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Hybrid Josephson junctions with s/d-wave symmetry of order parameter for elements of quantum computing systems

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Abstract. Hybrid s/d Josephson junctions Nb/Au/$Ca_{1-x}Sr_xCuO_2$/$YBa_2Cu_3O_7$ were made. I_CR_N products of 100÷200 μV were independent on $Ca_{1-x}Sr_xCuO_2$ (CSCO) layer thickness. The second harmonic of current - phase relation up to 40 percent was observed. By estimations, a microscopic quantum tunnelling regime of the junctions may be observed at temperature of 1 K, which is promising for qubit applications.

Introduction

A qubit - two quantum level system with macroscopically distinguished quantum states can be realised as a dc superconducting quantum interference device, which consists of Josephson junctions with nonsinusoidal current phase-relation (CPR). For first and second harmonic in the relation between superconducting current I_S and phase difference across the junction φ, one obtain [1]:

$$I_S(\varphi) = I_{C1} sin(\varphi) + qI_{C1} sin(2\varphi). \qquad (1)$$

where q is porion of the second harmonic. The device is called as "quiet qubit" because it is stable to magnetic flux fluctuations [2]. Qubit operation can be realised at temperatures below of the junction noise crossover temperature T*. For T>T*, thermal noise dominates. For temperatures less than T* , a microscopic quantum tunnelling process is realised and noise current becomes independent on temperature. For d/d bicrystal grain boundary junctions in $YBa_2Cu_3O_7$ (YBCO) d - wave superconductor, the temperature T* = 0.05 K was observed [3]. A source of additional noise in d/d junctions is tunnelling of normal (not superconducting) carriers in nodal direction of d -wave superconductor through a zero energy bound states. According to calculations in article [4], temperature T* in presence of the tunnelling in nodal directions is so low as 0.025 K. For Nb/Au/YBCO junctions with s - superconductor Nb, the nodal tunnelling is suppressed at low temperatures by s-wave energy gap, and T* of 0.3 K was calculated [5]. Here we present properties of Nb/Au/$Ca_{1-x}Sr_xCuO_2$/$YBa_2Cu_3O_7$ junctions.

1.Experimental

Josephson junctions Nb/Au/CSCO/YBCO were made from YBCO superconductor 100 nm in thickness, insulator CSCO layer with thickness d_C =12÷80 nm, and 10 nm Au film. The three layers were deposited by laser ablation in-situ. By ion etching and evaporation a Nb superconducting layer on the top - square junctions with size $L^2 = 10^2 \div 50^2$ μm^2 were made (Fig.1) . Nb and YBCO were superconducting at 4.2 K and four point I-V curves measurements were made. Detector responses were measured by modulation - demodulation technique.

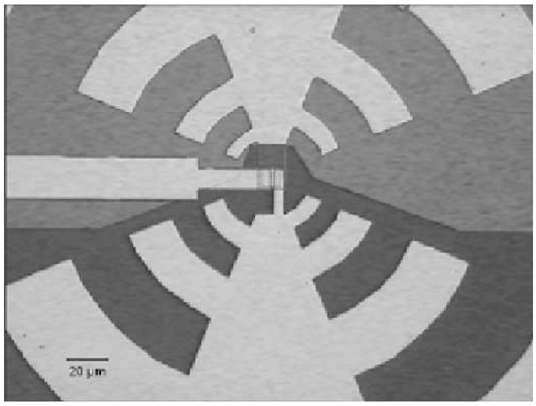

Fig. 1. Fig. 1. Hybrid junction, L=10 μm. Au/CSCO/YBCO layers - in upper half, and Nb - in bottom falf of picture

2.Results and discussion

It is known that junction with sinusoidal CPR shows integer Shapiro step and detector response V_1 under microwave radiation with frequency f at voltage $V_1 = hf/2e$. If the second harmonic of CPR exists half - integer step and response at $V_{1/2} = hf/4e$ appears [6]. Integer at and half - integer responses are shown in Fig 2.

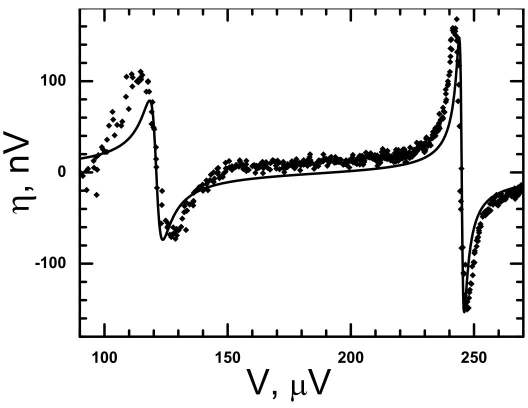

Fig. 2. Fig. 2. Junction detector response with d_C=20 nm, L=10 μm on f=119.5 GHz. Points are experimental data, line - RSJ model fit. Integer response is at 245 μV and half-integer - at 121 μV.

