ELSEVIER

Physica C 273 (1996) 21-29

PHYSICA C

Microwave dynamics of YBCO bi-epitaxial Josephson structures

K.Y. Constantinian [a,*], G.A. Ovsyannikov [a], A.D. Mashtakov [a], J. Ramos [b], Z.G. Ivanov [b], J. Mygind [c], N.F. Pedersen [c]

[a] *Institute of Radio Engineering and Electronics RAS, Mokhovaya 11, Moscow, 103907, Russia*
[b] *Physics Department, Chalmers Technical University, S-412 96, Gothenburg, Sweden*
[c] *Physics Department, Technical University of Denmark, Lyngby DK-2800, Denmark*

Received 25 August 1996

Abstract

The processes of interaction of microwaves (frequency $f_e = 30–55$ GHz) with a single high-T_c superconducting $YBa_2Cu_3O_x$ (YBCO) bi-epitaxial grain-boundary junction and with an array of two junctions connected in series, have been investigated experimentally at temperatures $T = 4.2–77$ K, and magnetic fields $B = -0.4$ to $+0.4$ mT. The results obtained experimentally were used as the input data for computer simulation which confirms the hypothesis that the current through the grain-boundary junction is transported by a parallel array of lumped Josephson junctions. This model for a grain-boundary junction explains the observed unusual magnetic field dependence of the critical current $I_c(B)$, and the deviations of dynamic processes from the predictions of the well known resistively shunted junction (RSJ) model: the existence of large amplitude subharmonic ($n = 1/2, 3/2,...$) Shapiro steps, as well as the subharmonic detector response at weak magnetic fields $\Phi < \Phi_0$. We also discuss the spectrum of this junction in connection with the half-integer Shapiro steps, and experimentally observed microwave field induced frequency synchronization of two series connected bi-epitaxial YBCO junctions.

Keywords: Josephson effect; Grain boundaries; Arrays; Spectrum

1. Introduction

The high anisotropy and short coherence length (1–2 nm) of metal-oxide high-T_c superconductors impose considerable restrictions on the creation of Josephson structures (JSs) based on well known fabrication techniques, as those used for conventional superconductors (see, e.g. Ref. [1]). For that reason some unusual approaches to solve the problem were evaluated utilizing the experimentally established evidence of weak link nucleation between the interfaces of the grain boundaries (GBs). Such GB JSs are usually formed by epitaxial thin film deposition over an artificially produced local inhomogeneity on the substrate as a step or over a bicrystal boundary [2–13].

For step-edge JSs one has to distinguish two cases: (a) when at bias current $I > I_c$ only one (single) GB JS works due to a large difference in the critical currents of the two GB JSs $I_{c1} < I_{c2}$; and (b) when I_{c1} and I_{c2} are of the same order and the two

* Corresponding author. Fax: +7 095 203 8414; E-mail: karen@hitech.cplire.ru

PII S0921-4534(96)00609-0

JSs are connected in series. This occurs [3,13] because of the non-identical conditions for each GB formation around a step, forming an angle with respect to the substrate (larger than 60°), with a height h equal to or sometimes exceeding the thin film thickness d. The existence of a array of two GB JSs has been already mentioned by experimental investigations [5], but most of the published data are only concerned with the case of a single GB JS [6,7,10–13]. The results on Josephson generation, emitted from a single high-T_c JS, indicated a significant deviation from the RSJ model [7,12,13], as the essential broadening of self-generation linewidths deviated from Lorenzian shape. At the same time the measurements of low frequency noise and magnetic characteristics indicate that GB JSs are to be considered rather as a complicated multijunction system, in some cases modelled by an array of N lumped Josephson junctions (JJs) connected in parallel. The comparison of experimental data and the results of computer simulation [10,11] confirms the applicability of such a model, which explains in particular the existence of subharmonic Shapiro steps at certain values of the applied magnetic field.

Recently a novel type of JS, modifying the step-edge geometry by sufficiently lowering the step height $h < d$ has been proposed [8,12]. This technique involves angular ion-beam substrate etching for a low height step fabrication and laser deposition of a c-oriented YBCO epitaxial film. The development of the substrate during ion beam etching leads to the formation of a thin film area rotated by 45° in the a–b plane, thus forming two GB JSs at the boundaries of the main film. This technique, which is similar to the case of step-edge JSs with $d \approx h$, applies to both cases, i.e. when the critical currents of two JSs are approximately equal $I_{c1} \approx I_c$, as well as when $I_{c1} \ll I_{c2}$.

In this paper we present the experimental results on mm wave frequency dynamics of both the single and double GB YBCO bi-epitaxial JSs, connected in series, as obtained at various temperatures T and a weak d.c. magnetic field B. The experimental data will be discussed in the context of the results of computer simulation of I–V curves, detector response and the spectrum of such structures, using the model of a parallel array of RSJ-type Josephson junctions for a single GB JS.

