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Accurate measurements of quantum voltage steps on arrays of bicrystal Josephson junctions

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Quantum voltages of an array of $YBa_2Cu_3O_7$ bicrystal junctions were calibrated against a programmable Josephson array voltage standard. We demonstrated that steps of the current–voltage characteristic of an array of bicrystal junctions at voltages of about 9 mV were flat over the current range of about 80 μA to within six parts in 10^8. The coincidence of quantum voltages on the array of high-temperature superconductor junctions at 64 K and the reference voltage on the array of niobium junctions at 4.2 K was measured with an uncertainty of two parts in 10^8. With the same uncertainty, we revealed the coincidence of the Josephson constant $K_J \equiv h/2e$ in $YBa_2Cu_3O_7$ and in metallic superconductors. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1458072]

Series-connected Josephson junctions with nonhysteretic current–voltage ($I-V$) characteristics are of great interest for use in the new generation of voltage standards.[1,2] As a reference the quantum dc voltage,

$$V_J = nN\frac{f}{K_J}, \tag{1}$$

generated on a Shapiro step with index $n = \pm 1$ was used. Here N is the number of junctions and f the irradiation frequency. The implementation of high temperature superconductor (HTS) junctions in voltage metrology offers new additional advantages and a reduction in the price of the cooling equipment. At the current state of HTS junction technology, shunted bicrystal Josephson junction arrays are one of the best choices for such an application.[3] However, their use in scientific and industrial metrology faces two significant challenges.

One of them is the universality of the Josephson relation, Eq. (1). Its independence of experimental conditions is of fundamental importance for quantum voltage metrology. The accuracy of Eq. (1) was the subject of many tests both for conventional metallic superconductors[1] and oxide HTS.[4–6] In the most precise experiments[7,8] it was established that K_J is the same in different types of metallic Josephson junctions to at least three parts in 10^{19}. However, the coincidence of the Josephson constant in oxide and metallic superconductors, especially at elevated temperatures, was revealed to have a much higher uncertainty, within five parts in 10^6.

The second challenge is to demonstrate experimentally the metrologically relevant flatness of Shapiro steps that are generated on arrays of HTS junctions. There are two reasons that lead to the final slope of the steps. They are the spread of the parameters in the array and thermal fluctuations at elevated temperatures. The influence of these effects on the slope of the step generated on an array of $YBa_2Cu_3O_7$ (YBCO) shunted bicrystal junctions at voltage $V_{J,\mathrm{YBCO}} \approx 10$ mV and liquid nitrogen temperatures was recently measured. It was demonstrated that the step is flat within an uncertainty of about one part in 10^6.[9]

The purpose of this letter is to report a substantial decrease in the uncertainty with which the slope of the Shapiro step on the array of bicrystal junctions and the Josephson constant in HTS was established. These results were obtained by direct calibration of quantum voltages of $V_{J,\mathrm{YBCO}}$ versus a programmable Josephson array voltage standard (JAVS) at the Physikalisch-Technische Bundesanstalt (PTB).[10]

Shunted bicrystal junctions were fabricated using Au–YBCO bilayers deposited *in situ* on symmetrical yttrium-stabilized zirconium substrates with a misorientation angle of 19°. Details of the technology of the HTS junctions were published earlier.[11] The full series array of 512 junctions, each 4 μm wide, had a length of 6 mm. Special thin-film low-pass filters allowed an independent dc bias and voltage measurement of separate parts of the array. For the microwave power irradiation, we placed the meander array in a microwave housing parallel to the feed line, which was made on a quartz substrate 0.3 mm thick.

