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Electric field effect on epitaxial $YBa_2Cu_3O_{7-x}$ thin films

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By applying a strong electric field perpendicular to the surface of an ultrathin, highly uniform epitaxial $YBa_2Cu_3O_{7-x}$ film, the critical current was depressed and enhanced over 20 % at temperatures close to T_c, and 5% at lower temperatures. Careful analysis of the electric field dependent I-V characteristics and Arrhenius plots indicate that the electric field effect can be interpreted as a change in the pinning potential and/or the vortex-antivortex interaction potential in the Kosterlitz-Thouless regime, as a result of a change in the carrier density in the superconductor.

1. INTRODUCTION

Although several groups already reported on electric field effects in thin layers of $YBa_2Cu_3O_{7-x}$ (YBCO) [1-3], not much consensus has been reached about the physical mechanism causing the observed effects. The electric field effect is much more pronounced in YBCO-films which contain many weak-links [4]. Consequently, the presence of grainboundaries due to island-like growth, screw dislocations or stress effects, can easily mask the real electric field effect.

The fabrication of our PBCO/YBCO/$SrTiO_3$/Au multilayers and device structures has been described previously [3]. Laser scanning microscopy [5] and both high and low magnification TEM showed excellent uniformity in thickness and current distribution over the complete device area of typically 100x50 μm^2. In addition, HRTEM showed good epitaxial growth of all layers.

From these observations we conclude that our measurements may be interpreted as electric field effects on epitaxial thin films, rather than on weak links.

2. MEASUREMENTS AND DISCUSSION

The discussion below is based on the measurements on a sample consisting of 10 nm PBCO, 5 nm YBCO and 100 nm $SrTiO_3$. T_c^0 was 40 K and J_c at 6 K was as high as 10^6 A/cm^2. Figure 1 shows a typical set of I-V characteristics at different gate voltages. By applying +6V and -2V to the gate electrode, I_c was depressed and enhanced by -5 % and +1.8 % at low temperatures, and -36 % and +16 % close to T_c. The change in the carrier density was -2 % and +0.7%, as concluded from capacitance measurements.

At low temperatures most vortices in the sample are generated by the magnetic self-field from the transport current. At large bias currents, where the behaviour is certainly flux-flow like, the change in the I-V curves is merely a parallel shift along the current axis, i.e. the main change is caused by a change in I_c. At somewhat higher temperatures thermally activated vortex motion becomes more important. Now, the I-V curves are no longer parallel, but diverge over a large voltage range. This agrees with Mannhart's interpretation

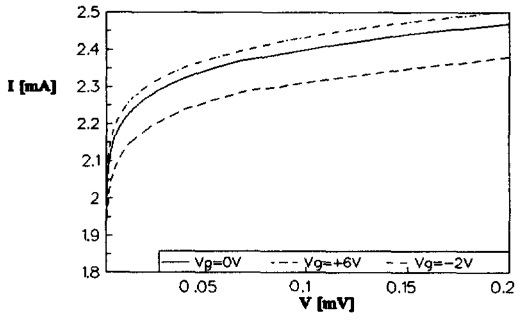

figure 1. Electric field dependent I-V curves, 6 K

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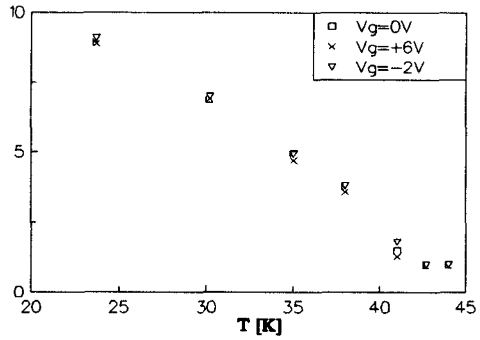

Figure 2. Temperature dependence of the K-T exponent α at different gate voltages.

of an electric field controlled vortex pinning potential [1]. At high temperatures vortices can also be generated by thermal fluctuations. In two dimensional systems, like ultrathin films, these vortices appear as vortex-antivortex pairs, as described in the Kosterlitz-Thouless (K-T) model [6]. Above 30 K, our I-V characteristics obey a power-law, $V \propto I^{\alpha}$, consistent with the K-T model. α(T) shows the expected linear behaviour and a jump from α ~ 3 to α ~ 1 is observed around 40 K (figure 2). According to K-T theory, the interaction potential of a thermally nucleated vortex-antivortex pair depends linearly on the (two dimensional) density of superconducting carriers: $A(n_s) = \frac{1}{8}h^2 n_s/\pi m$, where m is the electronic mass. Therefore it is expected that the current needed to unbind a vortex-antivortex pair changes with changing carrier density. The I-V curves will then show a change in I_c as well as in the thermally activated part, as we measured. We also observed an electric field effect on the exponent α, which stems from a change in the interaction potential as well. Walkenhorst et al. reported the possibility of tuning the K-T transition temperature T_{KT} by the electric field [7]. From our measurements it is not clear if such a dependence also occurs in our samples.

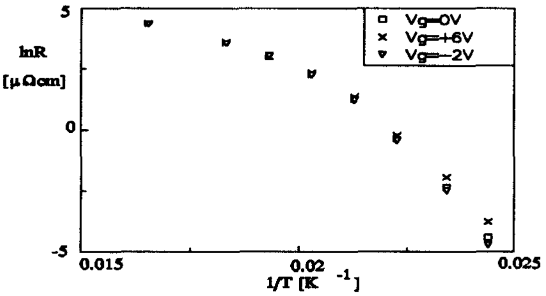

Figure 3. Arrhenius plot (lnR vs. 1/T) at different gate voltages.

Above T_c the resistance is ohmic. When measured at not too low currents, most vortex pairs will be unbound, and free vortices remain. From gate-voltage dependent Arrhenius plots (figure 3) it is clear that the electric field effect is maximal in the region where thermally activated vortex motion forms the dominant contribution to the resistivity. This, and the different slope of the Arrhenius plots at different gate voltages again indicates that also the pinning potential is influenced by the electric field.

3. CONCLUSIONS

Electric field effect measurements on highly epitaxial and uniform ultrathin YBCO-films have been interpreted by analyzing the electric field dependent I-V characteristics at different temperatures. At temperatures above T/T_c ~ 0.6 most vortices in the sample are vortex-antivortex pairs whose interaction energy can be modulated by the electric field. At low temperatures and above T_c most vortices appear as single vortices. In this regime, the electric field effect is interpreted as a change in the vortex pinning potential as a result of a change in the carrier density.

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