2. Experimental

The low height steps ($h = 2$–5 nm) on MgO substrates were formed by means of a photoresist mask and angular 60° ion-beam etching. After photoresist removal the YBCO film ($d = 250$ nm thick) was laser ablated on a heated 600–700°C substrate. The obtained thin films were c-oriented and exhibited critical temperature, in the range $T_c = 89$–91 K. A constricted thin film bridge structure with $w = 4$–8 μm was formed over the step by the conventional photolithography technique, using the ion-beam etching of a YBCO film [8]. A high enough critical current density $j_c = I_c/wd > 10^7\ \mathrm{A/cm^2}$ ($T = 4.2$ K) of YBCO electrodes, measured on both sides of the step, indicates homogeneity of the thin film and absence of weak links inside it. The j_c value, measured over the bridge crossing the step was suppressed to 10^2–$10^5\ \mathrm{A/cm^2}$, indicating the weak link formation around the step.

We have studied the I–V curves of those structures in an autonomous regime, for microwaves ($f_e \cong 30$–50 GHz) and d.c. controlled magnetic field. All measurements were carried out in a shielded room, using low frequency filters at each electric feeder, inserted into the cryostat. It is well known that a partial synchronization of the self-generation of the Josephson junction by applying a weak external electromagnetic field leads to a detector response $\eta(V)$ [1,7,14] with an odd-resonant type dependence in the vicinity of the bias voltage $V = hf_e/2e$. The $\eta(V)$ dependence is a convenient test to compare the dynamic characteristics of an autonomous JS (generation linewidth, spectrum of self-generation, etc.) with the theoretical models [7,12,14]. The computer modelling of the response of the JS to the applied microwaves and d.c. magnetic fields was provided by the PSCAN program [15], capable to automatically construct and integrate the differential equations for a multijunction Josephson network.

3. Results and discussion

The existence of two GBs in the obtained structure, formed due to rotation through 45° of the film fragment in the a–b plane, closely located to the step, was proved by transmission electron mi-

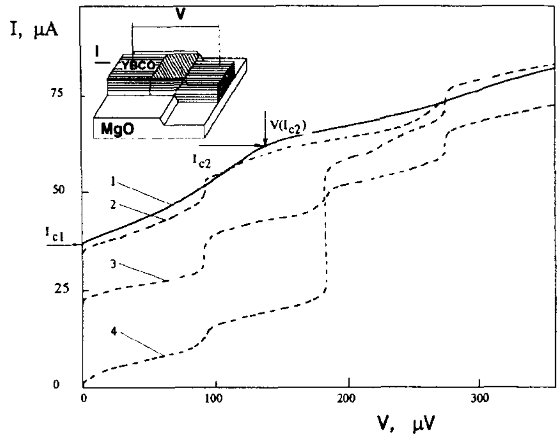

Fig. 1. The experimental I–V curves for JS YA2.6J2 at $T = 4.2$ K: the autonomous one - solid line (1); under microwave power at $f_e \cong 45$ GHz: the dashed lines, attenuation levels are 20 dB (curve 2), (3) - 10 dB, (4) - 5 dB. The arrows mark the critical currents of the first and the second junction, respectively. Inset shows a sketch of a substrate with high T_c thin film GB structure. The area to the left from the step corresponds to 45° rotated in a–b plane part of the film fragment, forming two GBs, connected in series. The arrow shows the direction of transport current. External magnetic field is perpendicular to the plane of the substrate.

croscopy [8]. The inset of Fig. 1 illustrates a sample with a deposited YBCO film over the low height step in the MgO substrate. The orientation of the film in the a–b plane coincided for both etched and the etch-free electrodes, whereas the thin-film area close to the step has been rotated through 45° (the angular cross-hatched area to the left of the step in the inset of Fig. 1). The location (near the step) of this in a–b plane misoriented film which was approximately 1 μm long, indicates that the film growth occurs in the shadowed area by the photoresist mask during the ion-beam etching.

A typical I–V curve of the investigated structures is shown in Fig. 1. Two parts can be discerned on the I–V curve, each one having approximately constant differential resistance R_d, separated by a singularity with a sharp R_d rise. Such a I–V curve shape is caused by a noticeable difference of the critical currents $I_{c1} < I_{c2}$ of the two GB JS. Increasing the transport current I leads to a sequence of transitions of both GBs into the resistive state, and a strong R_d singularity indicates the transition of a GB with a larger critical current I_{c2}. Further evidence of the existence of two GBs connected in series is the microwave test. For small applied powers P_e (curve 2 in Fig. 1) two current steps appear on both sides of $V(I_{c2})$. The current step at low voltage $V < V(I_{c2})$ strictly obeys the Josephson voltage–frequency relation: $V = V_{n,m} = nmhf_e/2e$, $n = m = 1$, where n is the harmonic number of the external microwave signal, causing the synchronization of Josephson self-generation, and $m = 1, 2$ is the number of JSs participating in this process. The second step on the I–V curve at $V > V(I_{c2})$ is an inclined one, and it depends on the applied microwave power P_e; its voltage consists of the sum of the voltages from the first junction for fixed bias $I(V > V_{1,1})$ and $V = hf_e/2e$ from the second one. Increasing the level of power P_e may lead to overlap of the current steps. As a result, we see on the I–V curve a set of current steps at the voltages $V_{n,2}$, for which the self-generation frequency of every GB is proportional to 2 eV/h (curves 3 and 4 in Fig. 1). At the same time the phase difference of the self-generating signals from the junctions could be of accidental value. This case differs from the mutual phase-locking in an array of coupled JJs, when the phase difference is fixed electrodynamically by the appropriate coupling [16].

