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Josephson Vortex Lattice Melting in $Bi_2Sr_2CaCu_2O_8$

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The Josephson vortex lattice state of the highly anisotropic high-T_c superconductor $Bi_2Sr_2CaCu_2O_8$ has been probed by measurements of the out-of-plane (c-axis) resistivity as a function of temperature, current density, magnetic field strength H, and magnetic field orientation angle θ. Anomalous dissipation is observed below a critical temperature identified as the melting transition of the Josephson vortex lattice. The critical T-H and T-θ phase boundaries are determined. The melting transition is interpreted as a Kosterlitz-Thouless depairing of interlayer vortex/anti-vortex pairs.

Crystals of $Bi_2Sr_2CaCu_2O_8$ (BSCCO-2212) were prepared using a traveling-solvent floating-zone (TSFZ) method described elsewhere[1]. The crystals were cleaved to the desired dimensions, and electrical contacts were made using silver paint, fired at 650°C.

Samples were mounted on a cryostat which allowed *in situ* alignment with the magnetic field with an angular resolution of 0.013°. The cryostat was placed in the bore of a superconducting solenoid, allowing the measurement of the c-axis electrical resistivity of the samples as a function of temperature, current density, magnetic field strength H, and magnetic field orientation angle θ.

Figure 1 shows the c-axis resistivity of a BSCCO-2212 sample in a field of 18 Tesla aligned parallel to the ab-plane for two measuring current densities. The general field-induced broadening below the superconducting transition temperature (T_c) is consistent with previous studies[2]. However, the high and low current data diverge below a temperature T_m, where the low current data show a sharp kink. Electric field as a function of current density (E(J)) curves taken above and below T_m show distinctly different

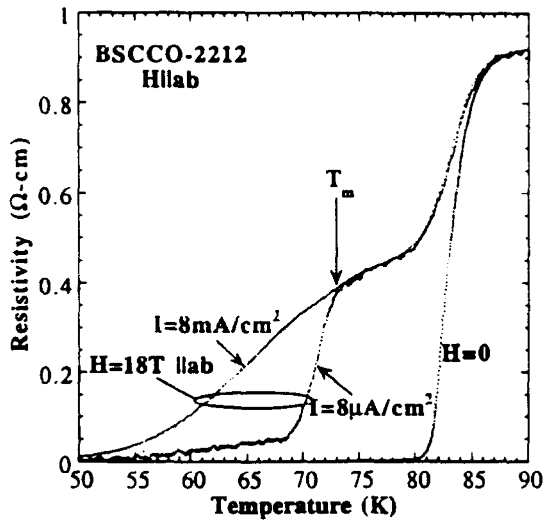

Figure 1. The c-axis resistivity of BSCCO-2212 at 18 Tesla||ab for two different measuring current densities. The zero field data are also shown.

behavior. For $T>T_m$, E(J) is always linear, but for $T<T_m$, E(J) is non-ohmic, displaying a well-defined critical current for the onset of dissipation with $E \sim (J-J_{crit})$ for $J>J_{crit}$ where J_{crit} is the critical current.

The kink in the resistivity seen in Fig. 1 is reminiscent of the kink in both the in-plane

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and c-axis resistivities versus temperature observed in $YBa_2Cu_3O_7$ (YBCO) crystals[3]. It is noteworthy that in YBCO the dissipation kink is clearly observable at a current density of $4 A/cm^2$, while in the configuration described here for BSCCO the kink is only apparent at much lower current densities, on the order of 10^{-4} A/cm^2. In the case of YBCO, the kink corresponds to melting of the Abrikosov vortex lattice or glass, with E(J) characteristics ohmic above and non-ohmic below the melting temperature.

We propose that T_m is the Josephson vortex lattice melting temperature in BSCCO-2212. T_m is therefore expected to have unique functional dependencies on the magnetic field magnitude and orientation which distinguish it from the melting transitions of the conventional (H||c) vortex lattices in BSCCO-2212[4]. We have repeated the measurements in Fig. 1 for different H field strengths and alignments to map out the T-H and T-θ phase boundaries.

Figure 2 shows the critical temperature T_m needed to induce melting as a function of magnetic field angle θ with the ab-plane for a field of 7.5 Tesla. Anisotropic effective mass scaling theory, which predicts quite well the dependence of T_m on θ in YBCO, cannot fit the data for BSCCO (dashed line). T_m falls off too sharply with increasing field misalignment; phenomenologically, $H_m=H_m(\theta=0)-A(H\sin\theta)^2$.

The $H_m(T)$ line also does not follow the expected form for three-dimensional vortex melting. Notably, we find $H_m(T)$ tends to zero at a temperature several Kelvin below T_c.

We propose[6] a model of a coupled Kosterlitz-Thouless and vortex lattice melting transition which can explain the H-θ and H-T phase diagrams. The Josephson vortex lattice is not expected to melt in the limit that the vortices are confined to lie in between superconducting planes[5]. However, segments of Josephson vortex are expected to be

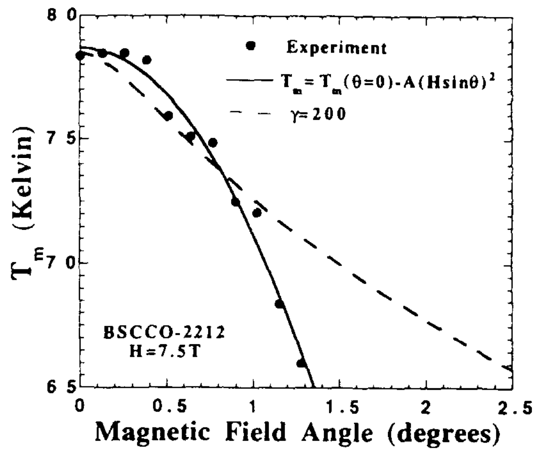

Figure 2. T-θ diagram for BSCCO-2212 with H=7.5 Tesla ||ab-plane.

thermally excited across the superconducting planes at finite temperature via creation of a Kosterlitz-Thouless vortex-antivortex pair. Above the Kosterlitz-Thouless transition temperature this pair is free to separate, and the vortices may cross the planes freely, so the Josephson lattice may melt. Below T_{KT}, melting is forbidden.

T_{KT} should be quickly suppressed with application of a perpendicular magnetic field, as we observe. Also, since T_{KT} in zero field is a few Kelvin below T_c, we expect H_m to tend to zero a few Kelvin below T_c, as observed.

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