Low-frequency noise reduction in $YBa_2Cu_3O_{7-\delta}$ superconducting quantum interference devices by antidots

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It is demonstrated that the low-frequency noise due to vortex motion in high-temperature superconducting quantum interference devices (SQUIDs) in ambient magnetic fields can strongly be reduced by a simple arrangement of antidots patterned into the SQUID. Sputter-deposited $YBa_2Cu_3O_{7-\delta}$ radio-frequency SQUIDs (rf-SQUIDs) with step edge junctions are characterized before and after patterning of antidots in the vicinity of the Josephson junction. No deterioration of the rf-SQUIDs due to the introduction of the antidots can be detected. In contrary, the onset of the increase of the low-frequency noise in an applied magnetic field is shifted from 10 μT for the bare SQUID to 40 (field cooled) and 18 μT (zero-field cooled) for the rf-SQUIDs with antidots. The reduction of low-frequency noise in ambient field is explained by trapping of vortices by the antidots. The comparison of zero-field and field-cooled experiments demonstrates that flux penetrating the washer does not affect the low-frequency noise as long as the vortices are homogeneously distributed and the flux is properly pinned in the vicinity of the junction. © *2000 American Institute of Physics.* [S0003-6951(00)04022-5]

The application of high-temperature superconductors (HTS) for highly sensitive cryogenic active devices strongly depends upon the reduction of noise. In particular low-frequency noise due to unwanted motion of quantized flux (vortices) in the superconducting thin films, which usually scales according to

$$\sqrt{S_\Phi(f,B)} \propto \frac{B^n}{f} \tag{1}$$

(f is the frequency, B the applied magnetic induction and $n = 0.5$), represents a serious limitation for the application of for instance superconducting quantum interference devices (SQUIDs) in unshielded environment.[1] Various remedies have been suggested and tested,[2–10] which in principle can be classified into two categories: (i) either vortex penetration of the superconductor has to be avoided[2–8] or (ii) vortices have to be pinned by sufficiently strong pinning sites in the superconductor.[7–10] In case of flux avoidance SQUID designs with extremely narrow linewidths w have to be used. According to theoretical predictions[11] and experimental results,[3] $w < 6$ μm have to be used for application in ambient field up to $B \approx 50$ μT (e.g., earth field), which is impractical for most applications and difficult to prepare without degradation of the SQUID performance. In contrast, noise reduction by vortices pinning seems to be technically easier to realize.

One of the most effective ways to create artificial pinning sites in thin films is provided by the preparation of submicrometer holes, so called antidots.[12–14] These defects can be placed arbitrarily in superconducting thin film devices and, in contrast to other pinning defects which have to be of the size of the superconducting coherence length ξ,[9] holes with sizes much larger than ξ will trap flux very effectively.[15] In previous work,[15] we demonstrated that arrays of submicrometer holes can be patterned into $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films without deterioration of the superconducting properties, which cause commensurability (demonstrating the attractive interaction between vortices and antidots) and affects the low frequency $1/f$ noise in ambient magnetic induction.[10,16]

In this presentation we demonstrate, that extremely simple arrangements of antidots in HTS rf-SQUIDs can reduce the $1/f$ noise in ambient field down to the level of zero-field noise. The onset field B_{on}, at which the low-frequency noise starts to increase according to $S_\Phi(B) \propto B$, is shifted from (i) $B_{on} \approx 10\,\mu$T without antidots to $B_{on} \approx 40\,\mu$T with antidots for field-cooled (FC) measurements and (ii) to $B_{on} \approx 18\,\mu$T for zero-field cooled (ZFC) experiments. A comparison of the noise spectra for ZFC and FC experiments yield $1/f$ noise spectra except for the field region around 18 μT(B_{on}) for ZFC measurements, for which Lorentzian type spectra are recorded. The spectra demonstrate, that vortices in the washer do not affect the low-frequency noise as long as the flux is properly pinned in the vicinity of the junction.

