

Highly sensitive magnetometers based on $\text{YBa}_2\text{Cu}_3\text{O}_7$ Josephson junction arrays

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The dependence of the critical current of a Josephson junction on the magnetic flux in the junction area can be used for the sensitive detection of external magnetic fields. In contrast to superconducting quantum interference devices, also the measurement of absolute magnetic fields is possible. To increase the transfer function $\partial V/\partial B$, we use serial arrays of up to 105 Josephson junctions between flux-concentrating areas on 24° SrTiO₃ bicrystal substrates. We investigate the scaling properties of the critical current I_c , the normal state resistance R_n and the flux density noise $\sqrt{S_B}$ in dependence on the number of Josephson junctions in the serial array. By the use of a magnetic field modulation scheme, the $1/f$ noise from critical current fluctuations in the junctions can be suppressed. At 77 K, we achieve a white noise level of $\sqrt{S_B} = 1.2$ pT/ $\sqrt{\text{Hz}}$ for a 105-junction array. © 1999 American Institute of Physics. [S0003-6951(99)03902-9]

Currently, the most successful approach in Josephson junction technology for devices from high-temperature superconductors (HTS) is the grain-boundary junction on bicrystal substrates. For magnetic sensors, these junctions are typically used in magnetometers based on superconducting quantum interference devices (SQUIDs), which achieve a field resolution $\sqrt{S_B}$ of about 30 fT/ $\sqrt{\text{Hz}}$ in simple single-layer layouts on 1×1 cm² substrates.^{1,2} Due to the dependence of the critical current on external magnetic flux, even a single Josephson junction can be used for sensing magnetic fields. In contrast to SQUID magnetometers, the flux-voltage characteristic is nonperiodic, hence, in principle absolute magnetic flux densities can be determined. In bicrystal junctions a high sensitivity is observed, due to the flux focusing effect of the electrodes directly adjoining the grain boundary. Rosenthal *et al.*³ found a clear $1/w^2$ dependence for the Fraunhofer field period of biepitaxial grain-boundary junctions of width w , instead of the classical $1/w$ relation. This behavior is attributed to corner effects on the current distribution in the electrodes. Martin *et al.*⁴ further enhanced the sensitivity of a single 24° bicrystal junction by an additional flux concentrator. With a junction width of 10 μm they achieved a sensitivity $\partial I_c/\partial B = 176$ A/T and a flux density noise level of $\sqrt{S_B} = 3.7$ pT/ $\sqrt{\text{Hz}}$. Also, a reduction of low-frequency noise from critical current fluctuations by field modulation was demonstrated.⁵ With several junctions in series, the signal-to-noise ratio can be further enhanced since the voltage signal linearly scales with the number N of junctions, whereas the voltage noise scales with \sqrt{N} if the noise sources are uncorrelated. Lee *et al.*⁶ used a similar approach for a serial array HTS SQUID magnetometer. Here, we present a magnetometer from a serial array of 105 bicrystal Josephson junctions with additional flux focusing areas. Voltage noise due to critical current fluctuations in the junctions is already suppressed by a simple field modulation

scheme. This is in contrast to SQUID-based magnetometers, where the out-of-phase current fluctuations of both junctions have to be suppressed by additional bias current modulation. Due to the high output voltage of the serial array, the demands on the electronics are much lower.

The serial array magnetometers are prepared in a single-layer technology on (100) SrTiO₃ bicrystals with 24° grain boundaries which are supplied by CrysTec GmbH, Berlin. For the $\text{YBa}_2\text{Cu}_3\text{O}_7$ thin-film deposition we employ our KrF-excimer laser deposition process that is described elsewhere in detail.⁷ We typically use a film of about 120 nm thickness. The large number of wide Josephson junctions makes high demands on the large scale quality of the grain boundary and the superconducting film deposited on it. Highly reproducible Josephson junction properties are achieved, since we have no droplets on our films and the outgrowth density is well below 10^4 cm⁻². After the patterning with conventional photolithography and argon plasma etching, the arrays are treated in an oxygen plasma. To reduce the contact resistance for low noise measurements, the contact pads are covered with 100 nm silver. In Fig. 1, an optical micrograph of a 21-junction subarray is depicted. For the whole 105-junction array, five of these subarrays are connected in series. Each Josephson junction has a width of 20 μm to achieve a high sensitivity to external magnetic fields. For a further increase of its sensitivity the array is embedded in flux focusing superconducting areas which cover almost the whole substrate