The dynamic characteristics of two JSs connected in series are defined first of all by the spread of critical currents of the JS. However, in order to study the high frequency dynamics of complex JS in the vicinity of the frequency f_e of Josephson self-generation f, the voltage position of the first Shapiro step $V_{1,1} = hf_e/2e$ and the voltage $V(I_{c2})$ at which the second junction (with higher critical current) transits into the resistive state [16,17] become essential quantities. For a low spread of parameters and high enough frequencies $f_e > 2eV(_{c2})/h$ when $V_{1,1} > V(I_{c2})$, the microwave response of the structure is caused by the interaction processes of two GB and by an external force. For the case with a large spread $I_{c1} >> I_{c2}$ when $V(I_{c2}) >> V_{1,1}$ we can neglect (for the first order approach) the influence of the JS with a larger critical current, assuming that the whole dynamics is defined only by one GB, as the second GB is in a superconducting state. The parameters measured at $T = 4.2$ K of several samples illustrating both cases are given in Table 1. We shall begin to discuss the obtained results from the case of two GB JSs, when $I_{c1} \approx I_{c2}$.

3.1. Two bi-epitaxial GB JSs connected in series

I–V curve measurements of the sample YA2.24J3 which satisfy the requirement $V(I_{c2}) \le V_{1,1}$ were carried out at three fixed frequencies $f_e \cong 36$, 44 and 52 GHz of the applied microwave signal at a temperature $T = 4.2$ K. This low temperature allows one to neglect the influence of thermal fluctuations. Note that at $f_e \cong 36$ GHz for this sample $V(I_{c2}) \cong V_{1,1}$. The set of I–V curves, obtained at various levels of the applied microwave signal at $f_e \cong 52$ GHz when $V_{1,1}$ is slightly higher than $V(I_{c2})$ is presented in Fig. 2. It is seen that the strongest of the current steps is that at $V = V_{1,2}$, corresponding to the sum of the first Shapiro steps, nucleated by two GB. The presence of two GB is seen also from curves 3 and 4 of Fig. 2, analysing the singularities around the current step at $V = V_{1,2}$. This current step, located at the strongly doubled voltage $V_{1,2} = 2hf_e/2e$ corresponds to the sum of the Shapiro steps of two GB, synchronized by an external microwave power. The singularities around the step (the sharp change in R_d) marked by arrows in Fig. 2 indicate the synchronization region by microwaves for a junction with a larger I_c in this structure of a series array. Note also that strictly vertical Shapiro steps at $V = V_{2,2}$ (these voltages are out of the figure) at small P_e have also been observed at all other experimental frequencies f_e.

The same figure also shows the vertical subharmonic current steps with $n = 1/2$, $m = 2$ (see curve 2 on Fig. 2). The subharmonic steps were registered in the whole experimental range of voltages $V \le 0.5$ mV. Note also that these steps, located at $V = V_{n,2}$ were divisible by $n = 1/4$, and, varying the applied power P_e, caused them to transform periodically to inclined ones and again into vertical steps. This behaviour can be explained by rather more severe requirements for phase locking by an external force of subharmonic steps than that of ordinary Shapiro steps. The critical current and the current steps, including the subharmonic ones, had oscillating dependence on the microwave current I_{RF} for both GBs.

Table 1
The main characteristics of the tested samples at $T = 4.2$ K

No	h, nm	w, μm	R_N, Ω	I_{c1}, μA	$V(I_{c2})$, μV
YA26J1	3	8	1	100	> 1000
YA2.6J2	3	4	6	36	140
YA2.4J1	3	8	36	30	120
YA2.3J5	5	8	2	7500	> 1000
YA2.7J5	2	8	2	3000	> 1000
YA2.24J3	10	7	2	80	70

