Noise Properties of $YBa_2Cu_3O_7$ Josephson Junction Array Magnetometers

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***Abstract*—We have fabricated magnetometers based on the magnetic field dependence of the critical current of 24° bicrystal Josephson junctions from the high temperature superconductor (HTS) $YBa_2Cu_3O_7$. The field sensitivity is increased with additional flux focusers up to $\partial I_c/\partial B = 130\,\mathrm{A/T}$. Because the voltage modulation and signal-to-noise ratio increases with the number of junctions, serial arrays of up to 105 junctions are employed. At 77 K we obtain a transfer function of $\partial V/\partial B = 7500\,\mathrm{V/T}$ and a white noise level of $\sqrt{S_B} = 1.2\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ for the largest array. The $1/f$ noise component from critical current fluctuations in the junctions is suppressable by a simple flux modulation scheme.**

I. Introduction

For magnetic sensors, Josephson junctions are commonly employed in superconducting quantum interference devices (SQUIDs), which have reached flux density noise levels as low as about $\sqrt{S_B} = 30\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ in simple single-layer layouts [1], [2]. A single Josephson junction can also be used as a magnetometer, if one takes advantage of the magnetic field dependence of the junction's critical current, commonly referred to as the Fraunhofer pattern. Although the underlying field period of the Fraunhofer pattern is in general much larger than a typical SQUID modulation period, a large sensitivity enhancement can be obtained with additional flux concentrating structures. This was successfully demonstrated by Martin *et al.*, who achieved a field sensitivity of $\partial I_c/\partial B = 176\,\mathrm{A/T}$ and a noise level of $\sqrt{S_B} = 3.7\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ by attaching a flux concentrator to a single 24° bicrystal junction of $10\,\mu$m width [3]. Bicrystal Josephson junctions are favourable, because flux can easily penetrate the junction area, and the junction's electrodes cause additional flux focusing, due to corner effects on the current distribution near the grain boundary [4], [5]. In contrast, ramp-edge junctions are much more shielded against external flux, because the top electrode covers the junction barrier. As in the case of SQUIDs, an important figure of merit is the amplitude of the voltage modulation for the current biased device when a magnetic field is applied. The signal-to-noise ratio can be increased by using several junctions in series, since the modulation amplitude scales linearly with the number of junctions N, whereas the voltage noise only scales with $\sqrt{N}$, if the noise sources are independent. Lee *et al.* used a similar approach for a serial array HTS SQUID magnetometer [6]. In contrast to SQUIDs, the operating point of the array magnetometer is related to the central maximum of the Fraunhofer pattern, hence in principle absolute magnetic flux densities can be measured. Voltage noise due to critical current fluctuations in the junctions can be suppressed by a simple flux modulation scheme, whereas the out-of-phase current fluctuations in SQUID magnetometers have to be suppressed by additional bias current modulation. Due to the high output voltage of a serial array, the demand on the preamplifier input noise is much lower than for a typical SQUID.

Here we present a magnetometer based on a serial array of 105 bicrystal Josephson junctions with additional flux focusing areas. Besides the scaling properties of the critical current I_c and normal state resistance R_n, the noise properties for different numbers of junctions in the array are discussed.

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II. Preparation

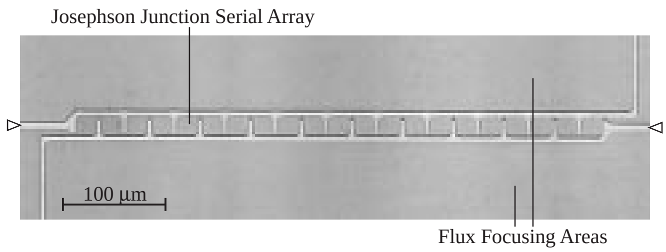

Fig. 1. Optical micrograph of a 21-junction serial array embedded between flux focusers. The figure displays an area of $570 \times 170\,\mu\mathrm{m}^2$. The position of the grain boundary is indicated by the arrows.