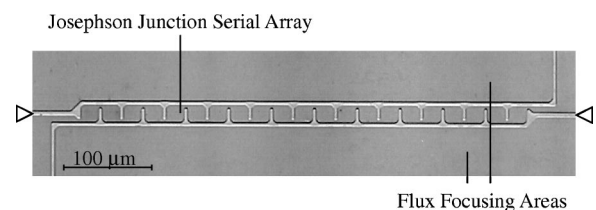


FIG. 1. Optical micrograph of a 21-junction subarray. The figure displays an area of 570×170 μm^2 . The position of the bicrystal line is indicated by the arrows.

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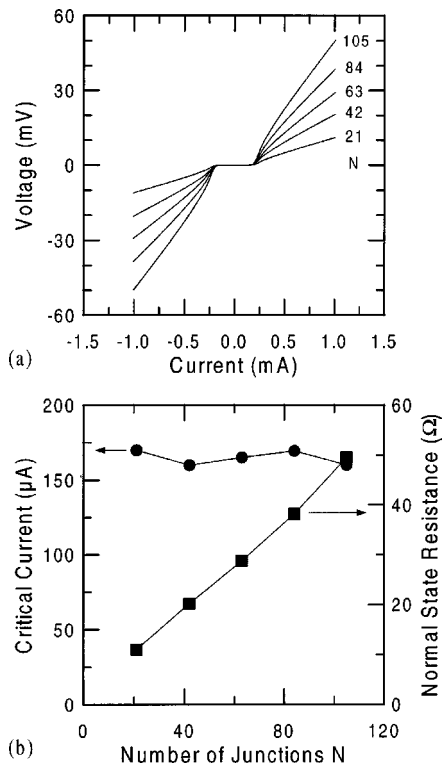


FIG. 2. (a) Current–voltage characteristics for subarrays of a different number of junctions N . (b) Critical current and normal state resistance for the subarrays vs N .

of $1 \times 1 \text{ cm}^2$. The gaps between these areas and the junctions are $4 \text{ }\mu\text{m}$ wide.

The arrays are characterized by electrical transport and noise measurements. In Fig. 2(b) we show the scaling properties for both, critical current I_c and normal state resistance R_n in dependence on the number N of junctions in the array. The values for I_c and R_n were deduced from the resistively shunted junction-like current–voltage characteristics of the subarrays which are depicted in Fig. 2(a). We find an almost linear increase of R_n and a constant critical current independent from N within 5%, resulting in a linear increase of the $I_c R_n$ product with N , up to 7.9 mV for 105 junctions. The effective flux collecting area for a single $20 \text{ }\mu\text{m}$ wide junction, as calculated from the spacing of the minima in the measured Fraunhofer pattern, is about $350 \text{ }\mu\text{m}^2$, i.e., 25 times larger than the geometrical area. This is attributed to the flux focusing effect of the junction's electrodes.⁸ For the 105-junction array embedded in the flux focusers we find a further increase of the effective area by a factor 4.2. The maximum field sensitivity obtained for this array is $\partial I_c / \partial B = 130 \text{ A/T}$ at 77 K . In Fig. 3(a) the voltage across the current biased subarrays is shown versus the external magnetic flux density. In each case the bias currents were adjusted to obtain the maximum transfer function. Because the $I_c R_n$ product scales linearly with N , we also find a linear increase of the voltage modulation as well as the maximum transfer function $\partial V / \partial B$ with N . The latter is illustrated by Fig. 3(b). For the largest array of 105 junctions we measure a voltage modulation of about 7.5 mV that corresponds well with the $I_c R_n$ product, due to low excess currents. The transfer function of 7500 V/T is comparable to directly coupled SQUID magnetometers from HTS single layers. They typically show

