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Copper Oxide Superconducting/Antiferromagnetic Interface

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Abstract. Superconducting $Nb/Au/Ca_{1-x}Sr_xCuO_2/YBa_2Cu_3O_7$ mesa-heterostructures were investigated. Dependencies of electrical parameters versus inverse capacitance were measured. A band diagram which takes into account an accumulation of holes in $Ca_{1-x}Sr_xCuO_2$ interlayer and band bending due to difference of work functions was proposed. The dependencies of electrical parameters were analyzed by examining the quasipartical and superconducting currents.

Introduction.

Processes in interfaces are important for carrier transport in high critical temperature (T_C) Josephson junctions. In $YBa_2Cu_3O_7/PrBa_2Cu_3O_7/YBa_2Cu_3O_7$ (YBCO/PBCO/YBCO) junctions an accumulation of mobile holes into the p–type PBCO takes place, which results in conversion of hopping conductor PBCO into a metal up to 50 nm in depth [1]. In $YBCO/La_{0.7}Sr_{0.3}MnO_3/YBCO$ junctions the manganite barrier provides depletion of the holes in p–type YBCO electrode and dielectric layer was formed [2]. Procedure to calculate hopping conductivity parameters from electrophysical properties of junctions was developed [3, 4]. Such high – T_C junctions usually exhibit I-V curves SNS – type [1, 5] and products of normal resistance R_N by critical current I_C are not very high. But up to now models of carrier transport and band diagrams for high – T_C junctions are qualitative [1,2] and require in-depth investigation.

Experimental.

We have fabricated $Nb/Au/Ca_{1-x}Sr_xCuO_2/YBa_2Cu_3O_7$ mesa-structures. Most of the data in this paper concern mesa-heterostructures with an interlayer made from G-type antiferromagnetic $Ca_{0.5}Sr_{0.5}CuO_2$ (AMS). $Ca_{0.5}Sr_{0.5}CuO_2$ (CSCO) could be treated as hopping conductor with reistivity at 300 K $\rho(300)\sim10 - 100$ m$\Omega\cdot$cm, which is more than for PBCO $\rho(300)\sim1$ m$\Omega\cdot$cm [1]. The YBCO films of 100 nm thick were deposited on $NdGaO_3$ substrate by laser ablation. Without vacuum breaking CSCO layer was deposited at the same run. An epitaxial growth of YBCO and CSCO films was provided. A thin protection layer of 15 nm Au was deposited *in-situ*. Top layers of 200 nm Nb and Au contacts were made in other chamber. A square junctions with areas A from 10x10 to 50x50 μm^2 and with CSCO interlayer with thickness d_M=5 – 80 nm were made [6].

Model and uniformity of mesa-heterostructures.

Superconducting current was observed for AMS with CSCO thickness d_M=12 – 50 nm with critical current density $J_C=I_C/A$ of 2 – 600 A/cm^2. Magnetic field dependencies $I_C(H)$ were studied. Fig. 1 demonstrates dependence of I_C vs. magnetic field at 4.2 K for AMS with relatively thin d_M=20 nm, A=10x10 μm^2. The up triangles are positive current biased critical currents and down triangles – negative ones. Singularities on $I_C(H)$ are caused by antiferromagnetic (AF) interlayer and are less pronounced than in [7] due to large J_C=350 A/cm^2. The main I_C oscillation period is of B_0≈45 μT. It has double width at H=0 that points on uniformity of critical current distribution at least for AMS with d_M≥20 nm. Field period B_0 estimated by differences between $I_C(H)$ minima in Fig. 1 gives an effective area for magnetic field penetration of 5 μm^2. The period was of 10 times smaller than the B_0 periods for mesa-structures without CSCO interlayer (MS). Small B_0 of AMS compared to B_0 of MS were observed earlier for other CSCO thicknesses [7]. This was explained by giant magnetic oscillations of critical currents of S-AF-S junctions [8].

