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The frequency and DC magnetic field dependence of the RF penetration depth in the solid and fluid vortex phases of Bi–Pb–Sr–Ca–Cu–O

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Abstract. The frequency and DC magnetic field dependence of the change in the RF penetration depth resulting from vortex-induced dissipation has been measured in Bi–Pb–Sr–Ca–Cu–O above and below the depinning transition. The dissipation is shown to have a linear dependence on $B^{1/2}$ at constant temperature in the solid and fluid vortex phases with a different slope in each phase. The dissipation is observed to be independent of frequency in the pinned regime but decreases with increasing frequency in the fluid state. The magnetic field at which the transition occurs at constant temperature is frequency dependent, decreasing with increasing frequency. The results are in general agreement with theoretical predictions of the magnetic field and frequency dependence of the penetration depth.

1. Introduction

The application of an RF magnetic field and a DC magnetic field perpendicular to the surface of a type II superconductor results in an increase in the surface resistance of the superconductor due to dissipation by the vortex oscillation induced by the $B \times J(t)$ force on the vortices. The dynamical response of the vortices to the RF current will depend on whether the vortex state is liquid or solid and this difference has been observed in a measurement of the DC magnetic field dependence of the surface resistance at 9.2 GHz [1–4]. The functional dependence of the surface resistance on the DC magnetic field changes at the depinning transition allowing a determination to be made of the irreversibility line in the surface regions of the superconductor [1–4].

An alternative method of studying vortex dissipation which has the added advantage of allowing variation of frequency is to measure the DC magnetic field dependence of the RF penetration depth by observing the change in the inductance of a coil containing the sample in the tank circuit of an RF oscillator. This method has not previously been used experimentally to investigate the difference between the frequency and DC magnetic field dependences of the vortex dissipation in the solid and fluid vortex states. However, theoretical analysis does predict that there should be differences, but these have not been experimentally verified to date.

The purpose of this work is to measure the difference between the DC magnetic field and frequency dependences of changes in the penetration depth due to vortex dissipation in the pinned and fluid vortex phases. The dissipation is obtained by measuring the DC magnetic field dependence of the RF penetration depth at a number of different frequencies in the two phases. The results are compared with theoretical predictions for the frequency and DC magnetic field dependence of the penetration depths in the two regimes [5, 6]. The DC field and frequency dependences of the penetration depth are measured using a modification of method developed by Schawlow and Devlin [7] to measure the temperature dependence of the penetration depth in the low-temperature metallic superconductors. The measurements are reported for the superconductor $Bi_{2-x}Pb_xSr_2Ca_{n-1}Cu_nO_{4+2n}$ which has a value of T_c of 113 K. The results represent the first observation of the depinning transition from a measurement of the DC magnetic field dependence of the penetration depth and provide an experimental verification of theoretical predictions of the different DC magnetic field and frequency dependences of the penetration depth in the pinned and fluid vortex phases.

2. Experimental procedure

The frequency dependence of the DC magnetic-field-dependent penetration depth is measured by pressing the sample in a cylindrical quartz tube about which is wound a coil that is part of the LC tank circuit of a marginal RF oscillator capable of oscillation from 2 to 10 MHz. The quartz tube and coil containing the sample are immersed in liquid nitrogen between the poles of an electromagnet such that the DC magnetic field is perpendicular to the axis of the coil and thus perpendicular to the RF $\boldsymbol{B}$ field. When the DC magnetic field is increased with the sample in the superconducting state, the penetration depth of the RF field into the sample increases and the inductance of the coil changes, resulting in a shift in the oscillation frequency given by [7]

$$\Delta f/f_0 = \tfrac{1}{2}\Delta L/L. \tag{1}$$

For the cylindrical coil the change in the penetration depth is related to the change in the frequency by [6]

$$\Delta\lambda = (A/\pi r)\,\Delta f/f_0 \tag{2}$$

where r is the radius of the sample rod and A the cross sectional area between the rod and the coil. The coil used in this experiment had $r = 1.5$ mm and $A = 5.5$ mm^2. The frequency dependence of the RF penetration depth is obtained by measuring $\Delta f/f_0$ versus B for different starting values of f_0. The measurements are made on the granular superconductor Bi–Pb–Sr–Ca–Cu–O which has a value of T_c of 113 K. The material is in the form of fine powder and is pressed into the quartz tube about which the coil is wrapped. The method of synthesis and characterization of the superconducting properties have been described previously [8].