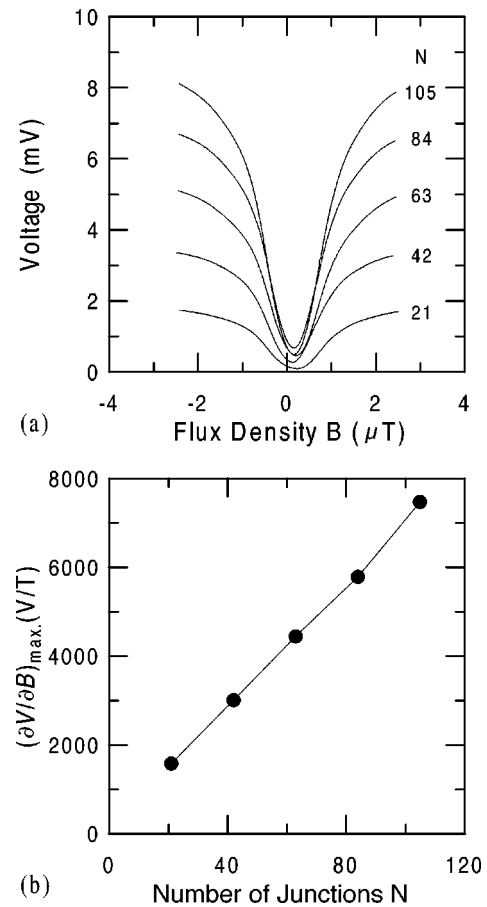


FIG. 3. (a) Voltage across the current biased subarrays vs the external magnetic flux density. (b) Maximum transfer function $\partial V / \partial B$ in dependence on the number of junctions in the array.

a sensitivity $\partial B / \partial \Phi$ of about $10 \text{ nT}/\Phi_0$, resulting in $\partial V / \partial B = 6300 \text{ V/T}$ for an assumed sinusoidally voltage modulation of $20 \text{ }\mu\text{V}$. The high transfer function of SQUID magnetometers is achieved by their very large effective area $A_{\text{eff}} = \partial \Phi / \partial B$ of about 0.2 mm^2 in conjunction with a much smaller voltage modulation. For the junction array we have a very large voltage modulation, but a small effective area.

In the theory of the resistively shunted tunnel junction the voltage noise spectral density of a single junction due to thermal fluctuations is predicted by⁹

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

where R_D denotes the dynamic resistance at the bias current I . Using typical parameters for our bicrystal junctions, a voltage noise level of about $\sqrt{S_V} = 120 \text{ pV}/\sqrt{\text{Hz}}$ is calculated. If we assume that the noise sources in the junctions are uncorrelated, the noise of the array should increase as \sqrt{N} and a level of about $1.2 \text{ nV}/\sqrt{\text{Hz}}$ for 105 junctions is expected. However, a small signal measurement at 2 kHz yielded a total voltage noise of about $9 \text{ nV}/\sqrt{\text{Hz}}$ that is well above the input voltage noise of the used preamplifier of $4 \text{ nV}/\sqrt{\text{Hz}}$. The measurements were made at 77 K at a fixed bias current of $169 \text{ }\mu\text{A}$ and a fixed bias flux of $0.75 \text{ }\mu\text{T}$, which yield the maximum transfer function. The deviation from the theoretical prediction is not yet clear, but it is also observed in SQUIDs from HTS Josephson junctions.¹⁰ Flux density noise

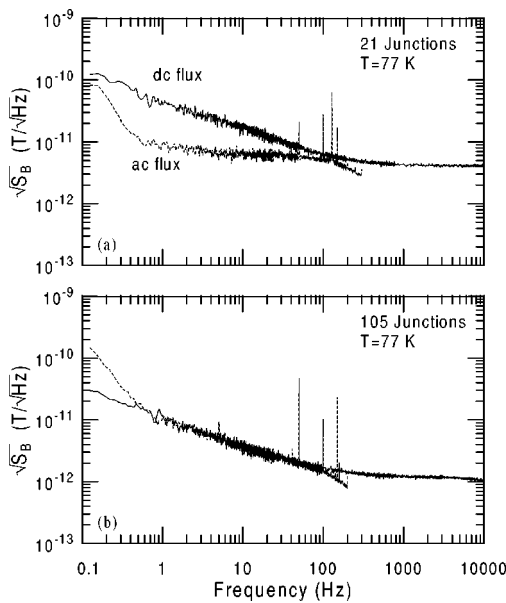


FIG. 4. Noise spectra of the Josephson junction array magnetometers with (a) 21 junctions and (b) 105 junctions. The spectra were measured at 77 K with static bias current either with static (dc) flux or with 2 kHz flux modulation (ac flux, dashed line). The cutoff at 100 Hz in the ac spectra is due to the limited bandwidth of the used lock-in amplifier.

