Journal of Alloys and Compounds, 195 (1993) 191–194
JALCOM 7445

Effect of Dimensional Crossover on Magnetoresistance of $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ Superlattices

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Abstract

We have studied magnetoresistance of the $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (YBCO/PrBCO) superlattices with different thickness of the separator layer (YBCO/PrBCO = 1:1, 1:3 and 1:5) in fields up to 12T at $T < T_c$. An excellent fitting by the Larkin two-dimensional superconducting fluctuation theory with only two scaling parameters (A(T) and $H_\Phi(T)$) for each R(T) curve shows that it is possible to apply this approach to interpret our magnetoresistance data. The resistive transition broadening in a magnetic field can be related to giant conductivity fluctuations in the quasi two- dimensional double CuO_2 superconducting layers in YBCO. The magnetoresistance increases with further separation of YBCO in the superlattices with a larger thickness of the PrBCO separator layers. For YBCO/PBCO=1:3 and 1:5 superlattices, the first scaling parameter A(T) determined by the fluctuation amplitude follows quite well the Larkin $\beta(T)$ function typical for 2D systems. For YBCO/PrBCO=1:1, the YBCO layers are not completely decoupled and A(T) deviates from $\beta(T)$. The temperature dependence of the second scaling parameter $H_\Phi(T)$, the phase coherence breaking field, is consistent with the theoretical prediction by Reizer for the quasi-two-dimensional electron-electron interactions.

1. Introduction

One of the peculiar features of high T_c superconductors is the broadening of the resistive transition R(T) in a magnetic field H. This broadening is often interpreted in the framework of the flux motion [1]. However, the observation of the Lorentz-force-independent behaviour in high T_c oxides [2] casts doubts on the explanations based on the flux motion and rises the possibility of the relevance of strong superconducting order parameter fluctuations. Several studies [3, 4] along this line have emphasized the importance of fluctuations. Recently, it has been reported that the magnetoresistance of the $Bi_2Sr_2CaCu_2O_8$ c-axis-oriented thin film [5] and single crystals [6] shows a scaling behaviour corresponding to Larkin 2D fluctuation theory [7], implying the validity of the giant 2D superconducting fluctuations theory.

Modern technology makes it possible to grow high quality high T_c multilayers, such as YBCO/PrBCO. Inserting nonsuperconducting PrBCO layers between YBCO layers and varying the PrBCO layers thickness result in a modification of the coupling strength between the CuO_2 bilayers which are responsible for superconductivity in the YBCO. Thus, in the YBCO/PrBCO multilayers we can modify in a controlled way the anisotropy of the YBCO/ PrBCO superlattices which may be used to study the magnetoresistance and the dissipation processes for different coupling strengths between the CuO_2 planes. In this paper we report a systematic study of the magnetoresistance R(H,T) in the YBCO/PrBCO superlattices. The scaling results of R(H,T) clearly show that the Larkin 2D fluctuation expression [7] can successfully describe our experimental R(H,T) data over a broad temperature and magnetic field range. In the YBCO/PrBCO superlattices with the progressively growing separation between the CuO_2 bilayers (1:1, 1:3 and 1:5) the temperature variations of the two fitting parameters (A(T) and $H_\Phi(T)$) also follow the theoretical dependences obtained by Larkin [7] and Reizer [8] for 2D superconducting sheets.

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2. Sample preparation

The YBCO/PrBCO superlattices used in this study were prepared by sequential dc sputtering from stoichiometric YBCO and PrBCO targets onto heated $SrTiO_3$ substrates ($T \approx 800$ °C). This pro-

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cess yields high-quality c-axis-oriented epitaxial $(YBCO_n/PrBCO_m)_l$ superlattice films [10]. The subscripts n and m correspond to the numbers of unit cells of the individual layers of YBCO and PrBCO, respectively, and l is the number of repetitions of the $YBCO_n/PrBCO_m$ supercell. Details of the preparation method and structural examination of the samples are described in Ref.[10]. All the patterned samples have the same width and the same distance between potential probes. The magnetoresistance measurements are performed at fixed temperatures with slowly varying magnetic fields. The magnetic field is always applied perpendicular to the ab plane of the superlattice films.