The serial arrays are prepared from a single epitaxial $YBa_2Cu_3O_7$ thin-film on a symmetrical (100) $SrTiO_3$ bicrystal with 24° misorientation angle. The $YBa_2Cu_3O_7$ films are deposited using our KrF excimer laser deposition process, that is described elsewhere in detail [7]. We typically use a film of about 120 nm thickness. The almost particle free films allow highly reproducible junction properties on a large scale which is a prerequisite for our junction arrays. After the patterning with conventional photolithography and argon plasma etching, the arrays are treated in an oxygen plasma. The contact pads are covered with 100 nm silver to reduce the contact resistance for low noise measurements. In Fig. 1, an optical micrograph of a 21-junction subarray is depicted. Five identical subarrays are connected in series, but each can be measured seperately. The junctions have a width of $20\,\mu$m to achieve a high sensitivity to external magnetic fields. Additionally, the array is embedded between flux focusing superconducting areas, which cover almost the whole substrate of $1 \times 1\,\mathrm{cm}^2$. The gaps between these areas and the junctions are $4\,\mu$m wide.

III. Measurements

The arrays were characterized by electrical transport and noise measurements. All measurements were made in liquid nitrogen with the arrays well shielded against ambient magnetic fields by a double Cryoperm shield.

A. Transport measurements

In order to investigate the degree of flux concentration from the flux focusers, we measured the critical current dependence on the applied magnetic field, both for a single $20\,\mu m$ wide junction without flux focuser and for the junction array embedded between superconducting areas. The resulting Fraunhofer patterns are depicted in Fig. 2.

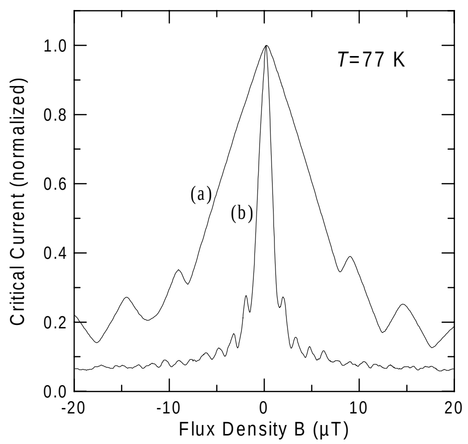

Fig. 2. (a) Fraunhofer pattern of a single bicrystal junction of $20\,\mu$m width without flux focusing and (b) Fraunhofer pattern of the serial array magnetometer of 105 junctions between flux focusers.

The triangular shape and the shallow minima of curve (a) indicate that the junctions are in the wide limit, i.e. the geometrical junction width is comparable or larger than the Josephson penetration depth [8]

$$\lambda_J = \left(\frac{\hbar}{4e\mu_0\lambda_L J_0}\right)^{1/2}. \qquad (1)$$

λ_L is the London penetration depth and J_0 the critical current density of the junctions. λ_J is about $2.4\,\mu$m for our junctions. The effective flux collecting area for the bare junction, as calculated from the spacing of the minima, is about $350\,\mu\mathrm{m}^2$, i.e. 25 times larger than the geometrical area. This sensitivity enhancement is attributed to the flux focusing effect of the junction's electrodes. For the array, the flux focusers again increase the sensitivity by a factor of 4.2, as is illustrated by curve (b) in Fig. 2. The regular shape up to the higher order side lobes emphasizes the high homogeneity of the grain boundary Josephson junctions in the array. At 77 K, a maximum field sensitivity of about $\partial I_c/\partial B = 130\,\mathrm{A/T}$ is obtained at the side of the center maximum. The excess current for the whole 105-junction array is about 6% of the critical current, as is estimated from the base level of the Fraunhofer pattern.

