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Transport Properties of $YBa_2Cu_3O_{7-x}/CaMoO_3$ Multilayers in a Magnetic Field*

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The transport properties of superconducting $YBa_2Cu_3O_{7-x}/CaMoO_3$ (YBCO/CMO) multilayers in the mixed-state were measured to study the effects of magnetic field, flux pinning and current density on the behaviors of Hall coefficient. The superconducting critical temperature was reduced due to the presence of CMO layers. The longitudinal resistivities under a magnetic field parallel to the c-axis shows a thermally activated behavior and pinning energy decreases with an increasing magnetic fields or currents applied. The pinning abilities are also affected by the thickness of YBCO or CMO layers. The negative Hall coefficient in the mixed-state depends on the flux pinning and decreases as the pinning force decreases. The results are consistent with the Wang and Ting's model [10].

PACS. 74.60.Ge – Flux pinning, flux creep, and flux-line lattice dynamics.

I. Introduction

Since $YBa_2Cu_3O_{7-x}/DyBa_2Cu_3O_{7-x}$ superlattices were successfully deposited on $SrTiO_3$ or MgO substrate by J. M. Triscone in 1989 [1], the transport properties of superlattices has been studied widely. One of the interesting case is the $YBa_2Cu_3O_{7-x}/PrBa_2Cu_3O_{7-x}$ (YBCO/PBCO) superlattice which has been reported largely in the physical periodicals [2,3,4]. It is known that the critical temperature is affected by the thickness of YBCO layers or PBCO layers, and the external magnetic field will change the activation energy based on the thermally activated flux flow(TAFF) model [5]. Most interesting of all, the sign reversal of Hall coefficients within the mixed-state is assumed to be related to the pinning ability which is affected by the thickness of YBCO layers and PBCO layers [4]. However, the mechanism of this phenomena is not quite clear yet.

$CaMoO_3$ (CMO) is a kind of perovskite-type semi-conducting oxide [6]. It's a monoclinic structure with lattice constant a = c = 7.8 A, b = 7.77 Å and β = 91.4" [7]. The lattice constant is about twice as large as that of YBCO (a = 3.84 A, b = 3.88 A, and c = 11.68 Å), so CMO is possibly deposited onto YBCO film epitaxially. In this work, the transport properties of the YBCO/CMO multilayers were studied and compared with that of the YBCO/PBCO superlattices to give a clue to the theoretical understanding of the transport properties in the high-T, superconducting superlattices or multilayers.

II. Experimental

The YBCO/CMO multilayers were in situ grown on the $SrTiO_3$ substrates by a rf magnetron sputtering system. Both the sputtering guns and shutters were controlled by a computer system. The YBCO layers and CMO layers were grown alternatively and deposited until a desired thickness. With a total thickness of about 1200 Å of YBCO layers, different YBCO-layer numbers of YBCO/CMO multilayers were grown. A series of the YBCO/CMO multilayers with a fixed thickness of 40 Å of CMO layers were studied. The YBCO/CMO multilayers were first characterized by the x-ray diffraction. In the $\theta-2\theta$ x-ray scans for the samples on $SrTiO_3$ only the (OOL) (L = **1 $\sim$ 7)** diffraction peaks were observed, indicating a strong c-axis orientation. However there was a pity that the satellite peaks were not observed in the x-ray diffraction patterns. Thus the YBCO/CMO samples were constructed as multilayers rather than superlattices. Nevertheless, the transport properties of these multilayers were measured and discussed.

For the resistivity and Hall measurements, the YBCO/CMO multilayers were photolithographically patterned to a 600 μm long and 50 μm wide line bridge with five terminals gold was plated. Two of these terminals were linked by wire to the current source, while the other three terminals were used as leads of the resistive and Hall signals. The current density in the measurements was about $10^4 \sim 10^5$ A/cm^2. The experimental data were taken in the temperature range of 5 $\sim$ 300 K and in applied magnetic fields up to 5 T.

III. Results and discussions

III-l. The critical temperature

The critical temperature of the YBCO/CMO multilayers is affected by the YBCO layer thickness. As shown in Fig. 1, with a fixed CMO-layer thickness of 40 Å, that is, 5 unit cells, and an increased YBCO-layer thickness from 20 Å to 400 A, the critical temperature increases as the YBCO layer thickness of the multilayers increases. This result is similar to other multilayers or superlattices presented before [3].