3. Experimental results and discussion

Fig.1 shows the magnetoresistance R(H,T) of the $(YBCO_1/PrBCO_3)_{60}$ superlattice, with $T_c(H=0) \simeq 63K$, measured at temperatures $T < T_c$. In the resistance region where R(H) is much smaller than the normal state resistance R_n, the magnetoresistance R(H) increases slowly with field in accordance with the predicted mechanism of thermally activated flux creep [1]; in higher fields the resistance R(H) varies logarithmically with field, clearly deviating from the linearity $R(H) \propto H$, expected from the flux flow model by Bardeen and Stephen [9]. The magnetoresistance is increasing as the temperature is rising up. The linear R vs logH behaviour is valid in a wide magnetic field range (Fig.1). In order to analyze these R(H,T) data, we

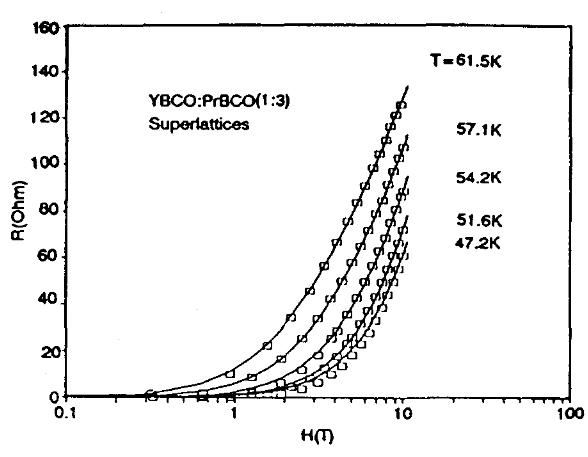

Fig. 1. The field dependence of the resistance, R(H), measured at different temperatures $T < T_c$ for Y:Pr=1:3. Open squares are experimental data and solid lines are theoretical curves (Eq.1).

use the expression for the magnetoresistance of quasi 2D systems [7]. This model takes into account the superconducting fluctuation contribution of the Maki-Thompson type with the strong influence of the magnetic field on the electron-electron interaction. The main result of Larkin's theory can be expressed as follows :

$$\Delta R = R(H) - R(H=0) = A(T) f_2(H/H_\Phi) \quad (1)$$

$$f_2(\frac{H}{H_\Phi}) = \Psi(\frac{1}{2} + \frac{H_\Phi}{H}) + ln(\frac{H}{H_\Phi}) \quad (2)$$

where Ψ is the digamma function, A(T) is the amplitude of the fluctuation contribution and H_Φ is the phase-coherence-breaking field. The latter is given by the phase coherence breaking time $\tau_\Phi(T)= \hbar c/4eDH_\Phi$, where D is the diffusion constant. In order to compare Eq. 1 with the experimental data, the values of A(T) and H_Φ are used as fitting parameters. The amplitude A(T) is given by [7]:

$$A(T) = \frac{e^2/2}{\pi^2 \hbar} R_L^2 \beta(T/T_c^*) = A_o \beta(T/T_c^*) \quad (3)$$

where R_L and T_c^* are, respectively, the fluctuating sheet resistance and the critical temperature of a quasi 2D superconducting layer, which corresponds to the CuO_2 double layer in high T_c compounds [5]. The temperature dependent parameter $\beta(T/T_c^*)$ is related to the type of effective interaction between the electrons and was tabulated by Larkin [7].

As displayed in Fig.1, the fitting of the magnetoresistance data with Eq.(1) for $YBCO_1/PrBCO_3$ superlattice clearly shows an excellent agreement with the theory over a wide range of temperatures and magnetic fields. Replotting Fig.1 as a normalized resistance R/A(T) in function of H/H_Φ, the R/A(T) curves for all different temperatures follows a simple universal function as described by Eq.2 (Fig.2). The nice scaling behaviour reveals that resistive transition broadening in magnetic fields can be described by Larkin's 2D fluctuation model, thus suggesting the complete suppression of the phase coherence between superconducting CuO_2 bilayers by magnetic field.

As a next step we have studied the suppression of superconductivity by magnetic field in superlattices by systematically increasing the separator thickness. For this purpose different

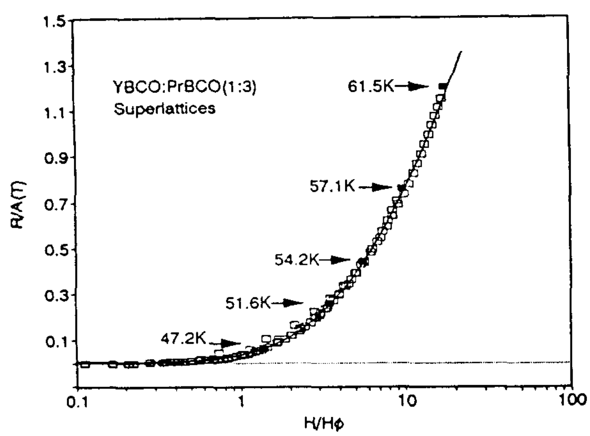

Fig. 2. The normalized magnetoresistance R/A(T) plotted as a function of H/H_Φ at different temperatures for $YBCO_1/PrBCO_3$ superlattice. The solid line corresponds to the $f_2(H/H_\Phi)$ function (Eq.2).