The part of the series array containing $N = 136$ junctions was synchronized by ac bias current in the frequency range

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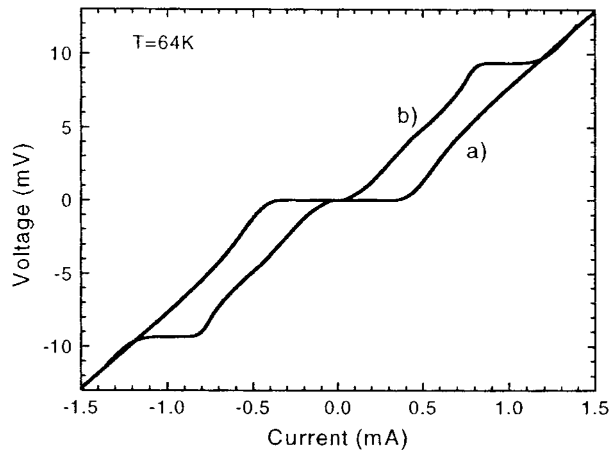

FIG. 1. Series array of 136 bicrystal junctions (a) without and (b) with microwave power at frequency $f=32.059\,18$ GHz.

of 25–40 GHz. As the microwave power source an HP 83640 synthesizer phase locked to a rubidium frequency standard with a relative frequency stability of 5×10^{-11} was used. This technique allowed us to observe metrologically relevant steps at voltages from 7 to 10.2 mV for $n=\pm1$ and at 14 mV for $n=\pm2$.[9]

The programmable JAVS at PTB is based on a superconductor–insulator–normal metal–insulator–superconductor (SINIS) array that is fabricated by reliable Nb–Al/AlO$_x$ technology. The SINIS array was cooled by liquid helium and operated at microwave frequencies of 70 and 73 GHz locked to a 10 MHz time base that traces back to PTB's atomic clock. At a microwave power of about 10 mW, large Shapiro steps with widths of more than 1 mA were obtained at a bias current of 2 mA.[10] The binary weighted 1 V array had 8192 junctions in 64 microwave strip line paths. To achieve a voltage of $V_J\approx9$ mV, 62 junctions were set to the first step (two bits).[10] The suitability of SINIS junctions for metrological purposes like Josephson voltage standards has been demonstrated previously.[12]

For a direct comparison, HTS and niobium arrays were set in series opposition and the difference voltage $\Delta V=V_{J,\mathrm{YBCO}}-V_J$ was measured with an analog EM N1a nanovoltmeter.[13] At certain bias current values, a computer read 20 data from a Keithley 182 nanovoltmeter that was connected to the output leads of the EM. With this setup two experiments were performed.

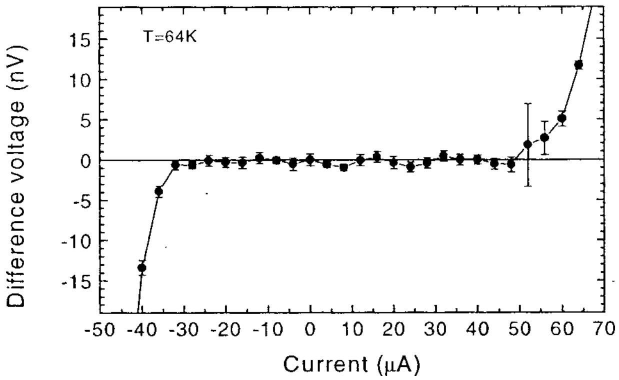

FIG. 2. High resolution plot of the quantum step induced on the HTS series array at frequency $f=32.059\,18$ GHz. The voltage was compensated for by the programmable SINIS array with 62 junctions at $f=70.340\,09$ GHz and $V_J=9.017\,999$ mV. Standard deviations (type A) are equal to 1σ. The line serves as a guide only.

TABLE I. Summary of experimental results and uncertainties.

Run No.	ΔV (nV)	σ (nV)	m	u_{c_m} (nV)	u_{c_zero} (nV)	u_c (nV)
2001-06-06	+0.787	0.911	12	0.260	0.63	0.63
2001-06-07	+0.104	0.870	24	0.180	0.90	0.92
2001-06-08	−0.176	0.707	24	0.145	0.10	0.15

We have investigated the flatness of the step generated in the HTS array. For that the voltage difference was measured with the dc bias being successively varied along the step of interest. To reduce uncertainties due to the drifts of thermal electromotive force (emf), every third measurement was made at the center of the step. These measurements were used to calculate the time-dependent drift of thermal emf and to correct all the data for that drift.[12] Over 3 days 12 measurement runs were performed. Each run included 30–50 measurements along the HTS current step. The uncertainty in the measurements, given as the standard deviation of the mean σ which changed from run to run, was limited due to null-detector noise and drift of the thermal electromotive force during calibrations.

