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To cite this article: A M Klushin *et al* 2006 *J. Phys.: Conf. Ser.* **43** 281

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Bicrystal Josephson junctions and arrays in a Fabry-Perot resonator

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Abstract. Full frequency locking of an array of 121 Josephson junctions was demonstrated upon millimeter wave irradiation employing a Fabry-Perot resonator at 73 GHz. This result indicates that such arrays exhibit promising properties to be utilized in quantum voltage metrology. On the other hand, the combination of such arrays with THz-Fabry Perot resonators is very challenging for developing Josephson array radiation sources for the THz frequency band.

1. Introduction

All Josephson voltage devices practically used at present in national calibration laboratories and companies make use of conventional superconductors like Nb [1, 2]. This requires a low operating temperature of 4.2 K and, in general, liquid helium for cooling. The use of junction technology on the basis of non-metallic high temperature superconductors (HTS) will allow to overcome this limitation. The HTS junction technology presently available for voltage metrology has been developed at Forschungszentrum Jülich GmbH. It enables fabrication of microwave driven series arrays for reference voltages of 10 mV [3]. The drive frequency amounts to 32 GHz. Due to the relatively low frequency, the microwave coupling circuit is large which prevents the use of a considerably larger number of junctions. As a result, the DC output voltage is low. To further improve the performance of HTS arrays, it is therefore of great importance to raise the maximum drive frequency to about 70 GHz. A higher output voltage would reduce the complexity and improve the reproducibility of the DC voltage calibrators and secondary voltage standards based on HTS arrays. Quantum based secondary standards could be employed in practically all laboratories applying Zener references and digital voltmeters with a Zener reference which requires permanent and expensive re-calibration. Moreover, increasing the output voltage with the use of a higher drive frequency would be an important step towards long-term development of a primary Josephson voltage standard on the basis of HTS junctions with very simple cooling.

The aim of this paper is investigation of Josephson junctions in the resonator Fabry-Perot in the frequency band from 70 GHz to 80 GHz which is a new method of irradiation of junctions with electromagnetic fields. An effective coupling of Josephson junctions with electromagnetic oscillations in an open resonator could be also used for elaborating electromagnetic sources up to terahertz frequency band. The arrays of parallel connected junctions will form the base of such sources.

2. Experimental results and discussion

2.1. Bicrystal junction technology

We have investigated Josephson junctions made on commercially fabricated symmetrical bicrystal yttria-stabilized zirconia (YSZ) substrates ([001] tilt) with misorientation angle 24°. According to the manufacturer, the accuracy of the misorientation angle was ~1°. Epitaxial $YB_2Cu_3O_7$ (YBCO) films were formed by reactive high-oxygen-pressure metal co-evaporation, using a rotating substrate holder. The substrate temperature was 665 °C and the deposition rate about 0.4 nm/s. To prevent interface reactions, 10 nm thick Y_2O_3 buffer layers were deposited prior to depositing the YBCO films. The details of the intermittent film deposition scheme have been published previously [4]. YBCO films with thicknesses d from 0.2 μm to 0.3 μm were fabricated. The contactless inductive method was used for measuring the transition temperature T_c and the critical current density of superconducting films. T_c was 87 K to 89 K. The critical current density j_c of these films was typically larger than 2×10^6 A/cm^2 at 77 K. *In situ* evaporated, thin gold films were used as a shunt layer. After cooling to room temperature in 200 mbar of dry oxygen, the chamber was evacuated again and a 100 nm thick gold cap layer was deposited. This process guarantees typical interface contact resistivities of the order of 10^{-8} Ω cm^2, which are essential for effective shunting of grain boundary junctions. Each 10×10 mm YBCO film or an Au–YBCO bilayer was patterned using a standard positive photoresist. The pattern transfer was achieved using Ar$^+$ ion milling at 250 eV with a beam current density of ~2.5 A/m^2. Patterned microbridges with a width of 6 μm across the grain boundary thus forming Josephson junctions. On each substrate two independent series arrays of 400 junctions with a lateral size of 4 mm were fabricated. Special thin film current leads allowed independent dc-bias currents and voltage measurements on separate subarrays. After cutting the substrate two samples with dimensions of 5×10 mm were investigated in Fabry-Perot resonator.

2.2. Fabry-Pérot resonator design

The Fabry-Perot resonator was arranged in a hemispherical configuration in which plane and spherical mirrors were used. In such configuration a flat sample can be used as a plane mirror and small diameter specimens can be investigated. Low sensitivity of the quality factor of the resonator to the deviation from the parallelism between the mirrors is also important. Such resonators have been used extensively at millimeter and sub millimeter wavelength for investigation of electromagnetic properties of YBCO films [5, 6], in electron spin resonance spectrometers for the study of spectra of metallic and dielectric (solid and liquid) samples [7, 8].