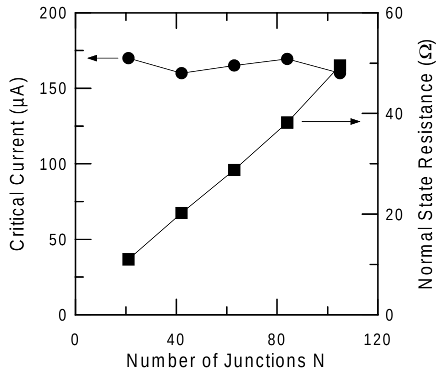

Fig. 3. Critical current and normal state resistance for the junction arrays at 77 K versus N.

The measured current-voltage characteristics of the subarrays can be well described by the resistively shunted junction model. In Fig. 3 the deduced values for I_c and R_n are depicted as a function of the number N of junctions in the array. To avoid the case that one subarray dominates all measurements, we chose different combinations of subarrays, so that no one was part of all five combinations. We find an almost linear increase of R_n and a constant critical current independent from N within 5%; hence the I_cR_n product also increases linearly with N. For 105 junctions we obtain $I_cR_n = 7.9\,\mathrm{mV}$. Additional differential resistance measurements were performed at 4.2 K to reveal the distribution of the individual critical currents in a 42-junction subarray. For the resolved critical currents a mean value of 2.8 mA and a standard deviation of $\sigma = 0.65\,\mathrm{mA}$ is found [9].

Our array magnetometers are operated in the current biased mode. Analogous to SQUIDs, the appropriate figure of merit is the voltage modulation as a function of the applied field and the corresponding maximum transfer function $\partial V/\partial B$. However, the array modulation is nonperiodic and the operating point is well defined, so that absolute field measurements become possible. This is in contrast to SQUIDs operated in the common flux locked loop (FLL) mode. For the same applied field, the dc output level of the SQUID FLL electronics can differ by discrete amounts, due to the periodicity of the

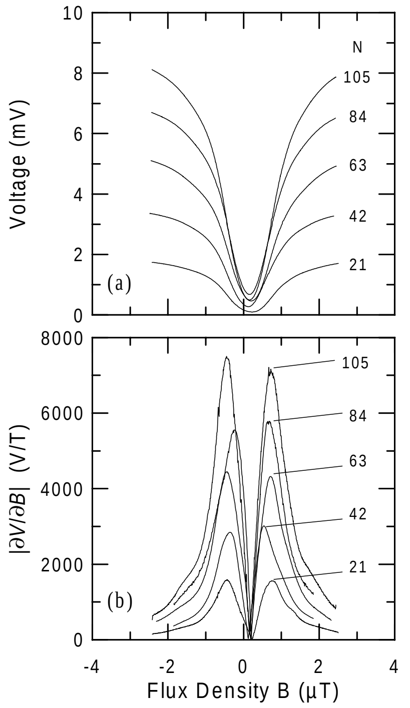

Fig. 4. (a) Voltage across the current biased junction arrays versus the external magnetic flux density. (b) Transfer function $|\partial V/\partial B|$.

SQUID's flux-voltage characteristics. Fig. 4(a) shows the voltage modulation for different subarrays versus the external magnetic flux density. Because the shape of the curves depends on the bias current, this was adjusted for each array to obtain the maximum transfer function. Due to the low excess current, nearly the full I_cR_n product is transferred into voltage modulation, i.e. about 7.5 mV for the largest array of 105 junctions. Differential measurements of the transfer function are depicted in Fig. 4(b). Although an increased linearity range can be expected from the triangular Fraunhofer pattern of the single junction in Fig. 2(a), this is not found for the arrays, where the operation with optimum sensitivity is limited to the narrow maxima in Fig. 4. The slight asymmetry in the characteristics complicates the noise measurement with flux modulation, that will be discussed in the following paragraph.