3. Results and analysis

Figure 1 is a plot of the frequency shift from 7.9903 MHz versus DC magnetic field at 77 K in the superconductor Bi–Pb–Sr–Ca–Cu–O. As described above, $\Delta f/f_0$ is proportional to the change in the RF penetration depth. In the region of magnetic field and temperature where the vortices are pinned, the penetration depth is theoretically predicted to depend on the magnetic field as [5]

$$\lambda_c = \left(B\Phi_0/\mu K\right)^{1/2} \tag{3}$$

where K is the pinning force constant, Φ_0 of the quantum of flux and μ the permeability. In the liquid vortex state where the vortices are not pinned the penetration is predicted to depend on field and frequency as [6]

$$\lambda_f = \left(2B\Phi_0/\mu\eta\omega\right)^{1/2} \tag{4}$$

where η is the viscosity and ω the RF frequency. Thus the transition between the flow and pinned regime should be manifested by a change in the slope of the penetration depth versus $B^{1/2}$. Equations (3) and (4) also predict that the frequency dependence of the penetration depth should be different in each phase being independent of frequency in the pinned regime but having a $1/\omega^{1/2}$-dependence in the flow regime. The concern in this work is to verify these predictions experimentally. Figure 2 is a plot of the frequency shift versus $B^{1/2}$ at two frequencies in the MHz range at 77 K in Bi–Pb–Sr–Ca–Cu–O. The data show that the penetration depth depends on $B^{1/2}$ and that there is a change in slope as observed in surface resistance measurements at 9.2 GHz which has been shown to be associated with the transition from the pinned to the depinned phase of the vortices [1–4]. Equations (3) and (4) indicate that the slope of the dependence of the penetration depth on $B^{1/2}$ in the depinned regime should be larger than in the pinned region, contrary to the experimental results shown in figure 2. The reason for this discrepancy is not clear but perhaps is associated with increased misalignment of vortices from the direction of the applied DC magnetic field in the fluid vortex phase. This conclusion is supported by previous work that demonstrates that there is some dissipation even when the RF current is parallel to the DC magnetic field [9].

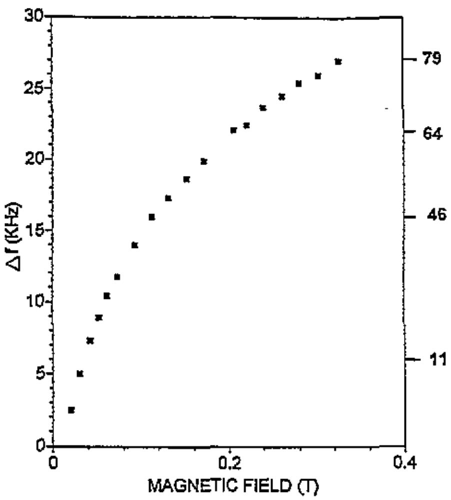

Figure 1. The measured shift of the frequency versus the DC magnetic field at 7.99 MHz in Bi–Pb–Sr–Ca–Cu–O at 77 K.

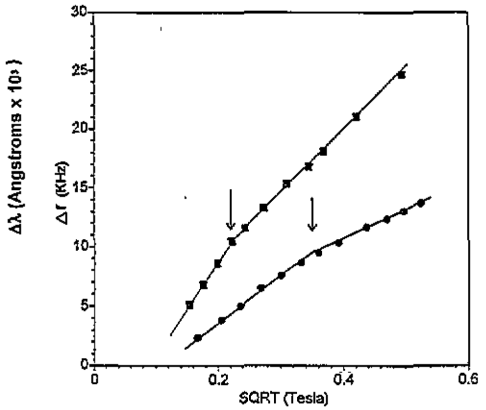

Figure 2. A plot of the frequency shift at 77 K versus the square root of the applied DC magnetic field at 7.990 MHz (■) and 4.342 MHz (●).