III-P. Anisotropic resistivity and activation energy

Fig. 2 shows the resistive transition for the YBCO/CMO (60 Å x 20/40 Å **x 19) multilayers in** magnetic fields of 0 $\sim$ 5 T which were applied parallel to the c-axis (Fig. 2(a)), and perpendicular to the c-axis (Fig. 2(b)). The broadening of the resistive transition in a magnetic field parallel to the c-axis is larger than that in a magnetic field perpendicular to the-c-axis. Based on the Anderson-Kim model [8], the activation energy U can be deduced by the temperature dependence of resistivity which has a thermally activated flux flow behavior:

$$P = \rho_0 e^{-U/kT}.$$

It is known that the flux lines penetrate through the YBCO layer vertically and are pinned by the extrinsic pinning sites as the applied magnetic field is parallel to the c-axis. Otherwise, when the applied magnetic field is perpendicular to the c-axis, the flux lines are pinned by the intrinsic pinning sites. Fig. 3 shows that the intrinsic pinning force is larger than the extrinsic pinning force according to the larger activation energy when the

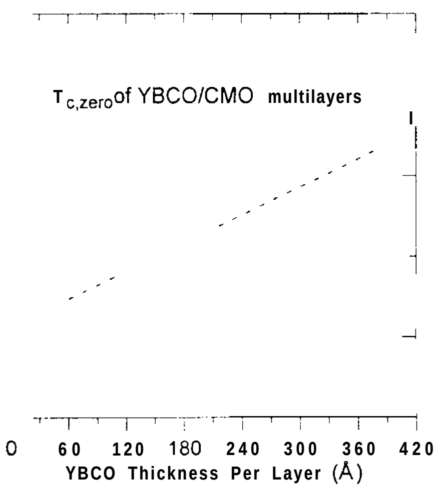

FIG. 1. The critical temperature vs the YBCO layer thickness for YBCO/CMO multilayers with CMO layer thickness of 40 Å.

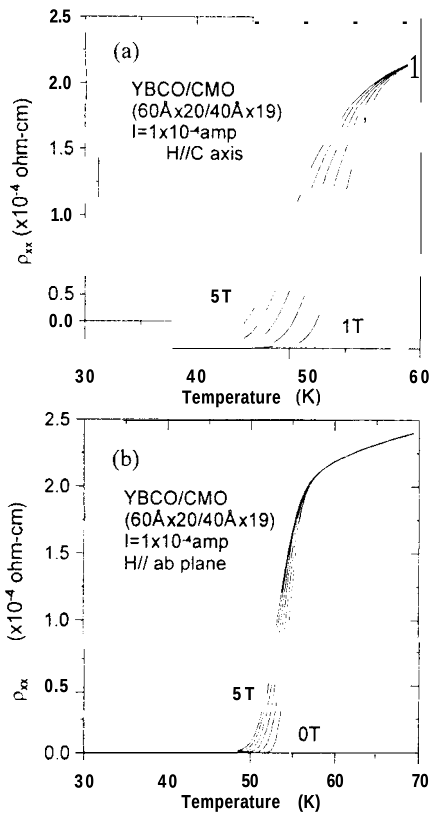

FIG. 2. Resistive transition for YBCO/CMO (60 Å x 20/40 Å x 19) multilayer in magnetic fields parallel to (a) the c-axis and (b) the a-b plane. The increment of the field is 1 T in each curve.

applied magnetic field is perpendicular to the c-axis in YBCO/CMO (60 Å x 20/40 Å x 19) multilayers. The results are similar to those of other kinds of multilayers and demonstrate the anisotropy of the transition properties in the multilayers.

The activation energy is also related to the magnetic field and currents. Fig. 4 shows the magnetic field dependence of activation energy with various currents applied to a YBCO/CMO (240 Å x 5/40 Å x 4) multilayer. The activation energy decreased as the magnetic field is increased. The data can be represented by the equation which has been presented by other group [9]:

$$U = a \log H + b,$$

where a and b are constants.

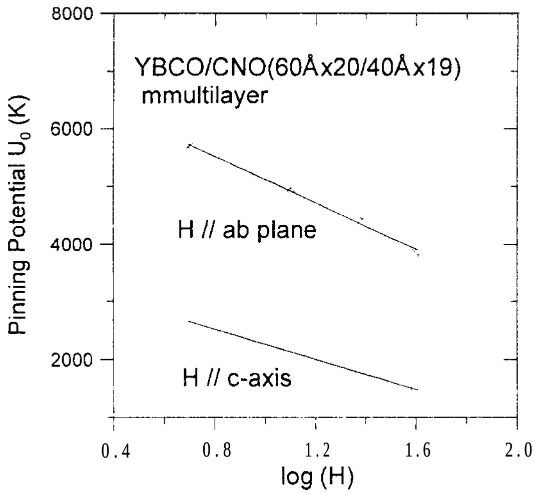

FIG. 3. Activation energy as a function of magnetic field for YBCO/CMO(60 Å×20/40Å x 19) multilayers under magnetic fields parallel to the c-axis and the ab plane.

