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Magnetic field, temperature and frequency dependence of complex conductance of ultra thin YBa$_2$Cu$_3$O$_{7-x}$ films

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Abstract. We have studied the magnetic field, temperature and frequency dependencies of the complex sheet conductance, $\sigma(\omega,T)$, of 1-3 unit cell (UC) thick YBa$_2$Cu$_3$O$_{7-x}$ films sandwiched between semiconducting Pr$_{0.6}$Y$_{0.4}$Ba$_2$Cu$_3$O$_{7-x}$ layers. Experiments have been carried out at frequencies between 2 MHz - 1 GHz, with one-spiral coil technique and at 250-500 GHz, by aid of a quasi optical spectrometer based on backward-wave oscillators. We have found a very large shift of the superconducting transition onset temperature and of the maximum Re$\sigma(T)$ position to higher temperatures with increasing $\omega$. The dependence of $H_{c2}(T)$ is exponential close to $T_c$, with a break in a slope at the Berezinski-Kosterlitz-Thouless (BKT) temperature $T_{BK}$, due to the vortex-antivortex pair unbinding, and linear below $T_{BK}$ because the Abrikosov vortex formation. We have compared our experimental results with the extended dynamic theory for the BKT transition and found that the research explored the dynamics of bound vortex-antivortex pairs with short separation lengths.

1. Introduction

Many studies provide evidence supporting two dimensional (2D) XY, i.e., Berezinskii-Kosterlitz-Thouless (BKT) –type ordering [1,2] effects in HTSC single crystals and thin films (see references in [3]). However, quasi two dimensional behavior of YBCO makes these observations questionable [3]. The solution of this problem is study of few unit cell (UC) thick really 2D films [4-6]. However, Repaci et al.[7] have pointed out that a precondition [8] for the BKT transition to occur in a superconductor, i.e. the sample size $L_s < \lambda_{eff}$, where $\lambda_{eff} = 2\lambda^2/d$ is the effective penetration depth and $d$ is the film thickness, is not satisfied in YBCO films as thin as 1-UC thick. It was shown, from the study of dc $I$-$V$ curves that free vortices exist even at low temperatures, indicating the absence of the BKT transition at $dc$. Indeed, low frequency study of conductance of YBCO films [9] have shown some features above $T_c$ attributed to the 3D XY model of statistical mechanics due to a blowout of vortex loops at temperature, where the $c$-axis phase coherence length $\xi_c(T)$ reaches the order of the film thickness $d$.

Minnhagen [10] suggested that although the usual BKT transition is not present when $L_s < \lambda_{eff}$, it is still possible to observe the BKT transition-like response at high frequencies from the bound pairs which have vortex separation length $r < \lambda_{eff}$. According to this theory, the electromagnetic response of a 2D superconductor is dominated by those bound pairs that have $r \sim l_\omega$, where $l_\omega = 14D/\omega^{1/2}$ is the vortex diffusion length and $D$ is the vortex diffusion constant. Using the Bardeen-Stephen formula for free vortices, $D = 2\varepsilon^2\xi_{GL}^2k_B^2T/\pi\hbar^2\sigma_B d$ [10], we estimate that $l_\omega < 1 \mu m$ at 10 MHz, which is much less than $l_\omega \sim 40 \mu m$ for the 1-UC YBCO film. Our preliminary study [3] have shown that it is possible to detect the response of vortex-antivortex pairs with short separation lengths at radio, RF (2MHz-1GHz), and microwave, MW (30 GHz), frequencies in the
In this paper, we report the extension of the frequency and temperature dependences of the complex sheet conductance, $\sigma(\omega, T)$, of 1- to 3-UC thick YBCO films sandwiched between semiconducting Pr$_{0.6}$Y$_{0.4}$Ba$_2$Cu$_3$O$_{7-x}$ layers in a frequency range between 1 MHz to 500 GHz. Here $\sigma(\omega, T) = \sigma_1(\omega, T) - i[\omega L_k(\omega, T)]^{-1}$, where $\sigma_1(\omega, T)$ is the dissipative component of the sheet conductance and $L_k(\omega, T) = \mu_0 \lambda^2/d$ is the sheet kinetic inductance, ($\mu_0$ - the permeability of free space). We observed suppression of the superfluid jump in a small magnetic field, leading the exponential dependence of $H_{c2}(T)$ close to $T_c$, with a break in a slope at the BKT temperature $T_{BKT}$, due to the vortex-antivortex pair unbinding, and linear below $T_{BKT}$ because the Abrikosov vortex formation at $T<T_{BKT}$. Vortex pinning with thermally activated vortex diffusion constant was found in the samples, while it did not destroy the vortex-antivortex pairs with short separation lengths.

