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Frequency and temperature dependence of complex conductance of ultrathin $YBa_2Cu_3O_{7-x}$ films: a study of vortex–antivortex pair unbinding

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Abstract

We have studied frequency and temperature dependences of complex sheet conductance of ultrathin (1–3 unit cell (UC) thick) $YBa_2Cu_3O_{7-x}$ films using a radio frequency (1–20, 100–1000 MHz) sheet impedance and a microwave (30 GHz) loss measurements. We found the activated temperature dependence of the vortex diffusion constant and scaling behaviour of the universal ratio $T^{DC}_{KTB}/L_k^{-1}(T_{KTB})$ for 1UC, 2UC and 3UC YBCO films, in close agreement with theoretical prediction for vortex–antivortex unbinding transition.

Keywords: AC susceptibility; Kosterlitz–Thouless–Berezinski transition; Microwave surface impedance; YBaCuO films

Observations of the Kosterlitz–Thouless–Berezinski (KTB) transition in high-T_c superconductors have been reported earlier. However, there are disagreements between theory and experiments possibly due to inhomogeneity, vortex pinning, and in particular, the short effective penetration depth [1]. At high frequency (HF) however, the electromagnetic response of a 2D superconductor is dominated by those bound pairs that have vortex separation length equal to the vortex diffusion length, $l_\omega = (14D/\omega)^{1/2}$ (D is the vortex diffusion constant) [2,3]. Indeed, we found previously [4–6] a change in slope of kinetic inductance $L_k^{-1}(T)$ and maximum of sheet conductance $\sigma_1(T)$ with a large difference of $T_c(\omega)$ measured at 4 MHz and 30 GHz for 1 and 2 UC YBCO thin films. Here we report the scaling behaviour of the universal ratio $T^{DC}_{KTB}/L_k^{-1}(T_{KTB})$ and the frequency dependence of transition temperature as a proof of observation KTB transition.

To observe the bound pair response, we have studied the frequency and temperature dependencies of the complex sheet conductance, $\sigma(\omega,T) = \sigma_1(\omega,T) - i[\omega L_k(\omega,T)]^{-1}$, of 1–3 UC thick YBCO films sandwiched between semiconducting $Pr_{0.6}Y_{0.4}Ba_2Cu_3O_{7-x}$ layers. Experiments have been carried out in a frequency range between: 1–20 MHz with one-spiral coil [4–6], 100 MHz–1 GHz with the cavity formed with a spiral coil of a half of a HF wavelength, and at 30 GHz with resonance cavity techniques, respectively [4–6].

Fig. 1 shows $\omega\sigma_1(T)$ and $L_k^{-1}(T)$ curves converted from a raw data at 8 MHz, the transmition signal $A_t(T)/A_t(80\,K)$ measured at different frequencies between 100 MHz–1 GHz, and high-frequency losses, $\Delta Q^{-1}(T)/Q_0^{-1}(4.2\,K)$, at 30 GHz for a 2 UC film. Qualitatively, the same behavior was observed for 1 and 3 UC samples. The most noticeable features of the data are linear $L_k^{-1}(T)$ dependence at low temperatures with a break in slope close to the onset of transition, the maximum of $\omega\sigma_1(T)$ and HF losses and large shift of the curves to higher temperatures with increasing frequency. The T^{DC}_{KTB} value was identified with the point where $L_k^{-1}(T)$ changes the slope [7]. We obtain the universal ratio $T^{DC}_{KTB}/L_k^{-1}(T_{KTB}) = 13.5$, 14, and 14.5 nH K for 1-, 2- and 3 UC films, respectively, in good agreement with fundamental prediction, 12 nH K [7].

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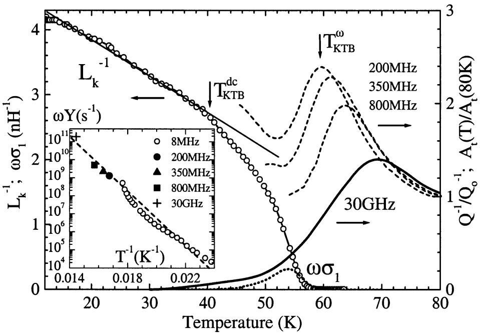

Fig. 1. Temperature dependence of $\omega\sigma_1(T)$ (dotted), $L_k^{-1}(T)$ (full circles) at 8 MHz, transmitted HF signal, $A_t(T)/A_t(80\,K)$, at 200, 350 and 800 MHz (dashed) and a microwave losses, $\Delta Q^{-1}(T)/Q_0^{-1}$ (4.2 K), at 30 GHz (solid line) for 2 UC film. Inset shows ωY versus $1/T$ dependence determined from these data.

According to KTB theory extended to high frequencies [2,3] the electromagnetic response of 2D superconductor has maximum for those bound pairs that have correlation length: $\xi_+(T) = l_\omega$. Therefore, we determined the HF transition temperature T^{ω}_{KTB} above which the bound-vortex picture breaks down, as the point where $Y = (l_\omega/\xi_+)^2 = 1$ [7]. Since $\xi_+(T)$ is slowly temperature dependent above T^{DC}_{KTB}, we found that the $\omega Y = 14D(T)/\xi_+^2(T)$ versus $1/T$ can be fitted with exponential form $\exp[E_0/k_B(T_{co}^{-1} - T^{-1})]$ (see inset in the Fig. 1), due to pinning of vortex core [8]. The pinning energy scales with thickness of the YBCO layer: $E_0/k_B = 1700$ and 3400 K for the 2- and 3 UC samples, respectively. The consistent picture of the frequency dependence of the data and the good scaling behavior of the fundamental ratio $T^{DC}_{KTB}/L_k^{-1}(T_{KTB})$ let us believe that vortex–antivortex interaction is observed with the presence of pinning. Fisher points out theoretically that weak pinning by point defects does not affect the KTB transition [9], but it is not clear for the case of strong pinning.

In summary, we have compared our experimental results on ultrathin YBCO films with the extended dynamic theory for the KTB transition and found that the vortex–antivortex pairs with short separation lengths are present.

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