B. Noise properties

According to the theory of the resistively shunted tunnel junction, the voltage noise spectral density of a single junction from thermal fluctuations is predicted to be [10]

$$S_V = \left[1 + \frac{1}{2}\left(\frac{I_c}{I}\right)^2\right] \frac{4k_BTR_D^2}{R_n}, \qquad (2)$$

where $R_D = \partial V/\partial I$ denotes the dynamic resistance at the bias current I. With typical parameters for our bicrystal junctions a voltage noise level of about $\sqrt{S_V} = 120\,\mathrm{pV}/\sqrt{\mathrm{Hz}}$ is calculated. The voltage noise of a serial array of N junctions should increase as $\sqrt{N}$, if the noise

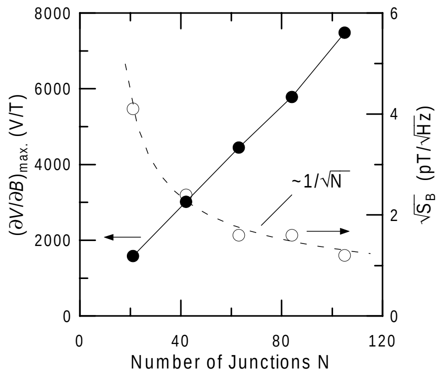

Fig. 5. Maximum transfer function and flux density noise at 2 kHz of the array magnetometers versus the number of junctions integrated in the array. The dashed line indicates a $1/\sqrt{N}$ dependence.

sources are uncorrelated. The flux density noise of the array is obtained by dividing the voltage noise by the corresponding transfer function

$$\sqrt{S_B} = \sqrt{S_V} / \left(\frac{\partial V}{\partial B}\right). \qquad (3)$$

From the linear increase of the I_cR_n product with N, a linear increase of the voltage modulation and the maximum transfer function is expected. The maximum values for $|\partial V/\partial B|$ were deduced from the curves in Fig. 4(b) and are plotted in Fig. 5. They clearly show the expected linear behaviour. The transfer function of $\partial V/\partial B = 7500\,\mathrm{V/T}$ for 105 junctions is comparable to directly coupled SQUID magnetometers from HTS single-layers. The high transfer function of the SQUID magnetometer, despite its small voltage modulation, is due to the large effective area $A_{\mathrm{eff}} = \partial\Phi/\partial B$ of about $0.2\,\mathrm{mm}^2$. On the other hand, for the junction array we have a very large voltage modulation, but a small effective area. For 105 junctions, $\sqrt{S_V} \simeq 1.2\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and $\sqrt{S_B} \simeq 160\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ for $\partial V/\partial B = 7500\,\mathrm{V/T}$ is expected. However, a small signal measurement at 2 kHz at a bias flux of $0.75\,\mu\mathrm{T}$ for the maximum transfer function yielded a voltage noise of about $9\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and $\sqrt{S_B} = 1.2\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at 77 K. The discrepancy with the theoretical prediction is not yet understood, but it is also found in SQUIDs from HTS Josephson junctions [11]. The flux density noise values for all measured subarrays are included in Fig. 5. Due to the linear increase of $\partial V/\partial B$, we find a decrease of $\sqrt{S_B}$ with N that fits well to the expected $1/\sqrt{N}$ behaviour. However, the absolute magnitude of the noise is larger than expected.

Flux density noise spectra for different subarrays at 77 K are depicted in Fig. 6. They were measured with fixed bias current either with static flux or with 2 kHz flux modulation. The modulation method is similar to that one commonly used in FLL electronics [12]. A schematic is given in the inset of Fig. 6(c). The amplitude and offset of the square current for the flux signal is adjusted to switch between the points of maximum transfer function. The preamplifier output is lock-in detected. Hence, in zero field no output signal is generated, and voltage noise

