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Resonant Tunneling in $Y(Dy)Ba_2Cu_3O_{7-\delta}/PrBa_2Cu_{3-x}Ga_xO_{7-\delta}/Y(Dy)Ba_2Cu_3O_{7-\delta}$ Ramp-Type Josephson Junctions

A.A.Golubov[a,b], M.A.J.Verhoeven[a], I.A.Devyatov[c], M.Yu.Kupriyanov[c], G.J.Gerritsma[a], and H.Rogalla[a]

[a] Department of Applied Physics, University of Twente, 7500AE Enschede, The Netherlands

[b] Institute of Solid State Physics, 142432 Chernogolovka, Russia

[c] Institute of Nuclear Physics, Moscow State University, Russia

We have investigated both experimentally and theoretically the normal state resistance and Josephson critical current of ramp-type Josephson junctions having YBCO (DyBCO) electrodes and 8-30 nm thick Ga-doped barriers $PrBa_2Cu_{3-x}Ga_xO_{7-\delta}$ with Ga content x = 0, 0.05 and 0.1. Analysis of the data shows that the behavior of the junctions can be well described by the model assuming transport through a finite number of localized states in the barrier.

Study of transport in $PrBa_2Cu_{3-x}M_xO_{7-\delta}$ (where M is a metal dopant like Co, Ga etc.) is both of fundamental and of practical interest. An unusual electronic structure of this compound was predicted [1,2]. According to these predictions, a strong hybridization of f-states in Pr with p-orbitals of 8 surrounding oxygens takes place [1]. Another hypothesis [2] is that with increasing of Pr content in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ the balance of hole distribution between chains and planes is shifted so that the holes move from the plains to the chains (charge redistribution). In both cases a-b plains become insulating, but there exist free holes in the chains. The semiconducting resistivity of PBCO is due to sensitivity of 1D chain conductivity to disorder. However transport properties of the material are yet far from being understood.

It is known that Ga substitutes for copper in PBCO on the chain sites [3], therefore Ga-doping is chemically equivalent to oxygen depletion. Strong increase of resistivity was observed in bulk Ga-doped [4] as well as in Co-doped [5] PBCO samples and is important for the fabrication of insulating barriers for high T_c Josephson junctions as well as for some other applications. A complementary approach is to study transport properties of finite size samples. Hopping transport in thin PBCO barriers in the c-axis direction was studied in [6]. Investigation of tunneling through PBCO barriers along ab-plane for different Ga-content is the subject of the present study.

Ramp type Josephson junctions have been fabricated using $YBa_2Cu_3O_y$ and $DyBa_2Cu_3O_y$ as electrode material and $PrBa_2Cu_{3-x}Ga_xO_y$ with x=0, 0.05 and 0.10 as insulator as well as junction barrier. Starting from a RF-magnetron sputtered YBCO/PBCGO bilayer, with an Ar-ion beam a ramp is etched making an angle of 20-25 degrees with the substrate surface. Next, after removal of the resist stencil and ion beam cleaning, the ramp is covered with a thin barrier with a thickness between 8-30nm followed by a counter electrode after which the final structure is defined, including metallization. Several junctions without barrier were made in order to find ways to minimize the damage of the ramp interface. In total about 30 chips were made each containing several junctions and their IV-characteristics measured for various temperatures down to 4.2K. Only those junctions showing clear RSJ-like curves were selected to be analyzed.

Junction conductance was determined from RSJ-like IV-curves at low voltages $V \approx$ 1-2mV. Thickness dependencies G(d) at T=4.2K are shown in fig.1 for x=0 and 0.1. The conductance of Ga-doped junctions decays like $\exp(-d/a)$ with the barrier thickness in the whole thickness range studied with localization length $a \cong 2.6$ nm. For Ga-undoped junctions in the small thickness range we obtain $a \cong 2.2$ nm, however for larger thicknesses d > 15 nm the behavior is better fitted by $\exp(-2d/3a)$ with $a \cong 2.6$ nm. According to Glazman-Matveev theory [7] this indicates a crossover between resonance tunneling via one localized state and that via two states in a barrier. In amorphous Si-barriers a crossover was observed before between direct $\exp(-2d/a)$ and resonant $\exp(-d/a)$ tunneling via one center [8].

