Copper Oxide Superconducting/Antiferromagnetic Interface

Yulii Kislinskii¹,4,a*, Karen Constantinian¹,b, Gennady Ovsyannikov¹,2,c, Anton Shadrin¹,e, Igor Borisenko¹,d, Yuri Khaydukov³,f, Alexander Sheyerman¹,g, Aleksandr Vasiliev⁵,h

¹Kotel’nikov IRE RAS, 125009 Moscow, Russia
²Chalmers University of Technology, SE-41 296 Gothenburg, Sweden
³Max-Plank Institute for Solid State Research, 70 569 Stuttgart, Germany
⁴Shubnikov Institute of Crystallography, 119333 Moscow, Russia
⁵Kurchatov National Research Center, Moscow, Russia

a* yulii@hitech.cplire.ru, b karen@hitech.cplire.ru, c gena@hitech.cplire.ru, e anton_sh@hitech.cplire.ru, d iboris@hitech.cplire.ru, f yury.khaydukov@frm2.tum.de, g sasha@hitech.cplire.ru, h a.vasiliev56@gmail.com

Keywords: accumulation and depletion of holes, band diagram, capacitance, high Tc Josephson junction, mesa-heterostructures, proximity effect, superconducting/antiferromagnetic interfaces.

Abstract. Superconducting Nb/Au/Ca₁₋ₓSrₓCuO₂/YBa₂Cu₃O₇ 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 Ca₁₋ₓSrₓCuO₂ 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 (Tc) Josephson junctions. In YBa₂Cu₃O₇/PrBa₂Cu₃O₇/YBa₂Cu₃O₇ (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/La₀.₇Sr₀.₃MnO₃/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 – Tc junctions usually exhibit I-V curves SNS – type [1, 5] and products of normal resistance Rₙ by critical current Ic are not very high. But up to now models of carrier transport and band diagrams for high – Tc junctions are qualitative [1,2] and require in-depth investigation.

Experimental.

We have fabricated Nb/Au/Ca₁₋ₓSrₓCuO₂/YBa₂Cu₃O₇ mesa-structures. Most of the data in this paper concern mesa-heterostructures with an interlayer made from G-type antiferromagnetic Ca₀.₅Sr₀.₅CuO₂ (AMS). Ca₀.₅Sr₀.₅CuO₂ (CSCO) could be treated as hopping conductor with resistivity at 300 K ρ(300)~10 – 100 mΩ·cm, which is more than for PBCO ρ(300)~1 mΩ·cm [1]. The YBCO films of 100 nm thick were deposited on NdGaO₃ 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 µm² and with CSCO interlayer with thickness dₘₜ=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, \(A=10\times10\) \(\mu\)m\(^2\). 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 \(B_0\approx45\) µT. It has double width at \(H=0\) that points on uniformity of critical current distribution at least for AMS with \(d_M\geq20\) 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 \(\Phi_{YBCO}\approx5 – 6\) eV [2]. The work functions of metals are low \(\Phi_{Au}\approx4.3\) eV, \(\Phi_{Nb}\approx4\) eV. We suppose that electron affinity of CSCO \(\chi_{CSCO}\) 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 \(\Phi_{YBCO}-\Phi_{Nb}=1-2\) eV.

A hopping conductor has conductivity dependency \(G(T)=G_0\exp[-(T_0/T)^{1/4}]\) 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 \(T_0=24/(\pi k g a^3)\), \(k\) is Boltzmann constant. Details of the calculations for junctions with hopping conductor were described in [3]. By localization radius CSCO \(a=5\pm2\) nm and by \(T_0\approx10^6\) K we have calculated \(g=(0.2 – 5)\times10^{18}\) (eV\(^{-1}\))cm\(^{-3}\) in [6].

Conductivity by resonant tunneling with average barrier height \(E_0\) is \(G_{res}=(\pi e^2/h)E_0\cdot g a \cdot \exp(-d/a)\). For dielectric thickness \(d\rightarrow0\) it is \(G_{res}=(\pi e^2/h)E_0\cdot g a\). 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 \(E_0=(h/2\pi^2 e^2)/[g a R_N A(d\rightarrow0)]\). The \(R_N A(d\rightarrow0)=0.18\) \(\mu\)Ωcm\(^2\) was extrapolated from experimental dependency of resistance on area products versus CSCO thickness: \(R_N A(d)\) [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]:

$$\beta_C = 2 - (\pi - 2)\alpha^2, \quad \alpha = I_{\text{RETURN}}/I_C.$$ 

By McCumber definition $\beta_C = 4\pi\varepsilon_0 R N^2 C/h$ and for $C = \varepsilon_0 A/d_0$:

$$\frac{d_0}{\varepsilon} = \varepsilon_0 A \frac{C}{C} = \frac{4\pi\varepsilon_0 A}{h} \frac{\pi R N^2}{\beta_C}.$$  \hspace{1cm} (1)