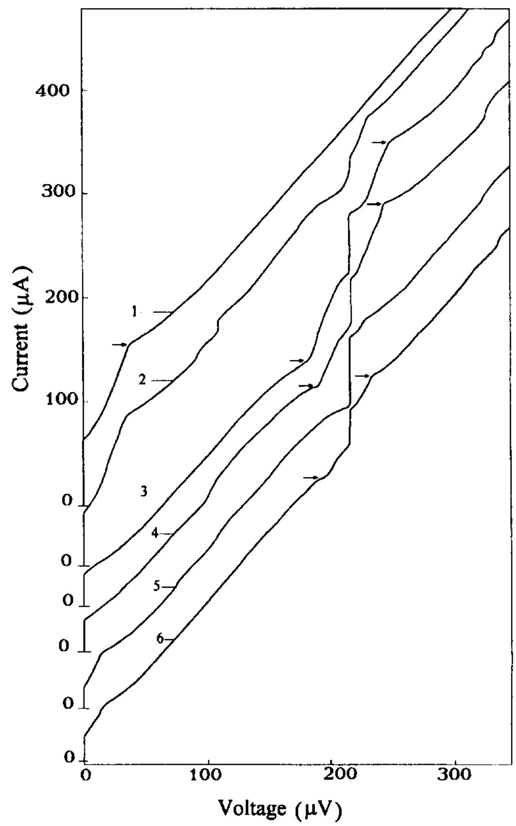

Fig. 2. The I–V curves for JS YA2.24J3 at $T = 4.2$ K, measured at various levels of microwaves at $f \cong 52$ GHz: (1) - no power, (2) - 32.5 dB attenuation, (3) - 21.0 dB, (4) - 17.4 dB, (5) - 15.2 dB, (6) - 12.8 dB. The arrows point out the singularities corresponding to the transition to the resistive state and the appearance of the Shapiro step of the second junction. The curves 2–6 are shifted along the I axis, the scales are kept constant for all curves.

The normalised dependence of the critical current $i_{c1} = I_{c1}/I_{c1}(0)$ and the current step $i_{11} = I_{11}/I_{c1}(0)$ measured at $V = V_{1,2}$ on $i_{RF} = I_{RF}/I_{c1}(0)$ at $f_e \approx 52$ GHz is presented in Fig. 3. The corresponding theoretical functions of the RSJ model for a lumped JJ, calculated for the experimental ratio $hf_e/2eI_{c1}R_{N1} \approx 1.65$, where the normal state resistance of the first GB R_{N1}, is given at the same figure. From Fig. 3 it is seen also that the $i_{c1}(i_{RF})$ and $i_{11}(i_{RF})$ dependence

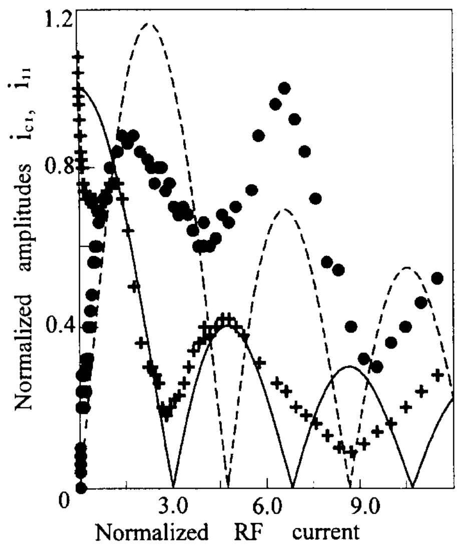

Fig. 3. The dependencies of normalised critical current $i_{c1} = I_{c1}(i_{RF})/I_{c1}(0)$: (the solid line - the RSJ model, crosses - experimental data) and Shapiro step amplitudes $i_{11} = I_{11}(i_{RF})/I_c(0)$, measured at bias voltage $V = V_{1,2}$ (RSJ model - dashes, experiment - the circuits) for JS YA2.24J3, $T = 4.2$ K, $f_e \cong 52$ GHz.

in the range $i_{RF} < 4.5$ (with i_{RF} up to the first local minimum of i_{c1}) are satisfactorily well fitted to the theoretical curve. This indicates that the estimated value of the JS critical frequency which is the main parameter of high frequency dynamic characteristics [1], is near to that obtained from d.c. measurements: $= (2e/h)I_c R_N$. At relatively high power levels $i_{RF} > 5$ there is a significant deviation (see the figure) of the experimental i_{11} data and RSJ model. Experimental curves lie higher than the theoretical ones at the second and the third local maxima. Note that in the case of operating of two independent JSs, such a discrepancy has too large an amplitude $i_{11}(i_{RF} \approx 6) \cong 1$, and is not allowed by the RSJ model [16]. A similar behaviour of the experimental quantities exceeding the maximal amplitude of the current step at $V = V_{1,2}$ as determined by theory (RSJ model) was reported on closely located Sn microbridges and was caused by mutual interactions of the junction via nonequilibrium quasiparticles [16,18]. At the same time the weak signal $i_{RF} < 0.1$ response of the detector at $f_e \cong f$ of the Josephson structure with two GBs did not demonstrate an odd-resonant shape, as expected for phase-dependent selective detection. Varying the magnetic field also did not lead to a synchronous detection, even for the case when the critical currents of GBs became equal $I_{c1} = I_{c2}$ (the sample YA2.6J2). These results provide evidence for the transformation of a totally independent generation mode of two JSs to a mode of partial coherence under the strong influence of an applied electromagnetic field [19], probably caused by the small but nonzero coupling energy of two GB JSs.

