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Frequency and size dependence of ac Josephson effect in Nb/Au/YBCO heterojunctions

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Abstract. High frequency dynamics of Nb/Au/YBaCuO heterojunctions on tilted $NdGaO_3$ substrates have been studied. The both integer and non-integer Shapiro steps have been observed at mm-wave frequencies. Unconventional dependence of the critical current and the amplitudes of Shapiro steps vs. applied microwave power have been registered. Observed behavior deviates from existing theories of Josephson effect for junctions made from conventional or d-wave superconductors. Although the maximal size of the heterojunctions was smaller than the Josephson penetration depth, calculated from an averaged value of the critical current density, the experimental magnetic field dependences $I_C(H)$ deviate from the Fraunhofer pattern, pointing on non-uniform distribution of superconducting current density. Experimental results could be speculatively explained by origination of self-induced fractional magnetic vortices, which may take place in a junction where the amplitude and the phase of superconducting current alternate significantly over the junction area. Introducing a new lengthscale, which is much smaller than the Josephson penetration depth, the fractional vortices are considered, modifying the high frequency dynamics, namely the ac Josephson effect. Experimental results have been analyzed taking into account the second harmonic of superconducting current-phase relation and the influence of heterojunction capacitance.

1. Introduction

It is known that in metal-oxide superconductors with high critical temperature, for example in YBCO, the d-wave symmetry of superconducting order parameter (D–superconductor) is predominant one in the basal (*a*-*b*) plane [1]. As a result the properties of contacts of usual S-superconductor (or N-metal) with a D-superconductor strongly depend on orientation of D-superconductor with respect to crystal orientation of electrodes. For example, the second harmonic in superconducting current-phase relation

(CPR) $I_S(\varphi)$ occurs for current direction along the nodes in the *a*-*b*-plane of d-wave superconductor, and also for the case of current flow along the *c*-axis. In the former case the midgap Andreev bound states produce an extra channel for current transport at low voltages $V<\Delta/e$. Electrical and magnetic properties of S/D heterojunctions with *c*-axis oriented d-wave superconducting thin film electrode have been studied in [2]. Epitaxial growth of YBCO films with dominating (110) orientation is very sensitive to formation of other phases, e.g., (103) YBCO. Thus, fabrication of mono-phase (110) YBCO film is rather challenging. Here we report the results of experimental studies of magnetic and microwave properties of Nb/Au/YBCO heterojunctions (HJs) exhibiting mono-phase YBCO film with crystallographic *c*-axis inclined from the substrate normal direction. Frequency and size dependence of Shapiro step amplitudes of HJs are discussed.

2. Experimental

The (7 10 2) $NdGaO_3$ (NGO) substrates were chosen for fabrication of the tilted YBCO films. The *c*-axis of the epitaxial YBCO film on this substrate inclines from the normal to the substrate plane by a angle $\gamma\approx11°$. Detailed X-ray studies of the obtained YBCO films have revealed the following epitaxial relation (001)YBCO‖(110)NGO and the orientation of the YBCO film became close to the (1 1 20). A single twin domain thin film structure was obtained for the inclined YBCO films used for fabrication of experimental Nb/Au/YBCO HJs [2]. Planar HJs were patterned with a square shape and varied length L = 10÷50 μm. Measurements of the I-V curves were carried out in a current bias regime at temperature T= 4.2 K. Magnetic field $I_C(H)$ dependences of HJs were measured at H<15 Oe along with experimental characterization at microwave frequencies. High frequency dynamics of I-V curves, particularly non-integer Shapiro steps, gives additional information [5] and in our case was studied at 36÷79 GHz. Moreover, detector response functions were measured by use of weak applied signals up to frequencies 110 GHz.

3. Results and discussion

For heterojunctions with L= 20 μm, the $I_C(H)$ function in the region of the first peak was close to the "Fraunhofer" pattern that is typical for lumped Josephson junctions. When magnetic field increases over H>5 Oe, the deviation from $|\sin H/H|$ increases, indicating that the distribution of the superconducting current can be treated rather as a non-uniform. More accurate approximation of the experimental $I_C(H)$ dependences for fields H>5 Oe could be obtained using a model, in which the absolute value and the sign of critical current density vary over the length of the junction [3, 4].

