AC-measured shifts in T_c of high temperature superconductors: The effect of interlayer structure

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Abstract. The apparent T_c of some high temperature superconductors such as BiSrCaCuO and TlBaCaCuO measured by low (10–20,000 Hz) a.c. inductance techniques is shifted downward by up to 30 K in the presence of modest (400 Oe) d.c. magnetic fields. Dc magnetization (SQUID) measurements of the same samples show no such shifts in the same magnetic fields. Other materials like YBaCuO and TlPbSrCaCuO do not show such shifts of T_c in a.c. inductance measurements in d.c. magnetic fields. While BiSrCaCuO and TlBaCaCuO are known to exhibit flux creep/flux flow phenomena resulting in low irreversibility line behaviour as measured by both a.c. and SQUID techniques, the above T_c shift is apparently a new phenomenon. Materials exhibiting this property contain two or more layers of metal ions between the CuO conductance layers (2212, 2223 structure). Materials with only one metal ion layer between the CuO layers (123, 1223 structure) do not show the apparent T_c shift, suggesting that the phenomenon is a result of the properties of magnetically-isolated CuO layers. Implications of the latter will be discussed.

Keywords. AC shifts; interlayer structure.

1. Introduction

The new high temperature superconductors show a rich variety of physical properties not seen in the previously known low temperature materials (Geballe and Hulm 1988). Among these properties are dynamic effects produced by time-varying magnetic fields, which for some materials cause strong field/temperature shifts in both apparent transition temperatures and susceptibility absorption peaks. It has also become recognized that a magnetic field/temperature relation not seen in low temperature superconductors, called the irreversibility line (Malozemoff *et al* 1988) exists in the new high temperature superconductivity (HTSC) materials above which flux moves reversibly in the material. This paper will show how the thermally assisted flux flow (TAFF) theory can explain these properties and some speculations will be made on how the layer structures of these materials affect their dynamic properties.

2. Theory

The basis of the TAFF theory (Ginsberg 1989) is the assumption that flux motion in the high temperature superconductors is thermally assisted over pinning centre; this property is expressed by the relation

$$F = F_0 \exp(-U_0/kT), \quad (1)$$

where F is the rate at which flux lines move past pinning centres of potential U_0 , and F_0 is the attempt frequency (Dews-Hughes 1988). Malozemoff (see Ginsberg 1989) shows that with assumptions about the presence of superconducting currents, back and forth flux hopping, the form of the pinning potential, and the temperature dependences of the

critical field and the coherence length, the experimentally testable relation

$$1 - T_p T_c \alpha [H k T_c \ln(F_0/F)]^{2/3} \quad (2)$$

results, where T_p is the temperature peak of the X'' susceptibility at a measuring frequency F . In a further development of the TAFF theory, van den Berg *et al* (1989) show that the apparent transition temperature T_0 can be expressed as

$$\frac{U_0}{k T_0} = \ln \left(\frac{2 M_0 F_0 H^2 V_c w^2}{\Pi F \mu_0 k T_0 l^2} \right), \quad (3)$$

where F is the frequency of measurement, M_0 is related to the real part of the permeability μ' , V_c is the active volume of the flux line lattice, w the distance. V_c moves in a thermally-activated jump and l a sample dimension. The frequency and magnetic field dependence of this relation can also be experimentally tested.

3. Experimental

The irreversibility line can be measured by determining the temperature of the peak of the imaginary susceptibility X'' as a function of magnetic field (Yeshurun *et al* 1989). A.c. inductance measurements were used to measure the complex susceptibilities of the materials of interest using previously described techniques (Flippen and Askew 1988). Measurements were made using frequencies from 100 Hz to 20 kHz in d.c. magnetic fields up to 400 Oe and a.c. measuring fields of 0.5–12 Oe. Single crystals of $Y_1Ba_2Cu_3O_x$, $Bi_2Sr_2Ca_1Cu_2O_y$ and $Tl_2Ba_2Ca_1Cu_2O_y$ were grown by common procedures (Subramanian *et al* 1988) and were typically $1 \times 1 \times 0.1$ mm. The samples were mounted with the d.c. and a.c. magnetic fields parallel to the c axis. Other

Figure 1. Magnetic field H versus irreversibility temperature T_p for three high temperature superconductors.

Figure 2. Complex susceptibilities of $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_y$ versus temperature and magnetic field.

Figure 3. $1 - T_p/T_c$ versus $H^{2/3}$ and frequency for $\text{Tl}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}_y$.