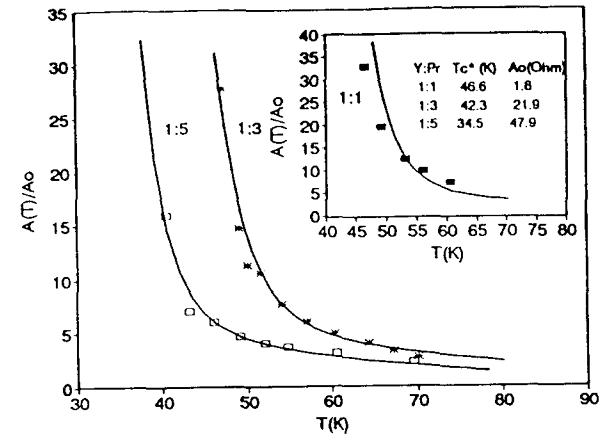

Fig. 3. The temperature dependence of the normalized coefficient $A(T)/A_o$ for $YBCO_1/PrBCO_3$ and $YBCO_1/PrBCO_5$ superlattices. The solid curves correspond to the Larkin function $\beta(T/T_c^*)$. The insert shows the $A(T)/A_o$ vs T plot for $YBCO_1/PrBCO_1$.

superlattices, $(YBCO_1/PrBCO_1)_{30}$ (T_c=66K) and $(YBCO_1/PrBCO_5)_{20}$ (T_c=53K) were chosen. Increasing the PrBCO separator thickness substantially enhances the amplitude of the magnetoresistance and clearly reflects the influence of the decoupling between the CuO_2 layers on the dissipation process. The overall features of the magnetoresistance curves are similar to those observed for the $YBCO_1/PrBCO_1$ superlattice and can be well scaled by the Larkin 2D fluctuation model.

In order to evaluate the critical temperature T_c^* of the quasi 2D superconducting layer, i.e. CuO_2 bilayers in YBCO, we fit A(T) with Eq.(3). The T_c^* and A_o values, obtained from the fitting, are 46.6K, 42.3K and 34.5K; 1.8Ω, 21.9Ω and 47.9Ω for $YBCO_1/PrBCO_1$, $YBCO_1/PrBCO_3$ and $YBCO_1$/-$PrBCO_5$, respectively. By taking into account the difference in the number of CuO_2 layers in these superlattices, we have found renormalized values $\tilde{A}_o$:64.8 Ω, 197 Ω and 192 Ω for 1:1, 1:3 and 1:5, respectively. As a result, we have obtained for Y:Pr = 1:5 and 1:3 nearly the same values: 192 Ω and 197 Ω, as one indeed should expect from the universal fluctuating sheet resistance of 2D fully decoupled YBCO layers. For YBCO/PrBCO = 1:1, the A(T) fit with the β(T) function is definitely worse than that for 1:5 and 1:3 systems, which indicate a stronger coupling between quasi 2D CuO_2 sheets. The sheet resistance (64.8 Ω) is also noticably smaller than in YBCO/PrBCO = 1:5 and 1:3 superlattices. The normal state resistance (700 Ω and 390 Ω for YBCO/PrBCO = 1:5 and 1:3, respectively) also correlates well with the number of the YBCO layers.

Recently Reizer has [8] studied the electron phase-coherence-breaking time τ_Φ and the Maki-Tompson correction to the conductivity. For temperatures far above the transition temperature in a quasi-two-dimensional case, he has obtained the following expression for τ_Φ : [8]

$$\frac{\hbar}{\tau_\Phi(T)} = \frac{\pi^3 k_B T}{8k_F^2 ld}\frac{ln[\hbar/(k_B T\tau)]}{[ln(T/T_c^*)]^2} \qquad (4)$$

where k_F is the wave-vector at Fermi surface, d is the thickness of the 2D layer, $l=v_F\tau$ is the electron mean free path and τ is the electron momentum relaxation time in an inelastic scattering process. For fitting $H_\Phi(T)$ with Eq.4, we need to insert $\hbar/\tau_\Phi$, given by Eq.4, into the relation $H_\Phi(T)= \hbar c/4D\tau_\Phi$. Thus, we find that

$$H_\Phi(T) = (\alpha T) \times \frac{ln[\hbar/(k_B T\tau)]}{[ln(T/T_c^*)]^2} \qquad (5)$$

where $\alpha = \pi^3 k_B/(32k_F^2 ldD)$, $l= \tau v_F$ and $D = v_F^2\tau/2$. With the two fitting parameters "α" and "τ", we were able to obtain a good agreement of the temperature dependence of $H_\Phi(T)$, used in our fit (Fig.3), with the Reizer's expression [8]. This