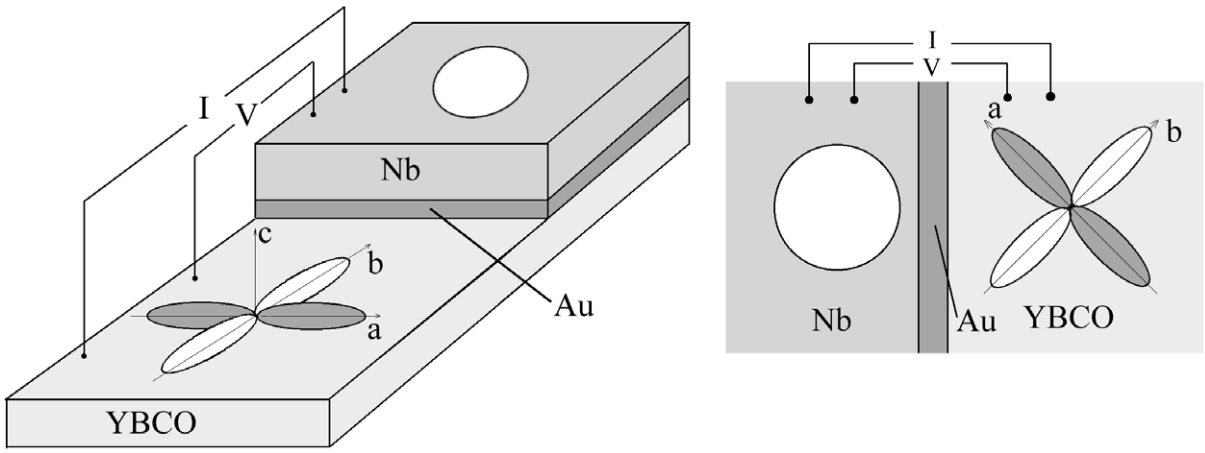

Fig.1. A sketch of S/D_c(a) and S/D_{45}(b) nano-junctions. D-wave and S-wave superconducting order parameters of the electrodes are shown schematically.

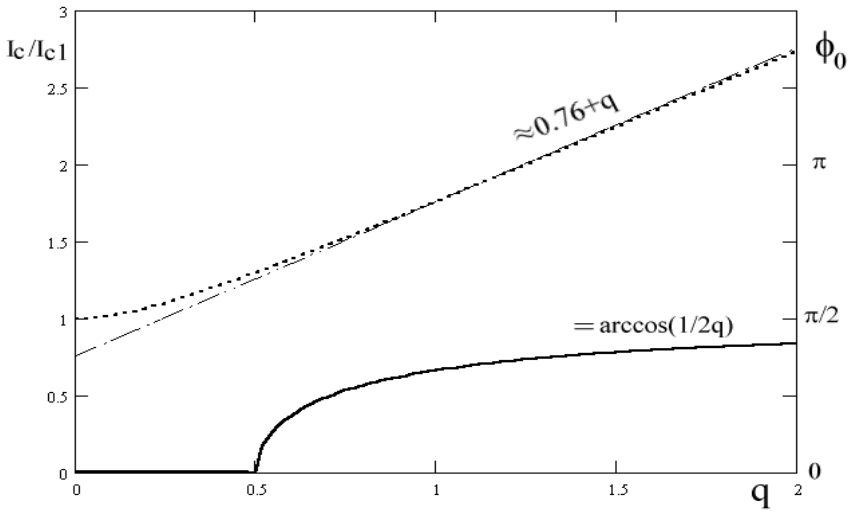

Fig.2. Normalized critical current vs. the weight q of 2-nd harmonic of CPR, (dashed line) and its asymptote (dash-dot line). Solid line shows the dependence of phase of the ground state $\varphi_0(q)$.

However it's impossible to unambiguously determine the distribution of the superconducting current density in a junction from experimental dependence $I_C(H)$. The surface morphology of (1 1 20) YBCO films on tilted substrate (7 10 2) $NdGaO_3$ was investigated by AFM that shows the film surface consists of rather large facets with lengths, exceeding the substrate roughness height, estimated 5 nm. While the surface facets of the *c*-axis oriented YBCO films on "standard" substrates (for example (001) $SrTiO_3$) have no preferable orientations, and the surface growth-facets of the YBCO films on the tilted substrates are parallel to the basic crystallographic axes of the film. Fig.1 shows a sketch of S/D_C and S/D_{45} nano-junctions formatted in our heterojunctions. Electrical properties of the originated S/D_C and S/D_{45} nano-junctions in Nb/Au/YBCO HJs are different because of strong anisotropy of YBCO. Superconducting current of such structure consists of the both 1-st and 2-nd harmonics of CPR: $I_S(\varphi)=I_{c1}\sin\varphi-I_{c2}\sin(2\varphi)=I_{c1}(\sin\varphi-q\sin(2\varphi))$, where $q=I_{c2}/I_{c1}$. Critical current of Josephson junction with such CPR will be smaller than the sum of harmonic amplitudes $I_c \le I_{c1}+I_{c2}$. Fig.2 shows normalized dependence of critical current I_c/I_{c1} vs. q and the phase of the ground state of HJ, which is no longer 0-junction if $q>1/2$, when the phase is shifted from $\varphi=0$ to some value $\varphi=\varphi_0(q)$.