The frequency dependence of the DC magnetic-field-dependent penetration depth in the pinned region can be determined by measuring the slope of $\Delta f/f_0$ versus $B^{1/2}$ for different values of f_0 below B^*, the magnetic field at which the depinning transition occurs. The measurement shows the penetration depth to be independent of frequency in agreement with equation (3). However, the same measurement above B^* shows that the penetration depth does decrease as the frequency increases as predicted by equation (4), but the small frequency range of the measurement prevents a definitive confirmation of the $1/\omega^{1/2}$-dependence. Figure 3 is a plot of the slope of $\Delta f/f_0$ versus $B^{1/2}$ above B^*. Another interesting feature of the data in figure 2 is that the DC field B^* at which the slope changes shifts to lower values at higher frequencies. Figure 4 gives a plot of B^*, the field at which the slope of Δf versus $B^{1/2}$ changes, versus frequency. This result is in agreement with theoretical predictions of the frequency dependence of the irreversibility line and experimental measurements of the irreversibility temperature, T_{irr}, in Bi–Sr–Ca–Cu–O at constant DC magnetic field which show that T_{irr} increases with increasing frequency [10, 11]. Since B^* and T_{irr} are related by the equation [12]

$$\left(1 - T_{irr}/T_c\right) = AB^q \tag{5}$$

B^* would be expected to increase with decreasing frequency, as observed.

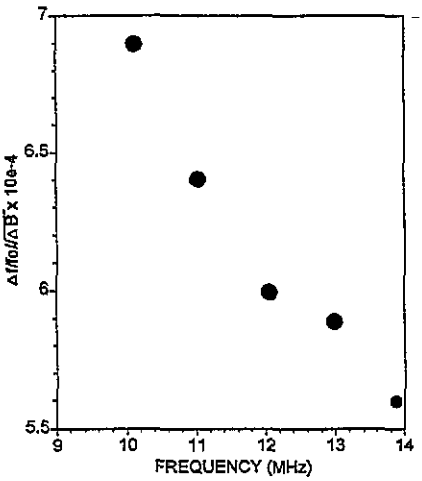

Figure 3. The frequency dependence of the slope of $\Delta f/f_0$ versus $B^{1/2}$ above B^* at 77 K, showing that the penetration depth decreases with increasing frequency in the vortex fluid state.

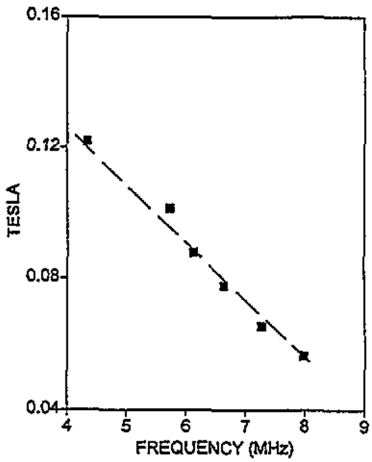

Figure 4. A plot of the frequency dependence of B^*, the DC magnetic field at which the transition from the pinned to the depinned state occurs.

4. Conclusion

The frequency and DC magnetic field dependences of the RF penetration depth have been measured in the superconducting state of Bi–Pb–Sr–Ca–Cu–O. It is shown that the RF penetration depth in Bi–Pb–Sr–Ca–Cu–O superconductor depends linearly on $B^{1/2}$ but has different slopes in the pinned and depinned regimes. The penetration depth is shown to be independent of frequency in the pinned state and decrease with increasing frequency in the depinned state, consistently with theoretical predictions. At constant temperature the DC magnetic field at which the depinning transition occurs increases with decreasing frequency, consistent with theoretical predictions and previous measurements of the effect of frequency on the irreversibility temperature at constant DC magnetic field. These results represent the first experimental verification of theoretical predictions of the difference between the DC magnetic field and frequency dependences of the penetration depth in the pinned and vortex fluid phases.

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