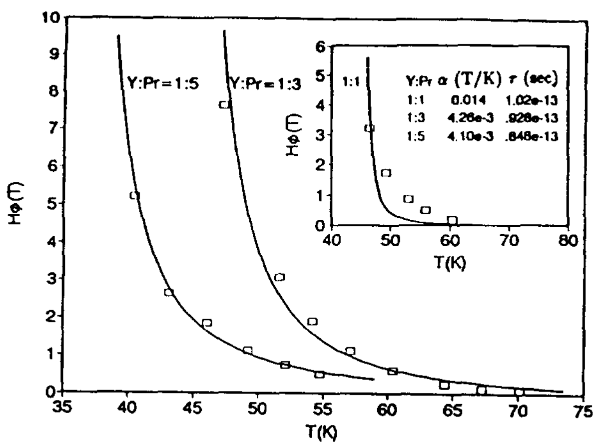

Fig. 4. The temperature dependence of the phase breaking field $H_\Phi(T)$ for $YBCO_1/PrBCO_5$ and $YBCO_1/PrBCO_3$ superlattices. The solid lines are the theoretical curves (Eq.5). The insert shows the temperature dependence of the phase breaking field $H_\Phi(T)$ for $YBCO_1/PrBCO_1$ superlattices.

fitting procedure is quite successful only for $YBCO_1$/ $PrBCO_5$ and $YBCO_1/PrBCO_3$ superlattices. However, for $YBCO_1/PrBCO_1$, the $H_\Phi(T)$ data deviate from the theoretical curve (see the insert of Fig.4). Similar to the $A(T)/A_o$ versus T behaviour (Fig. 3), the deviation observed in Fig.4 may be due to the insufficient decoupling of the YBCO superconducting layers in the $YBCO_1/PrBCO_1$ superlattices. An important point to be mentioned here is that *the same characteristic temperature T_c^*, corresponding to the divergence of $A(T)/A_o$* (Fig.3), *was used in our caculations to describe the $H_\Phi(T)$ behaviour* (Fig.4).

4. Conclusion

In conclusion, we have carried out a systematic study of the magnetoresistance of the YBCO/PrBCO superlattices. The convincing scaling behaviour of the normalized resistance $R/A(T)$ vs H/H_Φ clearly demonstrates the validity of Larkin's 2D fluctuation expression for YBCO/PrBCO superlattices in which superconducting CuO_2 double layers can be decoupled in a controlled way. This result reveals that the giant fluctuations, leading to a broadening of the resistive transition in the presence of an applied field, are an intrinsic property of the quasi-2D high T_c superconducting systems. The decoupling of superconducting planes by using separator PrBCO layers with the varying thickness results in a gradual suppression of the effective transition temperature T_c^* of the CuO_2 superconducting layers. The analysis of the temperature dependence of the phase coherence breaking field, $H_\Phi(T)$, confirms the theoretical prediction by Reizer [8] for the two-dimensional electron systems.

Acknowledgments :

We would like to thank C. Van Haesendonck and A. Gilabert for useful discussions. This work is supported by the Belgian High Temperature Superconductivity Incentive and Concerted Action Programs (at K. U. Leuven) and by the Bundesminister für Forschung und Technologie der Bundesrepublik Deutschland (at the T H Darmstadt). W. B. is a Research Associate of the Belgian Science Foundation (N.F.W.O.). V. V. M. acknowledges the financial support from the Research Council of the Katholieke Universiteit Leuven.

References

[1] T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer and J. V. Waszczak, Phys. Rev. Lett. 61 (1988) 1662.

[2] Y. Ando, N. Motohira, K. Kitazawa, J. Takeya and S. Akita, Phys. Rev. Lett. 67 (1991) 2737.

[3] R. Ikeda, T. Ohmi and T. Tsuneto, J. of Phys. Soc. Jpn. 48 (1989) 1377.

[4] U. Welp, S. Fleshler, W. K. Kwok, R. A. Klemm, V. M. Vinokur, J. Downey, B. Veal and G. W. Crabtree, Phys. Rev. Lett. 67 (1991) 3180.

[5] H. Raffy, S. Labdi, O. Laborde, and P. Monceau, Physica C184 (1991) 159.

[6] C. M. Fu, W. Boon, Y. S. Wang, V. V. Moshchalkov and Y. Bruynseraede, Physica C 200 (1992) 17.

[7] A. I. Larkin, JETP Letters 31 (1980) 219.

[8] M. Yu. Reizer, Phys Rev. B 45 (1992) 12949.

[9] J. Bardeen and M. J. Stephen, Phys. Rev. 140 (1965) A1197.

[10] G. Jakob, P. Przyslupski, C. Stölzel, C. Tomé-Rosa, A. Walkenhorst, M. Schmitt and H. Adrian, Appl. Phys. Lett. 59 (1991) 1626.