An existence of the 2-nd harmonic in CPR should be resulted in non-integer Shapiro steps and subharmonic detector response. Fig. 3a shows the experimental dependences of the critical current amplitudes I_C and the first Shapiro step I_1 vs. $a=I_{MW}/I_C$, where I_{MW} is microwave current. Increasing the size L, a considerable deviation is observed in experimental $I_C(a)$ and $I_1(a)$ dependences from the calculated ones from modified RSJ model [4]. An approach for estimation of q values from I-V curves, affected by microwaves is described elsewhere [4]. Fig. 3b shows dependence of maximal amplitudes of the 1-st Shapiro step, I_{1max} vs. frequency f of applied signal. Theoretical dependence, predicted by RSJ model is shown on Fig. 3b. Note, calculations for S/D Josephson junctions also give very weak $I_S(f)$ variations for frequencies much smaller than those, corresponding to the energy gap of Nb. Consequently, in the framework of existing theories, the change in the value of I_{1max}/I_C must be small in the experimental frequency band $f = 36 \div 79$ GHz. An influence of the non-uniform distribution of the external microwave current, caused e.g. by intrinsic resonance of heterojunctions, on the dynamics of formation of the Shapiro step (and the value of I_{1max}) cannot not be ruled out either. At the same time we did not registered singularities, analogously to the Fiske resonance steps [6]. In order to verify origination of fractional Shapiro steps at weak enough external electromagnetic fields, the subharmonic selective detector response dependences were registered at mm-wave frequencies, including the frequencies much higher than the critical frequency of HJ.

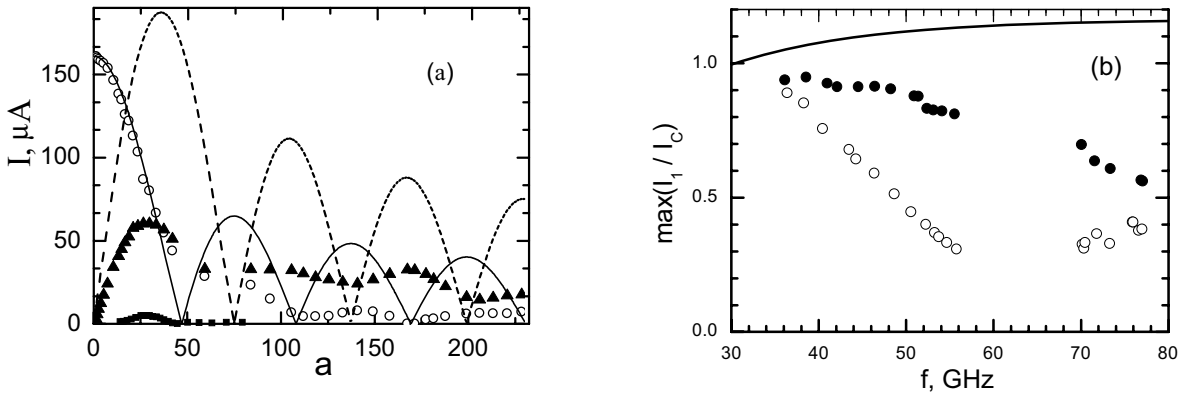

Fig. 3. (a) The critical current *Ic*, and integer and non-integer Shapiro steps I_1, $I_{1/2}$ vs. microwave current *a* for HJ with *L* = 40 μm at *T*=4.2 K and *f* =50.61 GHz. The theoretical $I_C(a)$ and $I_1(a)$ dependences are shown by solid and dashed curves, respectively. (b) Normalized maximal amplitudes of the first Shapiro step vs. frequency of applied microwave signal for HJ with *L* =20 μm (dark circles) and 40 μm (light circles). The solid line shows dependence, predicted by RSJ model.

4. Conclusion

The morphology of Nb/Au/YBCO heterostructure fabricated on tilted YBCO films shows existence of array of alternated S/D_c and S/D_{45} nano-junctions, having a second harmonic component in superconducting current-phase relation. The both magnetic and microwave properties of heterostructure demonstrate crossover from lumped to distributed Josephson junction behavior with effective magnetic field penetration length considerably smaller than calculated one, using an averaged critical current density. A reduction of penetration length could be speculatively attributed to appearance of splintered vortices in the HJs, considered as a array of nano-junctions with alternating sign of superconducting current density. The second harmonic of current-phase relation could be estimated using measurements of I-V curves under applied microwave signals when half-integer Shapiro steps occur, and from subharmonic detector response dependences. Our measurements demonstrate that the second harmonic of CPR increases with junction sizes, although the lumped Josephson junction limit was satisfied. The maximal amplitudes of the first fundamental Shapiro step heights exhibit frequency dependence, but the latter feature cannot be explained by splintered vortices model.

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