3.2. Single bi-epitaxial GB JS

For JSs having $I_{c1} < I_{c2}$ (see Fig. 4), the autonomous I–V curve exhibits only one part of the rise of R_d at low voltages $V < V_0 = I_c R_N$ with a

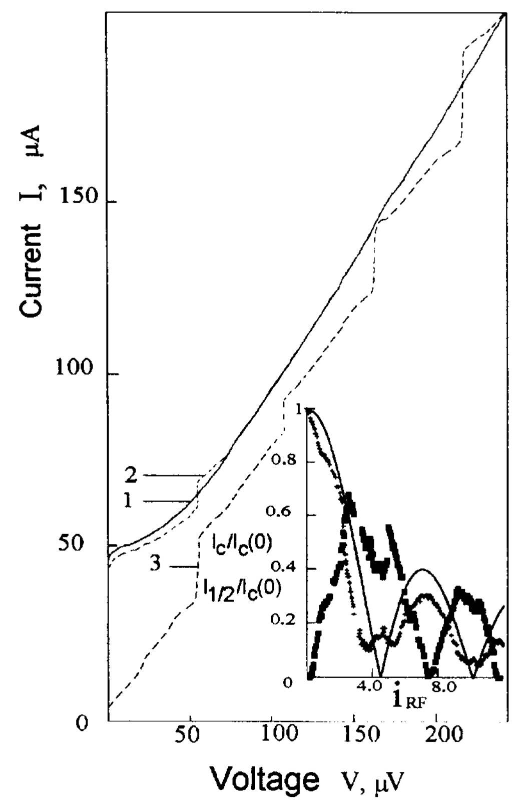

Fig. 4. I–V curves ($T = 4.2$) K under different power of microwaves ($f_e \cong 52$ GHz) for JS YA2.6J1 with one "operating" GB. Curve (1) - no power, (2) attenuation - 26 dB, (3)- 5,6 dB. The inset shows experimental dependencies from applied microwave signal (i_{RF}) of normalised critical current (the crosses) and subharmonic $n = 1/2$ Shapiro step (squares). The solid line $I_c(i_{RF})$ is a function of the RSJ model, calculated for the experimental value of $I_c R_N$ product.

shape predicted by the RSJ model. At the same time several discrepancies with the RSJ type behaviour have been revealed. For high bias currents $I >> I_c$ a noticeable excess current (the I–V curve shifts from the slope $V = IR_n$) took place. Such behaviour is known for superconducting weak links with nontunnel type of conductance. Similar peculiarities were noticed also for double GB structures. The harmonic current steps as well as the subharmonic ones are also seen in Fig. 4 at $V = V_{n,1}$ (dashed lines). Note that subharmonic steps with $n = 1/2$ and $3/2$ (see Fig. 3) exhibit oscillating dependence on i_{RF}, shown in the inset of Fig. 4. The subharmonic steps were also parallel to each other, with nucleation beginning from low $i_{RF} > 0.2$, then increasing with i_{RF} in the sequence $n = 1/2$, 1, 3/2, 2 and so on. According to the RSJ model, for a lumped JJ the subharmonic steps cannot be measured [1]. In the course of the experiment, independently of the n number, the current steps at certain values of $i_{RF} \leq 2$ crossed over the autonomous I–V curve and demonstrated that the shape is close to a hyperbolic one. In the inset of the Fig. 4 the $i_c(i_{RF})$ and $i_{1/2}(i_{RF})$ dependences are shown, obtained at $f_e \cong 52$ GHz and $T = 4.2$ K; the solid line shows the theoretical dependence $i_c(i_{RF})$ according to the RSJ model for $hf_e/2eV_0 \approx 1.5$. It is seen that the experimental dependence $i_c(i_{RF})$ corresponds to that of the RSJ with an oscillating period, but the minima of $i_c(i_{RF})$ are noticeably broadened. A correlation of the singularities is also evident: the drops at the maxima of $i_{1/2}(i_{RF})$ correspond to the hillocks at the minima of $i_c(i_{RF})$.

For a number of samples increasing the temperature allowed us to obtain a better fit of the experimental results to the RSJ model. At $T = 77$ K the oscillating period $i_c(i_{RF})$ and amplitude of the first maximum of the $n = 1$ Shapiro step corresponds to the RSJ model with 10% accuracy without any subharmonic steps.

Fig. 5 shows the experimental dependence of the critical current on the applied d.c. magnetic field $I_c(B)$. The direction of B is perpendicular to the substrate plane ($T = 4.2$ K). It is seen that independently of the direction of the transport current I, the oscillating type shape of $I_c(B)$ is practically symmetric relative to $I_c = 0$. In the case of high T_c junctions the symmetric (repeatability) of $I_c(B)$ is not obvious, that is why the obtained symmetric functions we treat as measurements not obtained by accident. The shift of the $I_c(B)$ maximum from $B = 0$ may be caused by the residual field B_a. However, we do not discuss in this paper the physical nature of such a shift. A significant difference from a Fraunhofer pattern function, typical for a JJ with a homogeneous distribution of a critical current density, is registered. The obtained dependence of $I_c(B)$ corresponds to JJs connected in parallel like SQUIDs, rather than a lumped JJ. Moreover, the appearance of more high maxima at increased values of B indicates the essentially inhomogeneous distribution of the current density at the GB [4,11]. At higher temperatures $T > 4.2$ K the registered $I_c(B)$ functions were squid-like too. The reason for such a behaviour is the significant degree of inhomogeneity in JS, indicated as well for other types of GB junctions [3]. The simplest model of such JSs can be an array of lumped JJs coupled in parallel inductively (due to superconducting electrodes) [10].

