field \( B_0 \) between the single vortex and collective vortex behavior.

![Magnetic field dependence of the low-field activation energy in Bi: 2212 thin film.](image)

### Fig. 5. Magnetic field dependence of the low-field activation energy in Bi: 2212 thin film.

### 4. Conclusions

High quality epitaxial Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_y\) (Bi: 2212) thin films were obtained by DC magnetron sputtering technique. X-ray diffraction indicates that the films are single Bi: 2212 phase and oriented with their \( c \)-axis perpendicular to the substrate surface.

AC susceptibility technique is a good option to study the flux motion mechanisms in the vicinity of the irreversibility line.

The obtained \( U(T_p, H_d) = U_0(1-T_p/T_c)\ln B \) dependence of the pinning barrier is in agreement by the TAFF picture and can be explained by using at small magnetic field, in the individually pinned vortices regime an exponential distribution for pinning energies.

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