A band diagram of the AMS is presented in Fig. 2. A YBCO electrode has high work function Φ_{YBCO} 5 – 6 eV [2]. The work functions of metals are low Φ_{Au}=4.3 eV, Φ_{Nb}=4 eV. We suppose that electron affinity of CSCO χ_{CSCO} is between: $\Phi_{YBCO}>\chi_{CSCO}> \Phi_{Nb}$. So, free holes from YBCO accumulate in p-type CSCO [1]. It is shown by up band bending in Fig. 2. By reference [2] if condition $\chi_{CSCO}>\Phi_{Nb}$ is fulfilled a depletion of holes appears in CSCO at Au interface, band bending is down. Total bending in AMS is equal to difference in work functions Φ_{YBCO}-Φ_{Nb}=1-2 eV.

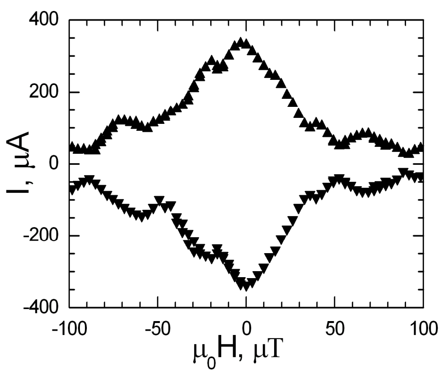

Fig. 1. I_C versus magnetic field dependence at 4.2 K for AMS with d_M=20 nm, A=10x10 μm^2. Up triangles are positive biased critical currents and down triangles – negative ones.

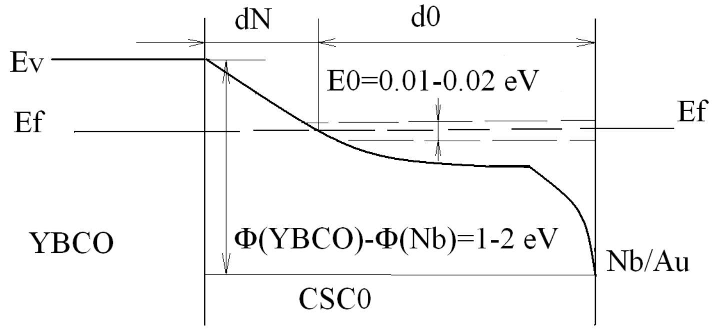

Fig. 2. Band diagram of AMS with CSCO barrier layer. Valence band E_V in YBCO and CSCO is shown as the bold line. Fermi level (dash line) is a constant in whole structure. Hopping sub-band of CSCO with an average barrier height E_0 is thin dash lines. Difference in work functions Φ is shown.

A hopping conductor has conductivity dependency $G(T)=G_0exp[-(T_0/T)^{1/4}]$ that exponentially decreases with lowering the temperature. Experimental constant T_0 depends on carrier localization radius a and density of states at Fermi level g as $T_0=24/(\pi kga^3)$, k is Boltzmann constant. Details of the calculations for junctions with hopping conductor were described in [3]. By localization radius CSCO a=5±2 nm and by T_0~10^6 K we have calculated g=(0.2 – 5)·10^{18} (eV)$^{-1}$cm^{-3} in [6].

Conductivity by resonant tunneling with average barrier height E_0 is $G_{res}=(\pi e^2/\hbar)E_0{\cdot}ga{\cdot}exp(-d/a)$. For dielectric thickness $d\to 0$ it is $G_{res}=(\pi e^2/\hbar)E_0{\cdot}ga$. By measured G/A versus d dependency and known values g and a barrier height in YBCO/PBCO/Au junctions was calculated E_0=51 meV [3]. We calculate the average height as $E_0=(h/2\pi^2e^2)/[ga{\cdot}R_NA(d\to 0)]$. The R_NA(d→0)≈0.18 μΩcm^2 was extrapolated from experimental dependency of resistance on area products versus CSCO thickness: $R_NA(d_M)$ [6]. The calculated value for CSCO is E_0=10 – 20 meV. The band diagram shows that there are metallic - type layer with thickness d_N and dielectric-type layer with thickness d_0.

Dependencies of electrical parameters and interface capacitance.