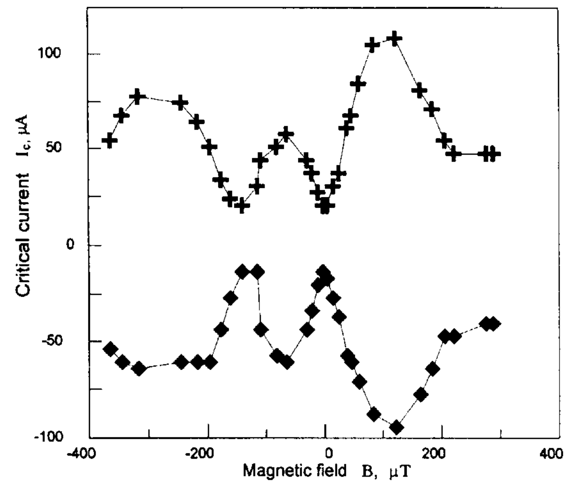

Fig. 5. Magnetic field dependencies of critical current for direct (crosses) and reverse (squares) current for JS YA2.6.J1 measured at $T = 4.2$ K.

4. The digital model and comparison with experiment

For digital simulation of a single GB JS we use a model of N lumped JJs, inductively coupled in parallel. Such an array of 5 junctions is shown on

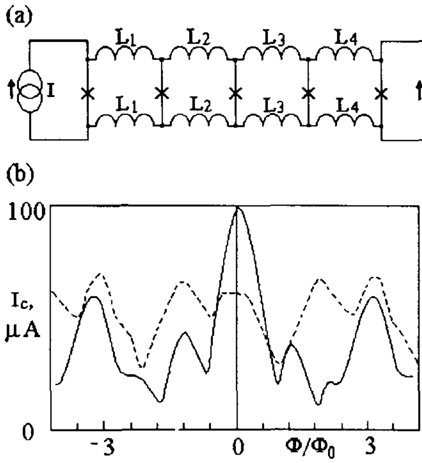

Fig. 6. (a)The model of GB JS consisted of $N = 5$ parallel lumped JJs, coupled via inductances $L_1 - L_N$. (b) The simulated by model (a) dependencies of the critical current versus magnetic flux $I_c(\Phi)$, obtained for small $L_1 = L_2 = 1.3$ pH, $L_3 = L_4 = 2.6$ pH inductances (solid line), and large inductances $L_1 = L_2 = 13$ pH, $L_3 = L_4 = 26$ pH (dashes).

Fig. 6a. The number of JJs is varied as $N = 4...8$. The bias current is fed symmetrically to the end boundaries of the array during the experimental procedure, where the superconducting thin film electrodes are used as bias leads of the JS. It is known that in a superconducting thin film of width w, d.c. current flows along the edges of width of $\lambda_\perp = \lambda_L^2/d$, where $\lambda_\perp$ is the magnetic field penetration depth into superconducting thin film with thickness less than the London penetration depth $d < \lambda_L$. Each of the JJs in this model is chosen obeying the RSJ model when the junction capacitance C is negligibly small (McCumber parameter $\beta_c = 2\pi CR_n < 1$). The fixed parameter is $V_0 = 100$ μV, the critical currents of all junctions in the array are chosen equal to each other, taking into account the experimentally measured value of I_c. For the case under discussion of sample JA2.6J1 (see Table 1) we have $I_c = 100$ μA. The sum of coupling the inductance $L_1 + L_2 + L_3 + L_4 = 8$ pH was equal to the inductance $L \cong \mu_0 w$ ($\mu_0 = 4\pi 10^7$ H/m is the magnetic permeability of free space) of a slot line which is as long as the junction width $w = 8$ μm. For the case of identical values of L_i the critical currents of each JJ is approximately equal to 20 μA. For the calculation the total current was taken as a sum of a d.c. and an oscillating component, the output controlled parameter was the time average voltage at the JS. Note that for the chosen parameters of inductances the total critical current for the model is about 97% of the sum of all critical currents of the array with $N = 5$; the dimensionless inductance of the circuits $l = (2\pi/\Phi_0)2LI_c$ varied with N in the range $l = 0.02$–0.1. It is found that beginning from $N = 5$, the model demonstrates a behaviour qualitatively similar to the experiment, and for that reason why we will discuss mainly this case. Fig. 6b shows the magnetic field dependence of the critical current for the array when the current was set for each of the four circuits. The magnetic flux Φ is proportional to the inductance of each circuit, thus each of them is influenced by an identical Φ value. The abscissa of Fig. 6b is the magnetic flux of the ensemble average of all circuits. For small inductances $L_1 + L_n + ... + L_4 < 8$ pH the maximum of I_c was at $B = 0$. The $I_c(B)$ function used to model the structure demonstrates some local maxima of different heights, caused by interference of two $I_c(B)$ components, characterised by different oscillating periods. The ratio of the periods was about 2 and is the result of our choice of inductances $L_1/L_3 = L_2/L_4 = 2$. A similar dependence of $I_c(B)$ was recorded in the experiment (see Fig. 5). The dashed line in Fig. 6b shows $I_c(B)$ obtained for a large L value, for this case the maximum of I_c is located at $B \neq 0$. It is caused by the current spread from the boundaries which becomes possible only for the case of large inductance $l \approx 1$. Note that this case gives a better fit to experiment, although such large inductances L_N ($N = 1..5$) exceeded the estimated inductance values for experimental JSs.