We have calculated dielectric thickness $d_0$ from experimental $A/C$ values. Calculation by (1) shows increase of $d_0/\varepsilon$ from $d_0/\varepsilon = 0.24 \pm 0.08$ at $d_M = 12$ nm to $d_0/\varepsilon = 11.7 \pm 2.9$ nm at $d_M = 50$ nm. Layer which does not contribute to capacitance could be extracted by the $d_0/\varepsilon$ dependency vs. $d_M$ [6]. This layer with a thickness of $d_N \approx 20$ 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 $R N A$ versus $d_0/\varepsilon$ ratios is shown in Fig. 3.

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:

$$R N A = k_{RS} \exp \left( \frac{d_0/\varepsilon}{a_{RS}} \right) \quad d_M \leq 20 \text{ nm}, \quad R N A = k_{RG} \exp \left( \frac{d_0/\varepsilon}{a_{RG}} \right) \quad d_M > 20 \text{ nm}. \quad \hspace{1cm} (2)$$

For steep exponent by a least squares fit method we obtain coefficients $k_{RS} = 0.5 \ \mu\Omega\text{cm}^2$, $a_{RS} = 0.6$ nm that is shown by dotted line in Fig 3. For AMS with $d_M > 20$ nm the exponential increase was more smooth: $k_{RG} = 9 \ \mu\Omega\text{cm}^2$, $a_{RG} = 6.6$ 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 $d_0/\varepsilon$ is shown in Fig 4. The fits are:

$$J_C = k_{JS} \exp \left( - \frac{d_0/\varepsilon}{a_{JS}} \right) \quad d_M \leq 20 \text{ nm}, \quad J_C = k_{JG} \exp \left( - \frac{d_0/\varepsilon}{a_{JG}} \right) \quad d_M > 20 \text{ nm}. \quad \hspace{1cm} (3)$$

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

Fig. 3. Dependency of $R N A$ of AMS versus $d_0/\varepsilon$. Open symbols are data for AMS with $d_M \leq 20$ 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 $d_0/\varepsilon$. Open symbols are data for AMS with $d_M \leq 20$ 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.
From Fig. 3 and Fig. 4 we conclude that transport mechanism in AMS changes during increase of thickness approximately at \( d_M \approx 20 \) nm. In case of \( d_M \leq 20 \) nm the steep slopes in \( R_N A(d_0/e) \) and \( J_C(d_0/e) \) dependencies may be explained by direct tunneling through thin barrier at CSCO/Au interface (Fig. 2). The barrier thickness may be estimated by \( e \sim 2 \) and \( d_0/e = 0.24 – 1 \) 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: \( E_p \approx h^2/(8\pi e m_a d_B^2) \) with \( m_e \approx 9 \cdot 10^{31} \) kg. Characteristic length \( a_0 \) may be obtained by dependencies for direct tunneling: \( J_C \sim \exp(-2d/a_0), R_N A \sim \exp(2d/a_0) \). Compared the dependencies with formula (2) and (3) one obtains \( a_p \approx 2e/a_{RS}, a_0 \approx 2e/a_{JS} \) that gives \( a_p \approx 4a_{IS} = 2 \) nm and \( E_c \approx 10 \) meV. The coefficients are the same \( a_{RS} \approx a_{JS} \), thus \( I_C R_N(d_0) \approx \text{const} \).

Because \( a_{RG} \approx a_G \) one obtains \( V_C(d_0) \approx \text{const} \) for \( d_M > 20 \) nm also. Large values of \( a_{RG} \sim 10a_{RS} \) and \( a_{GC} \sim 10a_{JS} \) lead to a barrier height \( E_p \approx a_B^{-2} \approx 0.1 \) meV small compared to \( kT \approx 0.36 \) meV at 4 K. So direct tunneling cannot 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 \( \Gamma = E_0 \exp(-d_0/a) < kT \) the pair breaking occurs. In opposite limit \( \Gamma > kT \) if Cooper pairs tunnel via resonant levels [10], it also yields \( V_C(d_0) \approx \text{const} \).

Note, at localization radius \( a < 1 \) nm no supercurrent was observed through PBCO interlayer 7.5 nm in thickness [3], but for larger \( a > 3 \) nm and PBCO thickness 20 nm a Josephson current was reported in [4]. In our AMS with superconducting/antiferromagnetic interfaces large radii \( a \) in \( \text{Ca}_{0.5}\text{Sr}_{0.5}\text{CuO}_2 \) 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.

Acknowledgment

This work was supported partially by the RAS, RFBR projects 14-07-00258, 14-07-93105, Scientific School grant NSH-4871.2014.2. P.V. Komissinki is grateful for fruitful discussions.

References