Planar washer type rf-SQUIDs with outer diameter of 3.5 mm, SQUID holes of $100 \times 100\,\mu m^2$, and 3-μm-wide step-edge junction are patterned via optical lithography and Ar ion milling into magnetron sputtered YBCO films on 2 in. $LaAlO_3$ substrates (see sketch in Fig. 1). Step height and film thickness are $h \approx 270$ nm and $t \approx 320$ nm, respectively. The field-to-flux coefficient is $dB/d\varphi \approx 9$ nT/Φ_0. High structural perfection and, especially, extremely small surface roughness are required for the subsequent patterning of the antidots without degradation of the performance of the SQUID (see Figs. 1 and 2). Only two antidots with a diameter of 1.5 μm are patterned into the rf-SQUID. They are positioned at both sides of the step-edge junction (junction-antidot distance$\approx$7 μm) in the washer (distance between the antidot

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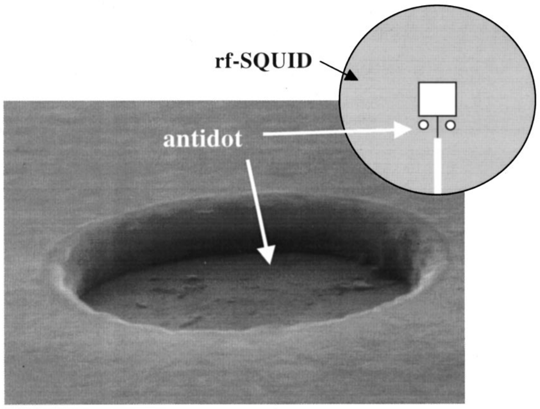

FIG. 1. Scanning electron microscopy image of an antidot ($r=0.75\ \mu$m) in a YBCO film on sapphire and a sketch of the rf-SQUID with integrated antidots.

and the edge of the washer$\approx 2.3\ \mu$m). Transfer function and noise level remained unchanged before and after patterning of the antidots (Fig. 2). The transfer function shows typically an amplitude of about 1.2 V and a voltage to flux coefficient of about $1.65\ \mathrm{V}/\phi_0$. The noise level in zero field is about $35\ \mu\Phi_0/\mathrm{Hz}^{1/2}$ $(0.3\ \mathrm{pT/Hz}^{1/2})$ at 1 kHz (white noise) and $200\ \mu\Phi_0/\mathrm{Hz}^{1/2}$ $(1.8\ \mathrm{pT/Hz}^{1/2})$ at 1 Hz ($1/f$ noise), respectively. The corner frequency is at about 25 Hz.

The rf-SQUIDs are characterized at liquid nitrogen temperature in a cryostat shielded with four μ-metal layers characterized by a residual static magnetic induction of B_{res} <5 nT. Inside the shielding magnetic inductions can be applied perpendicular and parallel to the plane of the SQUIDs using Helmholtz coils powered by lead acid batteries. The noise of the applied magnetic fields of $S_{\mathrm{coil}}<200\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$ at 1 Hz was at least one magnitude lower than the measured noise of the rf-SQUIDs. The rf-SQUIDs are operated in a flux locked loop using a 600 MHz rf-SQUID electronics. Due to the alternating-current (ac) mode of the electronics the $1/f$ noise due to fluctuations in the resistance or critical current of the Josephson junction is automatically eliminated.

Figure 2 represent noise spectra and transfer functions of the rf-SQUID before and after patterning of the two antidots in the vicinity of the step-edge junction. No modification of the noise spectrum and transfer function by the patterning process can be resolved. However, a distinct difference is observed for FC measured noise spectra in ambient magnetic induction B (perpendicular to the plane of the SQUID) for the SQUID before and after antidot patterning. Figure 3 shows the square root of the spectral noise density $S_\Phi{}^{1/2}$ recorded at 1 Hz as a function of the applied magnetic induction B. The data represent average values obtained from independent FC measurements. The onset of the characteristic increase of the low frequency noise according to $S_\Phi(B,1\,\mathrm{Hz})\propto B$ is shifted from $B_{\mathrm{on}}\approx 10\ \mu$T for the standard SQUID to $B_{\mathrm{on}}\approx 40\ \mu$T for the SQUID with antidots.