The measured data of detector responses $\eta(V)$ to microwave at $f \cong 30.5$ GHz and the corresponding I–V curves ($T = 4.2$ K, $B \cong +52$ μT and $B \cong -153$ μT) for a single GB are shown in Fig. 7. The results of structure simulation ($N = 5$) for the same Φ/Φ_0 values are presented in Fig. 7. The odd-resonant shape of the $\eta(V)$ functions, both experimental and simulated, is the evidence of a synchronous detecting process. At the same time the subharmonic Shapiro step is seen at $V = V_{1/2,1}$ on the theoretical curves, as well as the experimental curve measured at a magnetic field, noticeably suppressing $I_c(0)$. Such a discrepancy for conditions of magnetically suppressed and unsuppressed cases is caused by the deviation of the spectrum of Josephson self radiation

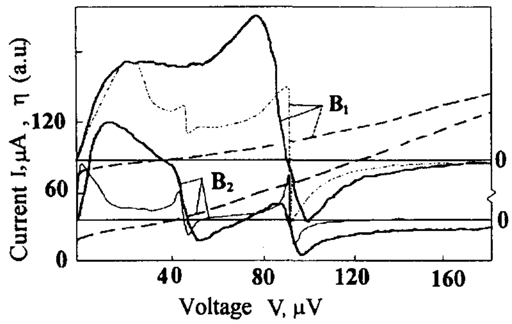

Fig. 7. The I–V curves (dashes) of JS and detector responses $\eta(V)$ in arbitrary units (solid lines) for two external d.c. magnetic fields: $B_1 \cong +52$ μT and $B_2 \cong -153$ μT. $T = 4.2$ K, $f_e \cong 30.5$ GHz. The $\eta(V)$ functions, corresponding to experimental conditions, obtained by digital simulation for the same magnetic fields are shown by the thin lines.

with respect to the magnetic field. The absence of subharmonic response at $I_c = I_c^{max}(B)$ in the experiment and its weakness in the theoretical modelling (also asymmetric around the $\eta = 0$) indicates the absence of any coherence of processes in this case.

This model for GB of a parallel connection of N JJs can also explain some other peculiarities, revealed experimentally. Thus, on the $i_{c1}(i_{RF})$ curves at $f_e \cong 44$ GHz and 52 GHz an N-like singularity (a local rise and a drop) occurred (see Fig. 3) in the vicinity of $i_{RF} \approx 1$, which for both frequencies corresponded to the first maximum of the subharmonic current step amplitude $i_{1/2}(i_{RF})$; for $f_e \cong 52$ GHz the maximum amplitude was as large as $i_{1/2}^{max}(i_{RF}) \cong 0.4$. The N-like singularity on the $i_{c1}(i_{RF})$ dependence was mentioned also in Ref. [10], where a single YBCO GB was modelled by $N = 2$ in parallel JJs, obeying the RSJ model. For this model in Ref. [10] the oscillating dependence of the Shapiro steps at $n = 1/2$, 1, 3/2 and 2 have also been obtained at certain levels of the magnetic field, corresponding to the minima of experimental $I_c(B)$ function. The maximum amplitude of the subharmonic Shapiro step [10] was about $i_{1/2} \cong 0.2$, which is approximately 3.5 times smaller than that of our experimental case (see inset in Fig. 4). The existence of excess in the $i_{c1} > 1$ amplitude over the RSJ model in the range of weak microwave signals $i_{RF} < 0.1$ (see Fig. 3) can be explained by the slow variation of the external magnetic field, which is essential for systems of parallel connected JJs, even in the case of ordinary usage of magnetic screens with nonzero residual magnetisation.

The spectrum analysis by means of this model shows the absence of any subharmonic self-radiating components. This indicates that subharmonic Shapiro steps are only caused by harmonics of self Josephson radiation and applied microwave signal, and that no processes similar to period doubling take place.

Using this model and the published results [20] on Josephson mm-wave radiation from inductively strongly coupled squids connected in series, the JS consisting of two bi-epitaxial JJs in series could be represented as a multijunction structure (say 5 parallel junctions), inductively weakly coupled by a superconducting film in between. This weak coupling explains the absence of mutual synchronization observed in the experiment in autonomous mode operation.

