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Long-range microwave field induced interaction of two series connected YBaCuO bi-epitaxial Josephson junctions

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We report on experimental data on microwave field induced interaction of two series connected biepitaxial grain-boundary YBaCuO Josephson junctions, located at the distance much larger than the electrodynamic scale of mutual interaction for Josephson junctions. A noticeable rise (over the theory for the amplitudes of the principal n=1, as well the half-integral n=1/2, 3/2 Shapiro steps) was observed in mm-wave range at weak magnetic field $\Phi<\Phi_0$.

1. INTRODUCTION

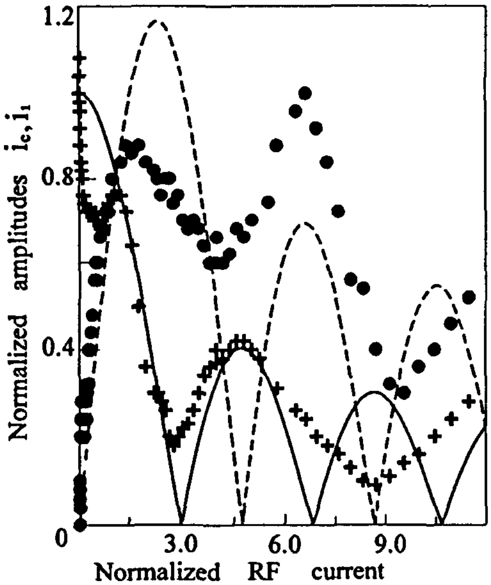
Update fabrication technologies of metal-oxide high-T_C superconducting Josephson junctions (JJs) utilize the experimentally proved evidence of weak links nucleation between interfaces of material grains. Such grain-boundary JJs are formed when an epitaxial thin film is deposited over an artificially made local nonhomogeneity as a step on a substrate, or using a bicrystal substrate. The first case usually leads to formation of two JJs [1], connected in series, separated at a distance l much larger than the coherence length ξ and the longitudinal penetration depth of quasiparticles into superconducting electrode l_Q. The latter one is known as a scale of mutual phase-locking due to quasiparticle interference over the coupling electrode [2]. Recently for the structures with two JJs in series, we have observed [3] a noticeable rise of the principal n=1 Shapiro step amplitude over the theoretical predictions of resistively shunted junction (RSJ) model. Because of absence of any effective coupling for JJs at experimental mm wave frequencies, the explanation of observed feature is not trivial and requires in-depth study for the both cases: of double junction structures, as well for a single JJ, serving as an interacting element in array.

2. EXPERIMENTAL

Patterned by photolithography w=4÷8 μm wide JJs were obtained using laser deposition of YBCO d=250 nm thick film over a low height step h=2÷5 nm on MgO substrates [4]. This technique involves angular 60° ion-beam substrate etching and laser deposition of c-oriented epitaxial film. Biepitaxial grain-boundary JJs were formed between the main electrodes and the thin film fragment l≈1 μm long, growth on the etched area with 45° rotation in a-b plane [4]. The I-V curves of those structures have been studied at microwaves $f_e\cong 30\div 50$ GHz and d.c. magnetic field. Samples exhibited critical current density $j_C=I_C/wd>10^7 A/cm^2$ (T=4.2K) for electrodes and $j_C\cong 10^2\div 10^5$ A/cm^2 for JJs. Measurements were performed in the shielded room, using low frequency filters for electric feeders, inserting the cryostat. Sample matching at mm waves was provided by the reduced height waveguide section and the impedance transformer to the standard one.