To check these assumptions we have studied G(T) dependencies in the range T = 4 - 70 K. For

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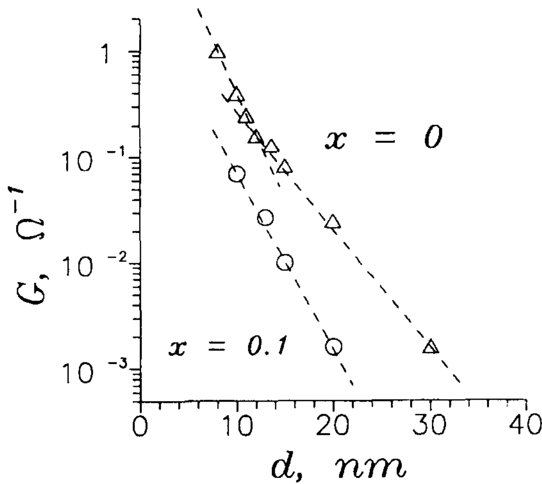

Fig.1. Thickness dependencies of a conductance. The dotted lines show exponential fit

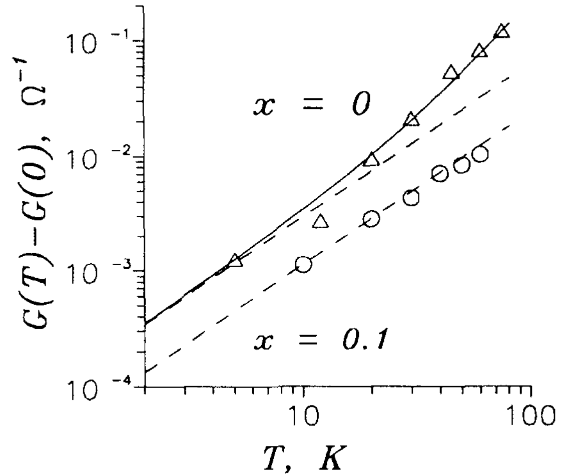

Fig.2. Temperature dependence of a conductance of two 20nm thick PBCO barriers

the thinnest barriers G(T)≈const while with increasing thickness G(T) grows with T. In fig.2 the experimental results for two junctions of d≈20nm for Ga-content x=0 and x=0.1 are shown. Solid line gives the fit $G = G_1 + T^{4/3}G_2 + T^{5/2}G_3$ according to the theory [7], where G_1 is a sum of direct tunneling and one-center tunneling contributions, while G_2 and G_3 are due to two- and three-center resonant tunneling. Dashed lines show the $G_2T^{4/3}$ contributions for both cases. For x=0 $G_1 = 5x10^{-2}\Omega^{-1}$, $G_2 = 1.1x10^{-4}\Omega^{-1}K^{-4/3}$ and $G_3 = 1.5x10^{-6}\Omega^{-1}K^{-5/2}$, whereas for x = 0.1 $G_1 = 7x10^{-4}\Omega^{-1}$, $G_2 = 5x10^{-5}\Omega^{-1}K^{-4/3}$ and $G_3 \approx 0$. The data correspond to a junction area of $10^{-8}cm^2$.

The contribution of indirect tunneling is proportional to a density of localized states in a barrier [7]. A number of channels involving one resonant center $N_1 = \pi(h/e^2)G_1$ is of order of 10^3 for x=0 and 10 for x=0.1. Thus the results are consistent with the assumptions that (a) transport through PBCO barriers along ab-planes is mainly due to tunneling via channels involving one or two resonant centers, (b) Ga-doping reduces the density of localized states. With increase of a barrier thickness crossover to bulk hopping conductivity involving many centers takes place.

The I_cR_n product is proportional to $1/(R_n)^m$ with exponent m≈0.6-0.9. It is shown in [9] that m = 1 for $d >> a$ and a weak Coulomb repulsion on the resonant centers, whereas m < 1 can be due to contribution of direct tunneling. The latter can be a reason for larger values of the I_cR_n product of 2-3mV for Ga-doped barriers d = 8 nm.

Alternative explanation in terms of resonant tunneling via negative U centers with Cooper pair interaction in PBCO was proposed in [10].

In conclusion, the behavior of the junctions can be well described by the model assuming transport through a finite number of localized centers in a barrier. Ga-doping reduces the density of localized states, but a localization length in a barrier is not changed. According to the picture of the unusual band structure of PBCO [1,2] these localized centers can represent some parts of normally conducting chains, which are interrupted due to oxygen disorder and twinning of a crystal.

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