2. Experimental Setup

A multi target pulsed-laser ablation system with a computer controlled laser triggering and target exchange system was used for deposition of epitaxial ultrathin YBa$_2$Cu$_3$O$_{7-x}$ films sandwiched between 100 Å buffer and 50 Å cover layers of Pr$_{0.6}$Y$_{0.4}$Ba$_2$Cu$_3$O$_{7-x}$ on atomically flat and well-lattice-matched (100) LaAlO$_3$ substrates. Detailed information about the preparation and superconducting properties of the film structures can be found elsewhere (see references in [3]).

The $\lambda(\omega, T)$ at radio-frequency, RF, in thin films was investigated employing a single coil self inductance technique. This technique [3] has the advantages of the well known two-coil geometry and was extensively used for the study of the $\lambda(T)$ dependence for YBCO and MgB$_2$ films [3]. In this RF (2 MHz – 50 MHz) technique (Fig.1a), the change of inductance $L$ of a one-layer pancake coil located in the proximity of the film and connected in parallel with a capacitor $C$ is measured. At larger frequencies (100 MHz – 1 GHz) we used improved version of this technique using the cavity formed with a similar spiral coil with no capacity in parallel (Fig.1b). The coil form the radio frequency resonator coupled to a two coupling loops and is driven by the radio - frequency signal generator/receiver. The film is placed at small distance (~0.1 mm) below the coil and is thermally insulated from the coil by Teflon foil. During the experiment the coil was kept at 4.2 K, whereas the sample temperature was varied from 10 K to 100 K. Such design allows us to eliminate possible effects in temperature changes in $L$ and $C$ on the measurements.

A change in the real, Re$M(T)$, and imaginary, Im$M(T)$, parts of $M(T)$ were detected as a change of resonant frequency $\omega(T)$ of the oscillating signal and impedance $Z(T)$ of the LC circuit, and converted into $L_0(T)$ and $Re\omega(T)$ with inversion mathematical procedure based on the same approach as in the two-coil mutual inductance methods. A detailed description of the analysis of the data and the evaluation of the Re$M(T)$ and Im$M(T)$ as well as the high frequency conductivity, has been given elsewhere. [3]

The measurements in the THz frequency range are performed using a coherent source interferometer in the spectral range between 200 GHz and 500 GHz in order to investigate the amplitude of the transmission through the film (see Fig.1c). The backward wave oscillator was employed as monochromatic and continuously tunable source. The arrangement of a Mach-Zehnder interferometer allows for measuring both the intensity and the frequency of the radiation transmitted through the sample, i.e., the YBCO film on the LaAlO$_3$ substrate. The evaluation of the THz conductivity of the YBCO film uses the general Fresnel formulas for a two-layer system i.e., the film on the substrate by analysis of the transmission spectra. A detailed description of the
3. Results and discussion

Figure 2 shows the $L_k^{-1}(T)$ curves in very low perpendicular magnetic fields, and zero field $\text{Re} \sigma(T)$ for the 1-UC and 2-UC films. We found that $L_k^{-1}(T)$ fit well over a wide temperature range by a parabolic dependence [3]: $L_k^{-1}(T) = L_k^{-1}(0)[1-(T/T_{c0})^2]$, shown as thin solid lines. We emphasize that this quadratics equation fit the data below characteristic temperature which we define as $T_{dc}^{BKT}$, and which is below the positions of the peaks in $\text{Re} \sigma(T)$, which we define as $T_{\omega}^{BKT}$. The mean field transition temperature, $T_{c0}$, determined by extrapolation of $L_k^{-1}(T)$ to 0, is larger than the onset of transitions of $L_k^{-1}(T)$. Also, the $L_k^{-1}(0)$ fitted data are the same for $H=0$ and 5 mT while have different $T_{c0}$. We plot theoretical BKT function $L_k^{-1}(T)$ as dashed straight line on Fig. 2, derived from the universal relationship: $K_R=d\hbar^2c^2/16\pi\lambda^2e^2k_BT_{BKT}=2/\pi$ predicted by theory [10]. It is obvious that the critical temperatures $T_{dc}^{BKT}$ determined from the intercept of dashed theoretical line with experimental $L_k^{-1}(T)$ is lower then the peak position of $\sigma_1(T)$. We determined the $T_{\omega}^{BKT}$ as the peak position of $\sigma_1(T)$ point.