spectra for two junction arrays at 77 K are depicted in Fig. 4. They were obtained by dividing the voltage noise spectra by the corresponding transfer function. Figure 4(a) shows two spectra of a 21-junction subarray. 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 SQUID electronics.¹¹ The amplitude and offset of the square current for the flux signal is adjusted to switch between the points of maximum sensitivity, so that the ac flux signal is symmetric with respect to the maximum of the Fraunhofer pattern. The preamplifier output signal is lock-in detected. Hence, no signal is measured in zero field and voltage noise due to critical current fluctuations is suppressed. Every external magnetic signal will lead to a 2 kHz component at the preamplifier output and to a lock-in signal. For comparison, in SQUIDs the out-of-phase critical current fluctuations generate flux noise in the SQUID loop that has to be suppressed with additional bias current modulation. As in SQUID systems, a flux locked loop (FLL) circuit can be employed to enhance the linear working range of the array magnetometer.⁵ 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 well suppressed to the white noise level of $\sqrt{S_B} = 4$ pT/ $\sqrt{\text{Hz}}$ using the flux modulation method. Second, the flux density noise spectra for the whole 105-junction array are shown in Fig. 4(b). Here, a white noise level of about $\sqrt{S_B}(5 \text{ kHz}) = 1.2$ pT/ $\sqrt{\text{Hz}}$ is obtained, however, the apparent $1/f$ noise was not suppressible. We attribute this excess noise to flux noise from vortex motion in the large flux focusers. A reduction of this flux noise is expected, if the flux focusing areas are provided with slots or holes that prevent the vortex penetration. This was recently demonstrated by Dantsker *et al.*¹² for washer SQUIDs. In Fig. 5 the white flux density noise of the arrays at 2 kHz is shown in dependence on N . We find a decrease of the noise with an increasing number of junctions

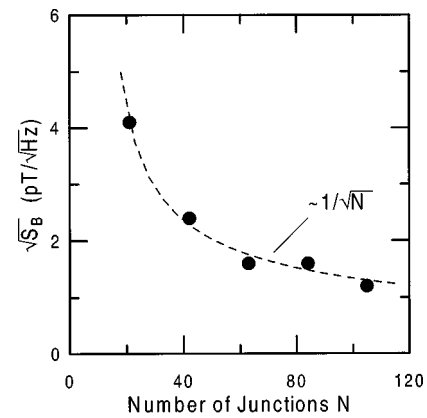


FIG. 5. Flux density noise at 2 kHz of the Josephson junction array magnetometers vs the number of Josephson junctions integrated in the array. The dashed line indicates a $1/\sqrt{N}$ dependence.

N because the transfer function scales linearly with N while the voltage noise only increases with \sqrt{N} . The dashed line in Fig. 5 illustrates the expected decrease with \sqrt{N} .

In summary, we have fabricated and characterized serial arrays of up to 105 bicrystal Josephson junctions from $\text{YBa}_2\text{Cu}_3\text{O}_7$ thin films. The measured scaling properties of the critical current I_c and the normal state resistance R_n at 77 K demonstrate the high homogeneity throughout the whole array. The serial arrays can be used as highly sensitive magnetometers with a noise level sufficient for many applications. However, highly reproducible Josephson junctions with high $I_c R_n$ products are necessary for the low noise operation of such magnetometers. The noise values can be further improved by the use of more Josephson junctions in the array and by enhancing the flux focusing into the junctions. The latter can be achieved by a reduced slit width between the array and the flux focusing areas, by an additional flip-chip flux focuser or with multilayer technology.

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