3. RESULTS AND DISCUSSION

Investigated samples with two series connected JJs usually demonstrate a noticeable spread of critical currents amplitudes. The "strong" junction with higher critical current was identified by well defined singularity on I-V curve due to transition to resistive state. Moreover, applying microwave field, the Shapiro steps amplitudes I_n (n=1/2, 1, 3/2, 2,...) for the "strong" JJ could be also easily defined in a wide range of microwave current I_{RF}, at list up to the first minimum of $I_n(I_{RF})$ function. In detail it discussed elsewhere [3]. Note, that at weak applied powers ($I_{RF}/I_C=i_{RF}<<0.1$) the measurements of detector response did not demonstrate an odd-resonant dependence [3], inherent to the phase-dependent selective detection. Minimization of the spread in critical currents in array with two JJs by application of d.c. magnetic field Φ, also did not lead to a synchronous lock-in detection even for the case when the critical currents became equal to each other.



The $i_C=I_C(i_{RF})/I_C(0)$: the solid line - the RSJ model, crosses - experiment. The $i_1=I_1(i_{RF})/I_C(0)$: dashes - RSJ model, experiment - the black circuits. T=4.2 K, $f_e \cong 52$ GHz.

At the all experimental frequencies $f_e \cong 36$, 44 and 52 GHz the observed Shapiro steps were strictly obeying to Josephson relation: $V=V_{n,m}=nm\Phi_0 f_e$, m=1 indicates the case of one operating JJ ($I_{C1} << I_{C2}$), m=2 is the case of two JJs, connected in series ($I_{C1} \approx I_{C2}$), Φ_0 - magnetic flux quantum. The critical current, and Shapiro step amplitudes $i_n=I_n(i_{RF})/I_C(0)$ had oscillating dependencies vs i_{RF} for the cases m=1 and m=2, as well for the both JJs in array. The critical current i_C and the Shapiro step amplitudes i_1 for n=1, m=2, measured at $f_e \approx 52$ GHz are given on the Figure. The corresponding theoretical functions have been calculated within the RSJ model for a single JJ, using experimental ratio $\Phi_0 f_e/I_{C1}R_{N1} \approx$ 1.65, R_{N1} - the normal state resistance of the first JJ, defined by differential resistance R_d at voltages $V< V(I_{C2})$. At applied power levels $i_{RF}>5$ a significant deviation of experimental $i_1(i_{RF})$ dependence and RSJ model took place: the experimental curves exceed over the theory at the second and the third local maxima at $i_{RF} \cong 13.5$ - (out of the figure). For n=1/2 the maximal amplitude $i_{1/2} \cong 0.56$ was measured as well. The higher order subharmonic steps had a similar behavior, indicated that the observed process differs from RSJ model predictions. Similar behavior of Shapiro step rise was reported in [2, 7], caused by mutual interaction due to nonequilibrium quasiparticles over the distance l_Q for closely located microbridges. In our experiment the distance l is much larger than $l>l_Q=(D\tau_E)^{1/2}$, D - the diffusity, τ_E - the branch mixing relaxation time. Using published data for YBCO thin films for T≅4.2 K on $D \approx 7 \cdot 10^{-3}$ cm^2/s [5] and on electron-phonon relaxation time $\tau_{e\text{-}ph} \approx 40$ ps [6] as a "measure" for τ_E in BCS approach at conditions of small energies ($kT << \Delta$, k - Boltzmann's constant, Δ - energy gap), the estimated $l_Q \approx 5$ nm. These results can be treated as an evidence of transformation of utter independent Josephson oscillation mode (for $i_{RF}=0$) of two JJs in a series array to a mode of a partial coherence under the influence of applied microwaves $i_{RF}>0$ and d.c. magnetic field $\Phi<\Phi_0$. Also, magnetic field has the strong influence on single JJ [3], but for the thin film separation region between two JJs it penetrates at the London depth $\lambda_L << l$ and has no influence on coupling of junctions. Discussed behavior can be caused [8] by a small, but a finite value of coupling energy of two JJs and by the shunting effect of the load impedance of waveguide system. At the same time, taking into account the results of modelling of such single grain-boundary as a parallel array of RSJ type JJs [3], the discussed microwave field induced interaction takes place for the system of two parallel arrays of junctions, coupled in series. This long range interaction took place at large applied powers $i_{RF}>1$, and had nonresonant nature, as been observed in a wide range of $f_e \cong 36 \div 52$ GHz.

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