**Fig.2.** (Color online) Temperature dependence of $L_k^{-1}(T)$ for 1-, 2- and 3-UC films at 8 MHz in perpendicular magnetic fields: 0 mT (circles), 2 mT (squares), 3 mT (triangles) and 4 mT (crosses). The solid lines curves shows $\text{Re} \sigma(T)$ at zero field. The thin solid lines are quadratic fits to $L_k^{-1}(T)$ below $T_{dc}^{BKT}$ and for magnetic field data. Also shown is the theoretical BKT $L_k^{-1}(T)$ function (dashed line).

**Fig.3.** (Color online) The penetration depth $\lambda^2(T)$ derived from $L_k(T)=\mu_0\lambda^2/d$ vs normalized temperature $T/T_{\omega}^{BKT}$ for: 1UC (crosses), 2UC (squares) and 3 UC (circles) films.

To see whether this description is correct, we plot in the Fig.3 the dependence of the magnetic penetration depth $\lambda^2(T)$ derived from $L_k^{-1}(T)$, versus scaling variable - normalized temperature $T/T_{\omega}^{BKT}$. It is clear, that all data for three studied films at 8 MHz fall on the same curve, which proof of our definition of $T_{\omega}^{BKT}$ as the peak position of $\sigma_1(T)$.

In Figure 4, we plot $\text{Re} \sigma(T)$ at 8 MHz, $\Delta Q^{-1}(T)/Q_0^{-1}(4.2K)$ determined from MW data (30 GHz) [3] and THz conductivity for 3-UC sample. The $dc$ resistive transition of the same sample is also shown in the figure. As we can see, the $T_{\omega}^{BKT}$ value largely increases as the frequency raise from 8 to 30 GHz and slightly increases at THz range. Even larger shift of $T_{\omega}^{BKT}$ was observed in 1-UC film and no shift was detected in a 2000 Å thick YBCO film.

**Fig.4.** (Color online) Temperature dependence of $dc \rho(T)$ (circles), $\text{Re} \sigma(T)$ at 8 MHz (red curve), $\Delta Q^{-1}(T)/Q_0^{-1}(4.2K)$ at 30 GHz (blue line) and THz conductivity as well for a 3-UC film.
The qualitative explanation of the frequency dependence of $T_{\text{BKT}}(\omega)$ and a peak in $\sigma_1(T)$ is based on bound vortex-antivortex pairs scenario.[3] The observed high frequency response is dominated by those pairs with $r \sim l_{\omega} \sim \omega^{-1/2}$. At temperatures below $T^{*}_{\text{BKT}}$, the dissipation is proportional to the number of vortex-antivortex pairs. This number grows gradually with temperature up to $T_{\omega}^{\text{BKT}}$. At the higher temperature side, $\sigma_1$ decreases with increasing temperature since $\sigma_1 \sim 1/(n_{f} \mu)$, where $n_{f}$ is the density of free vortices and $\mu$ is the vortex mobility. Dissipation is largest when the correlation length $\xi(T)$, i.e. the average distance between thermally induced free vortices above $T_{\alpha}^{\text{BKT}}$, becomes equal to $l_{\omega}(T)$ which determines the BKT transition temperature $T^{*}_{\text{BKT}}$ at a given frequency. However, we found rather small increase of the maximum position of $\text{Re} \sigma(\omega)$ at THz range which makes this scenario questionable at THz frequencies.

Now we turn to the discussion the magnetic field behavior of those films. Figure 5 shows the temperature dependence of $H_{c2}(T)$ of 1 UC thick YBCO film at different magnetic field perpendicular to the sample plane. It is clear that $H_{c2}(T)$ is rather peculiar. From first glance it seems that there are two $T_c$, but actually this behavior is due to destroy of BKT transition by small magnetic field. This is clear from the log$H_{c2}$ vs $T$ plot shown on the right side of this figure. We can see the break in slope of $H_{c2}(T)$ at almost the same temperature as a break on $L_{\omega}^{-1}(T)$ (Fig.3) proven the determination of $T^{*}_{\text{BKT}}$. Recently it was observed that the critical behavior of magnetization for 2D superconducting layers in a perpendicular magnetic field near the BKT transition is rather complex. [12]. Here we restrict our self from additional comments and the full analysis of $H_{c2}(T)$ dependence will be published elsewhere.

In conclusion, we report several results of high frequency conductivity of ultra thin YBCO films which are in qualitative agreement to the prediction of the dynamic theory of vortex-antivortex pairs with short separation lengths. The unbinding of the vortex pairs were observable at high frequencies even though a true BKT transition is absent in the samples.

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