The step flatness was measured for voltages from 9 to 9.4 mV. As an example, $I-V$ characteristics without and with microwave irradiation are shown in Fig. 1. Precision measurements of the critical current of the array revealed $I_c=300\ \mu$A at a temperature of 64 K, which was achieved by liquid nitrogen vapor pumping. The average resistance for shunted junctions was $R=0.064\ \Omega$. Therefore the minimum characteristic voltage $V_c=I_cR$ was 19.2 μV. As shown in Fig. 1(b) at frequency of 32.059 18 GHz and power level of about 12 mW, we observed the step at $V_{J,\mathrm{YBCO}}=9.016$ mV.

It was found that the amplitude of the Shapiro step is symmetrical for $n=\pm1$ and this amplitude ΔI_1 is about 0.25 I_c. The step amplitude varied over a range of 70–90 μA depending on the irradiation frequency in accordance with the uniformity of the microwave bias current distribution in the HTS array. The standard uncertainties over ΔI_1, given as 1 σ, were found to be in the subnanovolt range for 90% of the measurements (see Fig. 2). This result demonstrates that the current step is flat within six parts in 10^8 over the current range of 80 μA.

In the second experiment the precision calibration of $V_{J,\mathrm{YBCO}}$ was performed by the JAVS. For that the voltage difference ΔV was measured for two polarities of dc bias currents of the arrays. The typical amount of time for taking the data of such a single ± measurement was 1 min. Measurements of the three different quantized voltages were performed over 3 days as shown in Table 1. Here ΔV is the voltage difference which was measured for $m\pm$ measurements with standard deviation of the mean σ, u_{c_m} is the standard uncertainty of the measurement, while u_{c_zero} and u_c are the systematic uncertainties due to nonlinearity of the null detector for that measurement and the overall uncertainty for the comparison, respectively. Additional uncertainties for direct comparisons arose from leakage currents and offsets of the frequencies. We determined the uncertainty for the frequency as being equal to 2×10^{-10}, while the uncertainty for leakage resistance was estimated to be less than one part in 10^{10}.[14] Therefore, these two uncertainties can be neglected. The nonlinearity of the null detector measured in our case was about 1×10^{-3}, and led to an increase in the measurement uncertainty of u_{c_zero}. This influence of nonlinearity can be reduced when both polarities are measured at the same deflection. Although the stability of both our measuring systems was perfect, it was difficult to set both voltages (including the thermal voltages) to the values so that the null detector had the same deflection at both polarities. The zero balance of the null detector was limited by frequency adjustment. At least on the last day of the comparison, we found the required frequencies, which clearly reduced the uncertainty of ΔV to within two parts in 10^8 as shown in Table I for measurement run No. 3. In view of the voltage difference and the uncertainty in the comparison we had to take a weighted mean of the step-to-step measurements. The result of the comparison presented as the difference between the value assigned to a 9.3 mV standard and the combined standard uncertainty was $\Delta V=-0.04\pm0.17$ nV. Consequently, the Josephson constants in HTS and in metallic superconductors coincide within the estimated uncertainty of 1.7 parts in 10^8.

In conclusion, we have shown that arrays of YBCO shunted bicrystal junctions are suitable for metrological purposes at elevated temperatures. Presently, the quantum reference voltages achieved are used to develop dc voltage standards[15] with an uncertainty of the output voltage that is comparable to that typical of electronic standards based on Zener diodes,[16] but with noticeable advantages. The application of a reference voltage generated on HTS arrays permits one to ignore the influence of pressure, temperature and humidity on the output voltage of the standard. Moreover, the arrays investigated are promising for developing an arbitrary voltage waveform synthesizer with quantum-mechanical accuracy.[1,17] This device will be important not only in ac and dc voltage metrology, but also in modern communication systems and low-noise radar, and for the calibration of electronic instruments.

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