A sample with an array forming a plane mirror of a hemispherical resonator is shown in figure 1. The radius of the spherical mirror of $R = 25$ mm and the distance between the mirrors of about d = 24 mm determinate the optimum frequency from 73 GHz to 74 GHz. In this case the radii of the beam waist ω_0, which is obtained at the plain mirror for fundamental TEM_{00q} mode was equal to 2.5 mm. At the distance ω_0 normal to the center axis of the resonator the electric field falls to 1/e of its value on the axis.

For an effective coupling of the microwave power to Josephson junctions high quality factor, Q_0 of the resonator is very important. Each contribution to the resonant mode losses can be described in terms of individual Q-factor, Q_i, which combines in parallel to give $Q_0 = 1/\sum (Q_i)^{-1}$. In our case small width of the sample (5 mm) limits the quality factor of the resonator $Q_0 = 50$. With a plain mirror with dimensions of 10×10 mm the quality factor was equal to 3500, as it is shown in figure 2. The design of the Fabry-Perot resonator allows us to use a standard liquid nitrogen dewar for the irradiation of arrays in the millimeter wave frequency band from 70 GHz to 80 GHz.
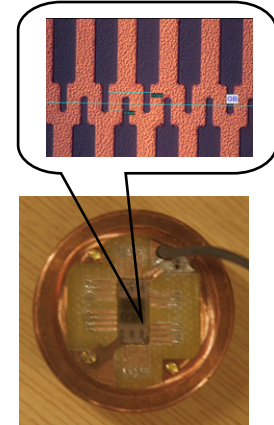

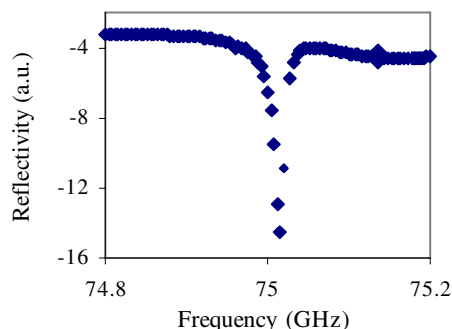Figure 1. Sample holder with mounted bicrystal substrate. Enlarged portion demonstrate meander type array.

Figure 2. Resonator reflectivity with a plane mirror 10×10 mm.

2.3. Influence of electric field polarization on the microwave coupling to Josephson junctions

When investigating the interaction of Josephson junctions with an external electromagnetic field in the resonator the mutual angle orientation of the polarization of the electrical field and the array of Josephson junctions is very important. For the coupling of microwave energy into the resonator we comprised a standard TE_{10} mode WR-10 waveguide butted into rectangular recess in the back surface of the spherical mirror. Loops of magnetic field emanate from the aperture which thus acts as a magnetic dipole radiating into a half space. The polarization of the field determinates the polarization of currents flowing along the plane mirror. Thus the orientation of the vectors of electric field is determinated by the orientation of the waveguide.

For the investigation of the angle dependence we rotated the sample holder relative to the waveguide. In figure 3 the current voltage (*IV*) characteristics of a single bicrystal junction are shown for two mutual orientations of the meander and electrical field E in the waveguide. *IV* curves were measured without microwave frequency (curves α) and at under irradiation at the resonant frequency $f = 73.913$ GHz (curves β), equal power level and temperature $T = 77$ K. Figure 3a represents the data for parallel orientation of the meander and electrical field. The mutual orientation is shown schematically in the insertion located at the foot in the right hand corner of figure 3a. In this case the Shapiro steps are clearly visible which documented strong coupling with an external electromagnetic field. It should be noted that the dependence of the Shapiro step height on the misorientation angle is not too strong. A small deviation from the parallelism between vector E and the meander does not influence the step height. But under 90° rotation of the sample on the coupling becomes lower as it is shown in figure 3b. The same result was achieved for the arrays of Josephson junctions.

The nature of such angle dependence is not fully understandable at present. We can suppose that under the condition shown in figure 3b the junctions are connected in series for dc current but par-
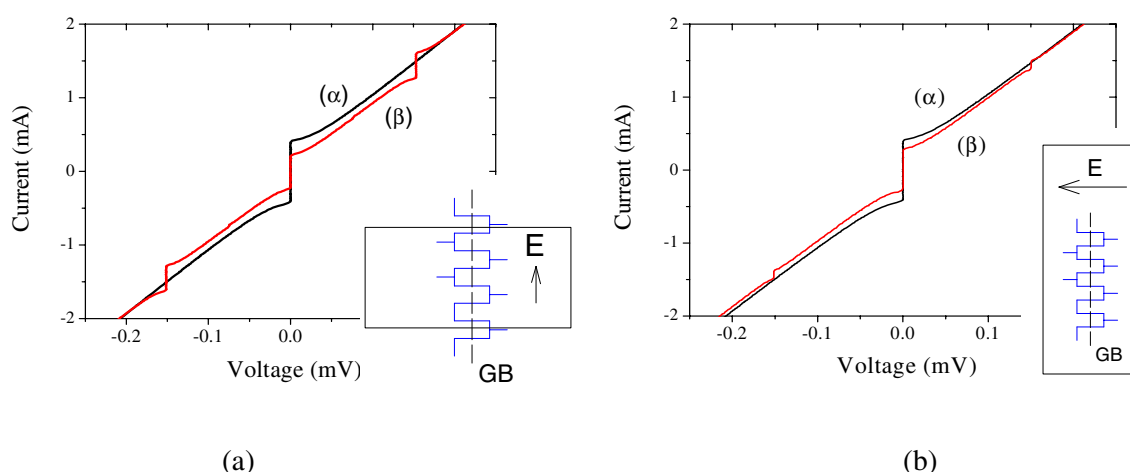