Finally, zero-field cooled measurements were performed by cooling the SQUID in zero-field, cycling the magnetic induction to a given value B and back to zero-field. Typical noise data recorded after the field cycle are given in Fig. 4. Up to $B\approx 18\ \mu$T no increase of the low-frequency noise is observed. Above 18 μT the low-frequency noise starts to increase according to Eq. (1) however with $n\gg 0.5$. The corresponding noise spectra in the field regime $18\ \mu\mathrm{T}<\mathrm{B}<22\ \mu$T change from the typical $1/f$ characteristic to a Lorentzian type spectrum. This indicates that at these fields the motion of single vortices or vortex bundles are the

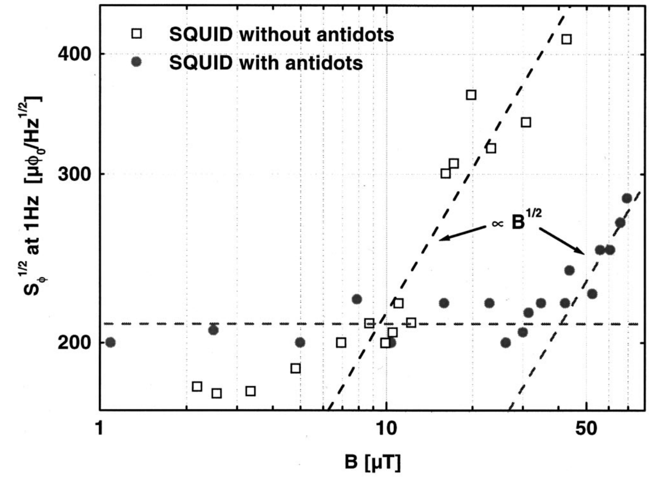

FIG. 3. Spectral noise density obtained for FC measurements at 1 Hz as function of the applied magnetic induction for an rf-SQUID before (open symbols) and after (solid symbols) integration of the antidots.

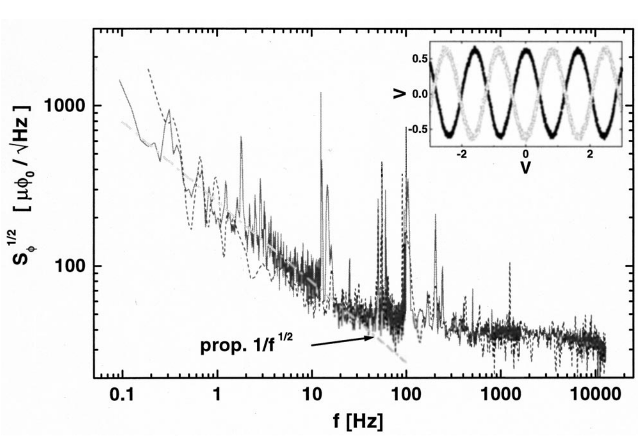

FIG. 2. Comparison of noise properties before (dashed line) and after (solid line) patterning of the antidots and (inset) transfer function before (dark symbols) and after (gray symbols) patterning.

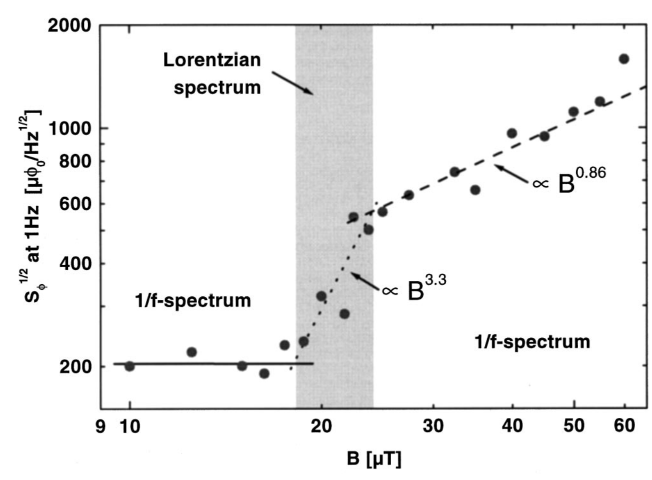

FIG. 4. Spectral noise density obtained for ZFC measurements at 1 Hz and zero-field as function of the applied magnetic induction to which the magnetic field has been cycled.

source for the low-frequency noise. At fields $B > 22\,\mu$T the ZFC spectra represent again a $1/f$-frequency dependence. But the field dependence remains unusual, i.e., we observed an increase of the noise density according to $S_\Phi(B) \propto B^{1.7}$.