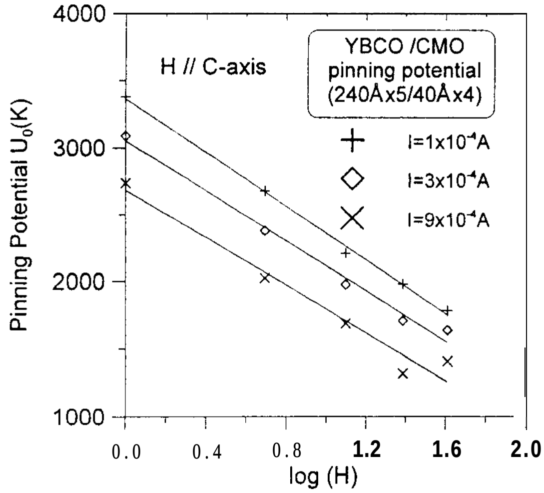

FIG. 4. Activation energy as a function of magnetic field for a YBCO / CMO(240 Å x 5/40 Å × 4) multi-layer.

Fig. 4 also shows that when the current is increased, the activation energy decreased. The activation energy affected by the magnetic field and current can be understood by the thermally activated flux flow behavior on the flux lines which can be represented as F = **J x** B, where J is the current density and B is the magnetic field. The increasing magnetic fields or the currents will increase the Lorentz force and therefore the activation energy decreases.

Fig. 5 shows the activation energy in different YBCO/CMO multilayers. Out of our prediction, the activation energy did not increase with the increasing YBCO layer thickness. For YBCO/CMO (60 Å x 20/40Å x 19) and (120 Å x 10/40Å x 9) mltilayers, the activation energy decreases as the YBCO-layer thickness increases. For YBCO/CMO (240 Å x 5/40Å x 4) multilayer, the activation energy increases again. To explain this, we proposed that there were two factors that affect the activation energy: the YBCO layer thickness and the number of YBCO layers. For the first two multilayers, the YBCO/CMO(60Å x 20/40 Å x 19) multilayer had 20 layers of YBCO, so its activation energy is larger than that of the YBCO/CMO(120Å x 10/40Å x 9) multilayer which has only 10 YBCO layers. In the YBCO/CMO(240Å x 5/40Å x 4) multilayer, the activation energy becomes larger as the YBCO-layer thickness increases. Whether this view point is true or not should be examined by more experiments.

111-3. **The Hall coefficient**

Fig. 6 shows the temperature dependence of Hall coefficient R_H of the YBCO/CMO (240 Å x 5/40Å x 4) multilayer in different magnetic fields. The sign reversal can be

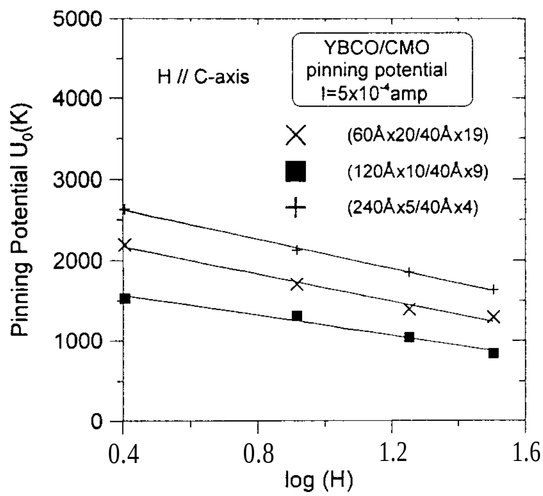

FIG. 5. Activation energy as a function of magnetic field for YBCO/CMO(240 Å x 5/40 Å x 4), (60 Å x 20/40 Å x 19) and (120 Å x 10/40 Å x 9) multilayers.

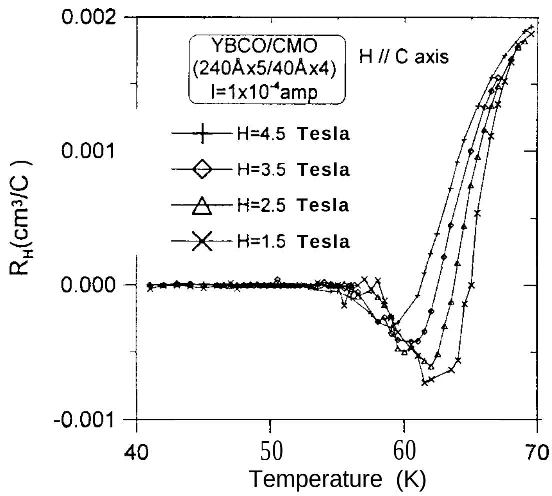

FIG. 6. Temperature dependence of the Hall coefficient for the YBCO/CMO(240 A x 5/40 A x 4) multilayer in various magnetic fields.

observed as shown in the plots. For the YBCO/CMO multilayers, the maximum negative Hall coefficient depends on the magnetic field. It can be seen that the maximum negative Hall coefficient is smaller as the applied field becomes larger. This result is similar to the observations on other kinds of multilayers.