(a)

(b)

Figure 3. Dependence of the width of the first Shapiro step on polarization of an electromagnetic filed E. Resonance frequency $f = 73.913$ GHz, temperature $T = 77$ K. Meander – schematic view of the series array of Josephson junctions, E – vector of electrostatic intensity of external millimeter wave field in a waveguide, GB – grain boundary.

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allel to ac current. In this case the dc and ac currents are flowing in opposite directions in one of the halves of the meander. This can be the reason of the week coupling of the external field with the array.

In the case shown in figure 3a due to the inductive coupling of external field to the meander loop ac and dc currents flow in the same directions thus providing more effective coupling of the junctions with external millimeter wave signal.
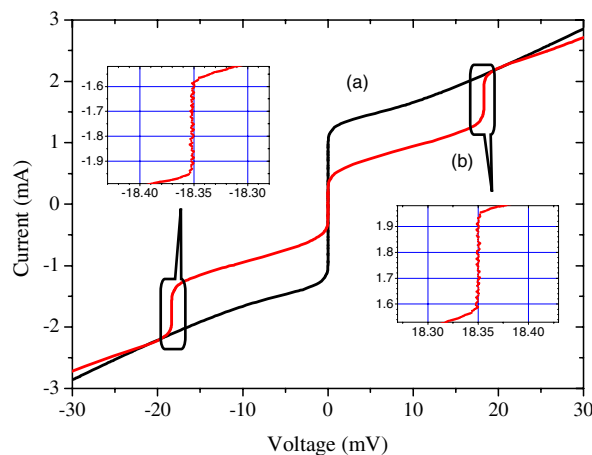

Figure 4. Current-voltage characteristics for a series array of 121 junctions at 77 K without (a) and with (b) external irradiation. Enlarged portions demonstrate the steps' widths and their steepness.

2.4. Arrays of bicrystal junctions

The Josephson junctions in the array had an average critical current of $I_c = 1$ mA, the resistance of the shunted junctions was $0.12\ \Omega$. The resulting characteristic voltage $V_c = 0.12$ mV was at optimum for the observation of the first voltage step under millimeter wave irradiation. Figure 4 shows current-voltage characteristics of a sub-array of 121 series connected junctions without and with applied power at frequency of 73.388 GHz. The inset in figure 4 shows an enlarged portion of the *IV*-curve (b) demonstrating steep steps with a height $\Delta I_1 > 0.3$ mA at a voltage $V_J = 18.35$ mV. This result documents that those arrays of HTS Josephson junctions exhibit promising properties to be utilized in quantum voltage metrology.

Conclusions

Investigations of arrays of Josephson junctions embedded in resonator Fabry-Perot show the effectiveness of the suggested method for synchronization of arrays with an external millimeter wave signal on resonance frequency. The further increase the output voltage generated on arrays of HTS junctions would be possible under increasing of the quality factor of the resonator. To increase the quality factor it is important to increase, first, the dimensions of the plane mirror and second, the resonant frequency. For example, one mm increase of the substrate dimension corresponds to one order increase of Q_0. The use of the whole 10×10 мм bicrystal substrate with a single circuit located in its centre is a suitable possibility for this purpose. Embedding such arrays of HTS junctions in THz Fabry-Perot resonator is very challenging for developing new THz-array oscillators.

References
[1]   Hamilton C A 2000 *Rev. Scient. Instrum.* **71** 3611
[2]   Niemeyer J 2000 *Supercond. Sci. Technol.* **13** 546
[3]   Klushin A M, Behr R, Numssen K, Siegel M, and Niemeyer J 2002 *Appl. Phys. Lett.* **80** 1972
[4]   Klushin A M, Weber C, Darula M, Semerad R, Prusseit W, Kohlstedt H, and Braginski A I
        1998 *Supercond. Sci. Technol.* **11** 609
[5]   Orbach-Werbig S 1994 WUB-DIS 94-9
[6]   Schwab R 1999 Forschungszentrum Karlsruhe GmbH, Karlsruhe
[7]   Clarke R N, and. Rosenberg C B 1982 *J.Phys. E: Sci. Instrum.* **15** 9
[8]   Rohrer M, Krzystek J, Williams V, and Brunel L-C 1999 *Meas. Sci. Technol.* **10** 275