In general there exist three different independent sources for $1/f$ low-frequency noise in SQUIDs: (i) fluctuations of the junction properties, (ii) direct noise due to motion of vortices in the superconducting material, and (iii) temperature fluctuations of the superconductor due the cooling by liquid nitrogen (e.g., bubble formation).[17] Fluctuations of the junction properties are electronically eliminated in our experimental setup via the ac mode of the rf electronics. The residual field inside of the magnetic shielding of $B < 5$ nT allows vortices (for our design about 24) to be frozen into the washer during zero-field cooling. However, the fact, that the $1/f$ noise is not affected by field-cooled experiments up to several μT, indicates, that these vortices cannot be the source for the $1/f$ noise measured at fields below the onset field B_{on}. The $1/f$ low-frequency noise level caused by thermal fluctuation of the liquid nitrogen cooled SQUID[17] is expected to be slightly lower than the measured noise level at fields $B \leqslant B_{on}$.[18] The physical origin of this slightly elevated noise at zero field has not been clarified.

However, the increase of low-frequency noise at fields $B > B_{on}$ has to be ascribed to vortex motion in the superconducting SQUID washer. This is demonstrated by the scaling $S_\Phi(B) \propto B$ for FC measurements in ambient field and the Lorentzian type noise spectrum observed at fields close to B_{on} in ZFC experiments. The latter is an indication for thermally activated motion of single vortices or vortex bundles in the washer. The comparison of the noise data recorded in FC and ZFC measurements demonstrates, that even larger densities of vortices do not affect the low-frequency noise as long as the flux is homogeneously distributed in the washer (a homogeneous distribution is expected for fc measurements). However, field gradients, which in our case have been created by cycling the field in ZFC experiments, lead to the penetration of vortices at the washer edge. The resulting vortex distribution has to be inhomogeneous. This inhomogeneous distribution together with thermal activation seems to cause vortex motion in the washer, which results in elevated low-frequency noise. For fields $B \approx B_{on}$ single vortices seem to penetrate the washer. These vortices are not pinned, the field gradient and the thermal energy leads to vortex jumps resulting in a Lorentzian noise spectrum. For larger fields larger numbers of vortices enter the washer resulting in a $1/f$-type noise spectrum. This explanation is supported by measurements of the flux entry in ZFC experiments.[19]

By introducing antidots in the vicinity of the junction vortices will be trapped in this area by the antidots.[10,15] Additionally, the repulsive interaction between vortices will hinder further vortex penetration of the junction area up to a field for which the vortex–vortex spacing becomes small enough to effectively couple flux to the SQUID hole. In a regular vortex lattice the vortex–vortex spacing is given by $a_0 = 1.075(\Phi_0/B)^{1/2}$. Inserting a magnetic induction of 40 μT (equivalent to B_{on} for FC experiments) yields a lattice parameter $a_0 = 7.6\,\mu$m, which coincides with the antidot-junction distance. This might be a coincidence, on the other hand it could be an indication that at these fields vortices start to penetrate the junction area between the antidots. Further experiments are in preparation, which might clarify this point.

In conclusion, we demonstrated, that an extremely simple arrangement of antidots in HTS rf-SQUIDs consisting of only two antidots in the vicinity of the Josephson junction can strongly reduce the $1/f$ noise in ambient field down to the level of zero-field noise. The onset field, at which the low-frequency noise starts to increase, is shifted from (i) $B_{on} \approx 10\,\mu$T without antidots to $B_{on} \approx 40\,\mu$T with antidots for FC measurements and (ii) to $B_{on} \approx 18\,\mu$T for ZFC experiments. The antidots act as pinning sites for the vortices in the vicinity of the step-edge junction of the SQUID. Vortices pinned in the washer seem to play a minor role in the creation of low-frequency noise as long as the applied field gradients are small enough. The use of these simple pinning sites in the superconductor, which can be patterned simultaneously with the SQUID structure, seems to be a very promising tool in reducing the low-frequency noise especially for applications in unshielded environments.

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