Fig. 7 shows the negative Hall coefficient of YBCO/CMO(240 Å x 5/40 Å x 4) multilayer diminishes by applying a larger current. The observation coincides with the Wang and Ting's [10] model which predicts a diminishing negative Hall coefficient with a lower pinning energy owing to a larger current applied. Otherwise, by applying a fixed magnetic field and a fixed current, the maximum negative Hall coefficient of YBCO/CMO(240 Å x 5/40 Å x 4) is the largest while that of YBCO/CMO(120 Å x 10/40 Å x 9) is the smallest as shown in Fig. 8. It is consistent with the magnitude of the activation energy as shown in Fig. 5. It demonstrates that that the maximum negative Hall coefficient becomes larger as the pinning energy increases.

IV. Conclusions

YBCO/CMO multilayers have been grown by a rf sputtering configuration and their transport prpperties in various magnetic fields were measured. The critical temperature of YBCO/CMO multilayers was affected by the YBCO layer thickness. With thicker YBCO layers, the T_c of multilayers increased and was always smaller than that of YBCO films. The R-T curves of the YBCO/CMO multilayers showed anisotropic resistivity and thermally activated flux flow behavior. The activation energy for an applied magnetic field perpendicular to c-axis is larger than that for an applied magnetic field parallel to c-axis.

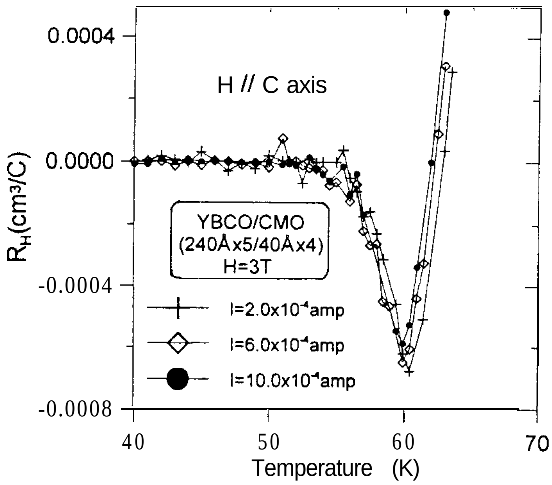

FIG. 7. Temperature dependence of the Hall coefficient for the YBCO/CMO(24O Å x 5/40 Å x 4) multilayer in various currents applied.

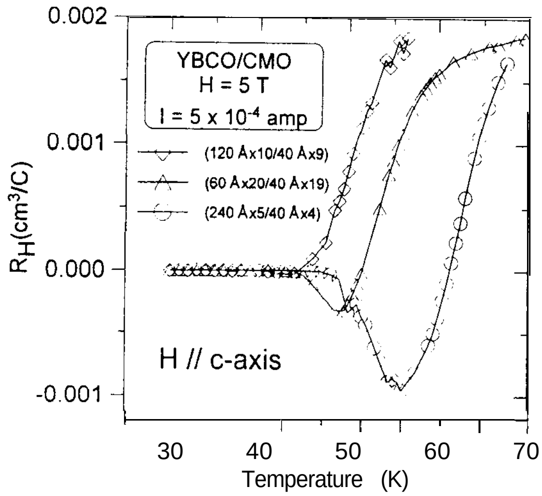

FIG. 8. Temperature dependence of the Hall coefficient for YBCO/CMO (240 Å x 5/40 Å x 4), (60 Å x 20/40 Å x 19) and (120 Å x 10/40 Å x 9) multilayers in magnetic field of 5 T.

It implies the intrinsic pinning force is larger than the extrinsic pinning force. Besides, the activation energy was affected by the applied magnetic field and current. When the magnetic field or the current becomes smaller, the activation energy increases. The activation energy as a function of the magnetic field could been described by the equation: $U = a\log H + b$.

The strange sign reversal of Hall coefficient was observed in YBCO/CMO multilayers. The maximum negative Hall coefficient depends on the applied magnetic field, current and the pinning abilities of the multilayer. The negative Hall coefficient decreases under a larger applied magnetic field or current, which reduces the flux-pinning forces. Those results were consistent with the predictions of the Wang and Ting's model [10].

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