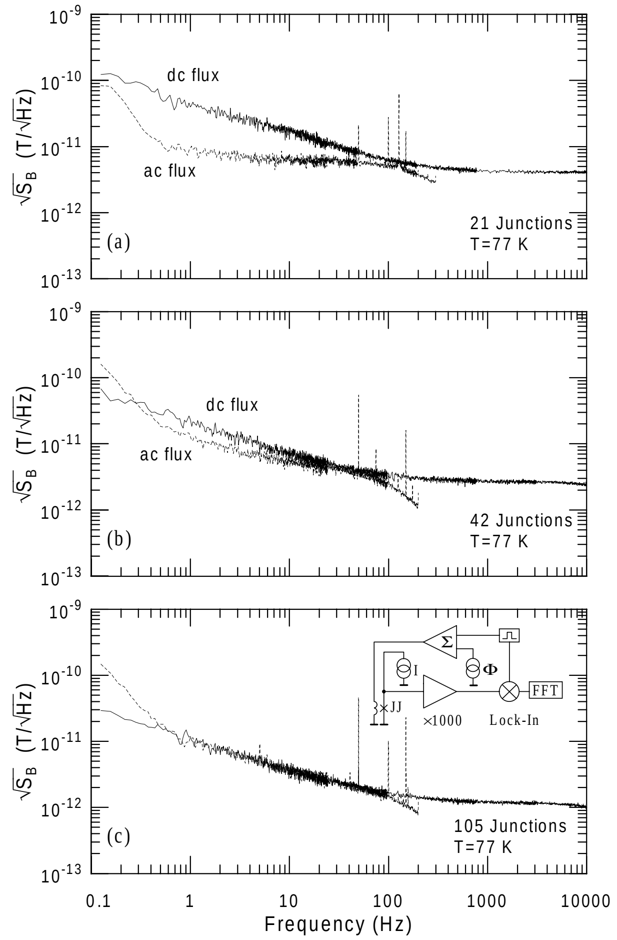

Fig. 6. Noise spectra of Josephson junction arrays with (a) 21 junctions, (b) 42 junctions and (c) 105 junctions. The spectra were measured with static bias current, either with dc flux or with 2 kHz ac flux (dashed line). The cutoff at 100 Hz in the ac spectra is due to the limited bandwith of the lock-in amplifier. The inset in (c) shows a schematic of the measurement system.

due to critical current fluctuations is suppressed. An external magnetic signal will lead to a 2 kHz component at the preamplifier output and to a lock-in signal. For comparison, the out-of-phase critical current fluctuations in SQUIDs generate flux noise in the SQUID loop, that has to be suppressed with additional bias current modulation. Fig. 6(a) shows the spectra of a 21-junction subarray. In the static case a frequency dependent $1/f$-noise component with a corner frequency of about 200 Hz was measured. However, this excess noise could be suppressed to the white noise level of $\sqrt{S_B} = 4\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ using the flux modulation method. The amount of excess low frequency noise is commonly expressed in terms of the normalized critical current fluctuations

$$\left|\frac{\delta I_c}{I_c}\right| = \frac{\sqrt{S_V}}{R_D I} \quad \text{for} \quad I \simeq I_c. \tag{4}$$

Referred to a single junction, we find a value of $|\delta I_c/I_c| = 6.0 \times 10^{-5}/\sqrt{\mathrm{Hz}}$ at 1 Hz in good agreement with data found in the literature [13]. Additionally, spectra of larger arrays are shown in Figs. 6(b,c). For the 42-junction array we only find a slight suppression of the low frequency noise, and for the largest array no reduction is obtained. We ascribe this excess noise component to flux noise from vortex motion in the large flux focusers, that is detected by the array in the same way as an external signal. This flux noise is probably due to the bias field of about $0.75\,\mu$T, that is necessary for the operation with maximum transfer function. The shielding currents generated by this field at the edges of the flux focusers can lead to vortex penetration into the film. The vortex motion presumably can be prevented, if the flux focusers are provided with slots or holes of sufficient small linewidth [14].

IV. Conclusions

We have fabricated and characterized a magnetometer based on the Fraunhofer pattern of a serial array of 105 $YBa_2Cu_3O_7$ Josephson junctions. The scaling behaviour of the critical current and the normal state resistance with the number of junctions underlines the high homogeneity of the bicrystal junctions. The white noise level of the array magnetometer is already sufficient for many applications. It can be further improved by the use of more junctions in the array or by increasing the amount of flux focused into the junctions, e.g. with a smaller slitwidth between the array and the flux focusers, with additional flip-chip flux focusers or with multilayer technology. The array magnetometer can be easily combined on-chip with common SQUID magnetometers.

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