Figure 4. T_0 versus $\ln(T_0 F / H^2)$ for $\text{Ti}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}_y$.

materials were measured in powdered form. Measurements were made of the temperature dependence of X' and of the peak temperature of X'' for a fixed set of measuring a.c. field, d.c. field and frequency as the temperature was lowered from above T_c . Plots of H versus T_p for crystals of the three families of high temperature superconductors are shown in figure 1 for 20 kHz frequency and 0.5 Oe. measuring field. Figure 2 shows X' and X'' for $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_y$ at 100 Hz as a function of d.c. magnetic field. A plot of $1 - T_p/T_c$ versus $H^{2/3}$ is shown in figure 3 and a plot of T_0 versus $\ln(T_0 F / H^2)$ in figure 4 for $\text{Ti}_2\text{Ba}_2\text{Ca}_1\text{Cu}_2\text{O}_y$.

4. Discussion

Figure 1 shows that the HTSC materials possess markedly different irreversibility lines, that of YBaCuO being much steeper than the other two. Since a critical current cannot be sustained above the IL (Malozemoff *et al* 1988), as steep as possible and IL is desired for applications involving magnetic fields, and in pure crystals at least, YBaCuO is superior to both BiSrCaCuO and TiBaCaCuO at 77 K. Figure 2 shows the complex dynamic behaviour of BiSrCaCuO at 100 Hz. Not only is there a large shift in the temperature of the X'' peak with magnetic field, there is also an apparent shift downwards in the transition temperature of X' . Data for TiBaCaCuO is similar. Dc SQUID

magnetometer data for the same sample of BiSrCaCuO, shown in figure 2, shows that the shift in T_c is only apparent, however, as the material still excludes flux up to the zero field transition temperature. Data for YBaCuO over the same range of parameters shows only a small shift in the X'' peak and no shift in T_c .

The above data permit an experimental test of the TAFF theory. Figure 3 shows a plot of $1-T_p/T_c$ versus $H^{2/3}$ for the TlBaCaCuO sample. A linear relation is seen at a given frequency, as predicted by equation (1). A previous plot for BiSrCaCuO shows good agreement at low frequencies with data obtained by another method (Flippen and Askew 1990). A further indication of the validity of the theory is the roughly logarithmic dependence of $1-T_p/T_c$ on the measuring frequency. The same relations have been shown to apply to $Y_1Ba_2Cu_3O_x$ but with a much smaller slope (Malozemoff *et al* 1988).

Application of the TAFF theory to the apparent shift in transition temperature for $Tl_2Ba_2Ca_1Cu_2O_y$ is shown in figure 4. Again the expected relation of T_0 to the magnetic field and frequency predicted by the theory is obtained in the range of parameters covered by the assumptions in the theory. The same agreement with the TAFF theory has been obtained elsewhere for $Bi_2Sr_2Ca_1Cu_2O_y$ (van den Berg *et al* 1989).

The strong dependence of the properties of the HTSC materials upon dynamic magnetic fields is rooted in the ease with which flux lines can move in them, particularly at higher temperatures. The applicability of the TAFF theory in correlating their sometimes complex physical behaviour shows that flux-pinning in the materials is generally weak and can be overcome by thermal energy. Yet the relatively strong magnetic field dependence of the properties of $Bi_2Sr_2Ca_1Cu_1O_y$ and $Tl_2Ba_2Ca_1Cu_2O_y$ compared to that of $Y_1Ba_2Cu_3O_x$ suggests that the structures of the materials play an important part in their magnetic behaviour. The major structural difference in the 123 versus 2212 compounds is the increased spacing apart of the Cu–O units in the latter. Apparently the further apart the units the less pinning is available to hinder the flux motion. Preliminary measurements as above on $Tl_5Pb_5Sr_2Ca_2Cu_3O_y$ show a steeper IL than $Tl_2Ba_2Ca_1Cu_2O_y$ and no shift in T_0 , supporting this suggestion. Additional measurements on compounds in the TlBaCaCuO system with structures (1245), (1234), (2201), (2212), (2223), etc allow the same conclusion (Flippen and Subramanian 1990), and in addition suggest that the more the Cu–O layers per unit, the stronger the flux pinning.

Details of how magnetic flux moves in the HTSC materials remain to be worked out, however. The nature of the flux pinning occurring in and between the structural units is not known. The IL in polycrystalline samples is much lower than in single crystals, suggesting that flux motion in the material among single grains is less pinned than in bulk material. Whether flux motion in this region is also thermally activated is not yet known.

5. Conclusions

It has been shown that the TAFF theory provides an explanation for the dynamic magnetic properties of HTSC materials. It is suggested that increased flux-pinning provided by the closer spacing of Cu–O units in $Y_1Ba_2Cu_3O_x$ compared to that of $Bi_2Sr_2Ca_1Cu_2O_y$ and $Tl_2Ba_2Ca_1Cu_2O_y$ accounts for the weaker field dependence of $Y_1Ba_2Cu_3O_x$. This conclusion is supported by measurements on other structures, which further suggest that an increased number of Cu–O layers also increases the flux pinning in these materials.

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