A dielectric thickness d_0 may be less than interlayer thickness d_M if the accumulation takes place [1]. Dependence d_0 versus d_M was calculated from C - capacitance of AMS [6]. By hysteresis of voltage-current curves McCumber parameters were calculated by Zappe formula [9]: $\beta_C=[2-(\pi-2)\alpha]\alpha^{-2}$, $\alpha=I_{RETURN}/I_C$. By McCumber definition $\beta_C=4\pi e I_C R_N^2 C/h$ and for $C=\varepsilon\varepsilon_0 A/d_0$:

$$\frac{d_0}{\varepsilon}=\varepsilon_0\frac{A}{C}=\frac{4\pi\varepsilon_0}{h}\cdot\frac{AI_CR_N^2}{\beta_C}\quad . \tag{1}$$

We have calculated dielectric thickness d_0 from experimental A/C values. Calculation by (1) shows increase of d_0/ε from $d_0/\varepsilon=0.24\pm0.08$ at $d_M=12$ nm to $d_0/\varepsilon=11.7\pm2.9$ nm at $d_M=50$ nm. Layer which does not contribute to capacitance could be extracted by the d_0/ε dependency vs. d_M [6]. This layer with a thickness of $d_N\approx20$ nm has metallic type behavior. For samples with $d_M>20$ nm there is a wide dielectric layer $d_0\approx d_M-d_N$. Dependence of R_NA versus d_0/ε ratios is shown in Fig. 3.

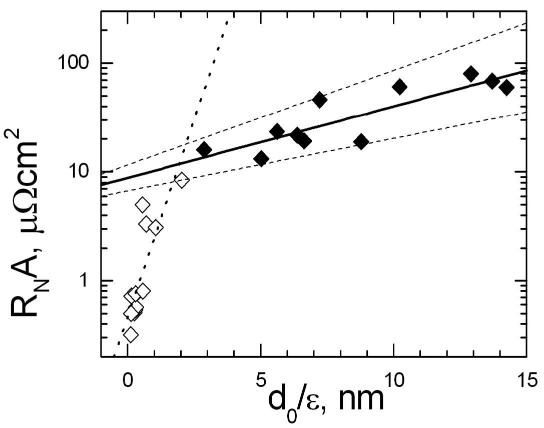

Fig. 3. Dependency of R_NA of AMS versus d_0/ε. Open symbols are data for AMS with $d_M\leq20$ nm, exponential approximation for the data is dotted line. Closed symbols show data for samples with $d_M>20$ nm, exponential approximation – solid line, it`s standard deviation – dashed lines.

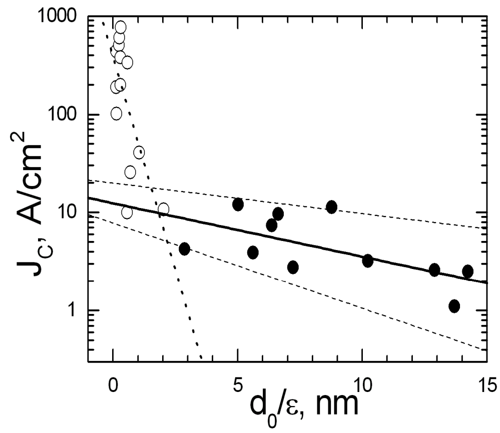

Fig. 4. Dependency of current densities versus d_0/ε. Open symbols are data for AMS with $d_M\leq20$ mn, exponential fit is dotted line. Closed symbols – data for $d_M>20$ nm, it`s exponential approximation – solid line, standard deviation shown as dashed lines.

In Fig 3 data for AMS with small CSCO thicknesses $d_M=12$, 20 nm and for thicker CSCO with $d_M=28$, 40, 50 nm were fitted separately by steep and smooth sloping exponents. The fits are:

$$R_NA=k_{RS}\exp\left(\frac{d_0/\varepsilon}{a_{RS}}\right)\quad d_M\leq20\text{ nm},\qquad R_NA=k_{RG}\exp\left(\frac{d_0/\varepsilon}{a_{RG}}\right)\quad d_M>20\text{ nm}. \tag{2}$$

For steep exponent by a least squares fit method we obtain coefficients $k_{RS}=0.5$ μΩcm^2, $a_{RS}=0.6$ nm that is shown by dotted line in Fig 3. For AMS with $d_M>20$ nm the exponential increase was more smooth: $k_{RG}=9$ μΩcm^2, $a_{RG}=6.6$ nm that is solid line. An error of calculation of the coefficient gives interval $5<a_{RG}<9$ nm that is shown as dashed lines.