According to [7] portion of the second harmonic q:

$$q = \frac{1}{2}\sqrt{\frac{\eta_{\frac{1}{2}} R_{D1}}{\eta_1 R_{D\frac{1}{2}}}} \qquad (2)$$

where $\eta_{1/2}$ is the difference between maximum and minimum of $\eta(V)$ for half integer response, η_1 the difference for integer one, R_{D1} differential resistance at V_1 and $R_{D1/2}$ the resistance at $V_{1/2}$. The formula is valid in high frequency limit $V_1 >> I_C R_N$. The q value is 0.3 for data in Fig. 2. By model of resistively shunted junction (RSJ) the line halfwidth of Josephson junction self generation is:

$$\Delta V = 40MHz \cdot \frac{hR_D^2}{2eR_N} \cdot (1 + \frac{I_C^2}{2I^2}) \qquad (3)$$

where I is the junction current. The experimental line width is 2 times wide, than calculated one by the model. We examined critical current density $j_C = I_C/L^2$ versus thickness and observed a decrease with d_C and $R_N L^2$ increase exponentially with d_C as shown in Fig. 3 and 4.

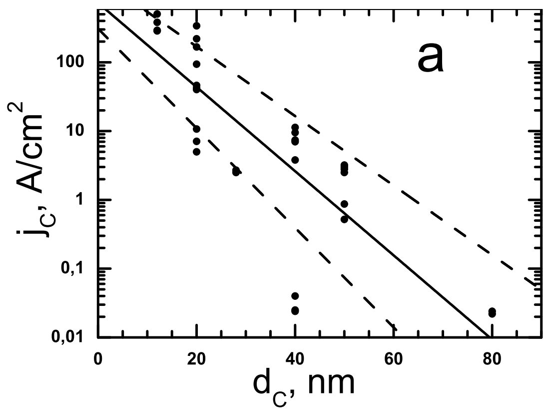

Fig. 3.

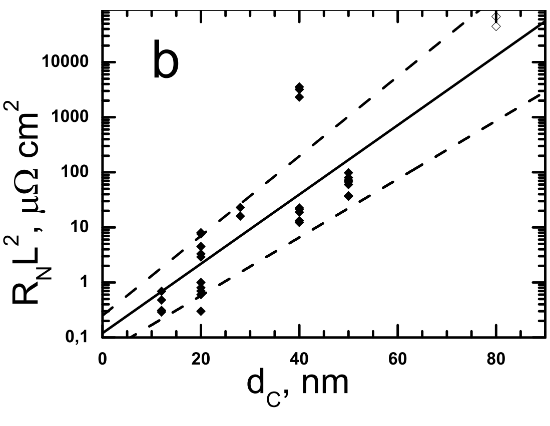

Fig. 4. Fig. 3 and 4. Dependencies of current density (Fig.3, a) and normal surface resistance (Fig.4, b) versus CSCO layer thickness d_C. Exponential fits for the values are solid lines. Prediction bands with 0.67 probability are shown as dashed lines

Experimental dependency $j_C(d_C)$ was exponential:

$$j_C(d_C) = A_j \cdot exp(-\frac{d_C}{\xi_j}) \qquad (4)$$

A_j=730 A/cm^2 and ξ_j=7.1 nm are evaluated from experimental data. Resistances increase with d_C exponentially too:

$$R_N L^2(d_C) = A_R \cdot exp(\frac{d_C}{\xi_R}) \qquad (5)$$

From data in Fig. 2 we obtain: A_R=0.12 $\mu\Omega cm^2$ and ξ_R=6.9 nm. Having $\xi_j \cong \xi_R$ the products of $I_C R_N$ do not decrease with CSCO layer thickness at least in 12÷50 nm range. At upper temperature of quantum tunneling a deviation of phase difference , which is activated by temperature, is less than a microscopic quantum tunneling deviation. Using this approach from [5] we estimate T*:

$$T^* = \frac{e}{k_b}\sqrt{\frac{hI_C}{4\pi eC}} \qquad (6)$$

where k_b - Boltsman constant and C is the junction capacitance. By the estimation formula we obtain for typical hybrid junctions with I_C=50 μA and C=2 pF, the temperature T* in order of 1 K. Note, that hybrid junctions with c-oriented YBCO have no zero bias conductance peak, so zero energy bound states was not observed in it. Our approximation does not take into account noise from dissipative current of normal carriers through an intrinsic shunt resistance of the junction. Accurate numerical calculations, which consider the shunt resistance [5], gives T* value of 3 times smaller than the estimation formula for Nb/Au/YBCO. But the $R_N L^2$ of our hybrid junctions were at least two order large than the reistances of Nb/Au/YBCO, which was considered in [5]. The value of temperature of microscopic tunneling in our c - oriented hybrid junctions was not reported until now and is a subject of future experimental measurements and calculations.

Acknowledgements

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