5. Conclusions

The presented results on the experimental study of high T_c bi-epitaxial JSs, formed in a YBCO thin film bridge, crossing a low height step on the substrate, are typical for GB Josephson structures characterized by a noticeable inhomogeneous distribution of critical current density taking place in a wide temperature range $T < T_c$, which leads to a significant deviation from RSJ model. The analysis of the dynamics of the transformation of the I–V curves under the influence of applied microwave signals demonstrates a moderately good fit of the critical frequency to the RSJ model: $f_c \approx V_0/\Phi_0$. At the same time the experimental evidence of the deviation from the RSJ model, such as "squid-like" behavior of $I_c(B)$, the presence of subharmonic Shapiro steps at small magnetic fields and some other features, can be at least qualitatively explained by a model for GB of a parallel inductively coupled array of JJs, each obeying the RSJ model.

The detector response on a weak mm-wave signal of a single GB, measured at various voltages, corresponding to the subharmonic Shapiro step $n = 1/2$ and occurring for certain values of the applied magnetic field, is evidence of a significant deviation of the phase-frequency characteristics of the self-radiation spectrum (with pronounced harmonic components) of a parallel array of JJs (the model) from the RSJ model spectrum of a lumped JJ. It means that the $I-V$ curve and the spectrum of self-radiation are strongly dependent on the external weak magnetic field $B < \Phi_0/wd$, which defines the high frequency dynamics of GB, revealed when a microwave signal is applied. The experimental data on two GB connected in series indicate that their mutual interaction occurs only under the influence of a strong external electromagnetic field $i_{RF} > 1$, reducing the parameter sensitivity on the Shapiro steps. The synchronization becomes possible due to small but nonzero coupling energy of two GB via the superconducting films between the two GB of the JSs. The registered wide range of parameters f_e and P_e, corresponding to frequency synchronization of two GB JS in series can be treated as evidence of their nonresonant interaction. The absence of phase synchronization even for the case when their critical currents were equal (due to the applied magnetic field) showed that the coupling energy of these GBs is too small for mutual phase locking in the autonomous mode.

Acknowledgements

The authors wish to acknowledge P.B. Mozhaev and V.K. Kornev for fruitful discussions. The work was partially supported by the Russian Programme "Actual Problem of Condensed Matter Physics", subdivision "Superconductivity"; Russian Fund for Basic Research; INTAS project of EU; and NATO Collaborative Research Grant 960173.

References

[1] K.K. Likharev, B.T. Ulrikh, Systems with Josephson junctions Moscow State University (1978) p. 446.
[2] D. Dimos, P. Chaudhari, J. Mannhart, Phys. Rev. B 41 (1990) 4038.
[3] J. Halbritter, Phys. Rev. B 48 (1993) 9735.
[4] B.H. Moeckly, D.K. Lathrop, R.A. Buhrman, Phys. Rev. B 47 (1993) 400.
[5] K. Hermann, G. Kunkel, M. Siegel et al., J. Appl. Phys. 78 (1995) 1131.
[6] E. Serenely, P. Chaudhari, J. Lacy, Appl. Phys. Lett. 62 (1993) 774.
[7] Yu. Yak. Divin, A.V. Andreev, G.M. Fischer et al., Appl. Phys. Lett. 62 (1993) 1295.
[8] J. Ramos, Z.G. Ivanov, S. Zarembinski, T. Claeson, Appl. Phys. Lett. 63 (1993) 2141.
[9] J.A. Edwards, J.S. Satchell, N.G. Chew et al., Appl. Phys. Lett. 60 (1992) 2433.
[10] E.A. Early, R.L. Steiner, A.F. Clark, K. Char, Phys. Rev. B 50 (1994) 9409.
[11] R.L. Kautz, S.P. Benz, C.D. Reintsema, Appl. Phys. Lett. 65 (1994) 1445.
[12] G.A. Ovsyannikov, J. Ramos, Z.G. Ivanov et al., Physica C 235-240 (1994) 3239.
[13] L.E. Amatuni, R.M. Martirossian, K.Y. Constantinian, Phys. Tech. Lett. 20 (1994) 128.
[14] G.A. Ovsyannikov, G.E. Babayan, V.N. Laptev, V.I. Makhov, IEEE MAG-27 (1991) 2688.
[15] S.V. Polonsky, V.K. Semenov, P.N. Shevchenko, in: Extended Abstracts, Third Intern. Superconducting Electronics Conf., Glasgow, 1991, p. 160.
[16] L.E. Amatuni, V.N. Gubankov, G.A. Ovsyannikov, Sov. J. Low Temp. Phys. 9 (1983) 484.
[17] K.Y. Constantinian, G.A. Ovsyannikov, A.D. Mashtakov et al. in: Proc. 5th Intern. Superconducting Electronic Conf. (ISEC'95) (1995) p. 384.
[18] M. Octavio, W.J. Skocpol, J. Appl. Phys. 50 (1979) 3505.
[19] S.I. Borovicki, A.M. Klushin, Sov. Phys. Tech. Letters 7 (1981) 382.
[20] V.K. Kaplunenko, J. Mygind, N.F. Pedersen, A.V. Ustinov, J. Appl. Phys. 73 (1993) 2019.