Dependency of critical current density J_C versus ratio of d_0/ε is shown in Fig 4. The fits are:

$$J_C=k_{JS}\exp\left(-\frac{d_0/\varepsilon}{a_{JS}}\right)\quad d_M\leq20\text{ nm},\qquad J_C=k_{JG}\exp\left(-\frac{d_0/\varepsilon}{a_{JG}}\right)\quad d_M>20\text{ nm}. \tag{3}$$

A steep exponential decrease with coefficients $k_{JS}=380$ A/cm^2, $a_{JS}=0.5$ nm was obtained by the least squares fit. Dependence for AMS with $d_M>20$ nm gives the parameters: $k_{JG}=12.5$ A/cm^2, $a_{JG}=8.0$ nm. It is shown as solid line in Fig. 4. The error interval $5<a_{JG}<14$ nm is shown as dashed lines.

From Fig. 3 and Fig. 4 we conclude that transport mechanism in AMS changes during increase of thickness approximately at d_M=20 nm. In case of $d_M \leq 20$ nm the steep slopes in $R_NA(d_0/\varepsilon)$ and $J_C(d_0/\varepsilon)$ dependencies may be explained by direct tunneling through thin barrier at CSCO/Au interface (Fig. 2). The barrier thickness may be estimated by $\varepsilon \sim 2$ and $d_0/\varepsilon = 0.24 - 1$ nm (Fig. 3) that gives $d_0 \approx 0.5 - 2$ nm. The rest of CSCO layer is metallic – type due to the accumulation. The height of a rectangular barrier may be estimated as: $E_b \approx h^2/(8\pi e m_e a_D^2)$ with $m_e = 9 \cdot 10^{-31}$ kg. Characteristic length a_D may be obtained by dependencies for direct tunneling: $J_C \sim exp(-2d/a_D)$, $R_NA \sim exp(2d/a_D)$. Compared the dependencies with formula (2) and (3) one obtains $a_D \approx 2\varepsilon \cdot a_{RS}$, $a_D \approx 2\varepsilon \cdot a_{JS}$ that gives $a_D \sim 4a_{JS}$=2 nm and $E_b \sim 10$ meV. The coefficients are the same $a_{RS} \approx a_{JS}$, thus $I_CR_N(d_0) \approx$const.

Because $a_{RG} \approx a_{JG}$ one obtains $V_C(d_0) \approx$const for $d_M > 20$ nm also. Large values of $a_{RG} \sim 10a_{RS}$ and $a_{JG} \sim 10a_{JS}$ lead to a barrier height $E_b \sim a_D^{-2} \approx 0.1$ meV small compared to kT≈0.36 meV at 4 K. So direct tunneling can not explain the smooth exponential slopes. Other explanation may be proximity effect which originates from resonant tunneling through pair states in CSCO barrier [10]. In case of narrow widths of energy states $\Gamma = E_0 exp(-d_0/a) < kT_C$ the pair breaking occurs. In opposite limit $\Gamma > kT_C$ if Cooper pairs tunnel via resonant levels [10], it also yields $V_C(d_0)$=const.

Note, at localization radius $a \approx 1$ nm no supercurrent was observed through PBCO interlayer 7.5 nm in thickness [3], but for larger $a \approx 3$ nm and PBCO thickness 20 nm a Josephson current was reported in [4]. In our AMS with superconducting/antiferromagnetic interfaces large radii a in $Ca_{0.5}Sr_{0.5}CuO_2$ antiferromagnetic interlayer support long proximity effect and result in experimentally observed decrease of quasipartical current with d_M, keeping V_C very slightly dependent from CSCO thickness.

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