Investigation of Low-frequency Excess Flux Noise in dc SQUIDs at mK Temperatures

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Abstract—The excess low-frequency flux noise in dc superconducting quantum interference devices (SQUIDs) operated at ultra-low temperatures was studied. A large number of single SQUIDs as well as SQUID arrays from 16 wafers fabricated over a period of six years were characterized at 4.2 K and <320 mK. Considering the large spread in the low-frequency noise at 4.2 K, there was no observable dependence of the low-frequency energy resolution \( \xi_{\nu} \) on the SQUID design or fabrication parameters. In contrast, below 4.2 K the low-frequency noise changed moderately or increased strongly depending on whether the bottom Nb or the insulation layer were fabricated in our newer sputter system instead of the older one. The corresponding excess noise levels \( \xi_{\nu} \) at <320 mK and \( f = 10 \text{ Hz} \) are typically 40 h and 300 h, respectively (\( h \) is Planck’s constant). The excess noise scales as \( \xi_{\nu} \propto f^{-\alpha} \) with \( \alpha \) typically around 0.6 for good devices. For devices with strong low-frequency excess noise, \( \alpha \) increases up to about 0.9. The best energy resolution \( \xi \) achieved so far with a 50 pH test SQUID operated at 16 mK is 0.62 h at 100 kHz, increasing to 1.64 h at 1 kHz and 14 h at 10 Hz.

Index Terms—1/f flux noise, energy resolution, SQUID current sensor, ultra-low temperature.

I. INTRODUCTION

The dc superconducting quantum interference device (SQUID) is a highly sensitive detector of magnetic flux [1]. Commonly, an input coil is magnetically coupled to the SQUID loop thereby creating a low-noise current sensor. In August 2003, the first PTB current sensor wafer was fabricated. Since then, various current sensor design versions C1 to C6 were developed [2]-[5], and over 1000 SQUIDs were tested in liquid helium. Originally, most of our current sensors were operated at \( T = 4.2 \text{ K} \). Since 2005, we deliver an increasing number of SQUIDs for applications where the device is operated at mK temperatures, e.g., the readout of transition-edge sensors (TESs) [6] or metallic magnetic calorimeters (MMCs) [7]. For these applications, the SQUIDs are carefully selected by using the characterization at 4.2 K and considering the typical trend in the SQUID parameters between 4.2 K and <1 K. SQUID characterization at mK temperatures is done on sample basis to check the fabrication quality, or in cases where the user wishes devices 100% tested at the intended working temperature. This way, we collected flux noise data at 10-320 mK for a variety of SQUIDs of different designs from wafers fabricated over a period of six years.

Low-frequency excess flux noise in SQUIDs (in particular at ultra-low temperatures [8]) remained a challenge for over 20 years; recently, the interest in this topic increased [9]-[12]. For our SQUIDs, a degradation in the low-frequency noise performance is observed when the devices are cooled to mK temperatures, and the 1/f noise corner (the frequency for equal 1/f and white noise densities) moves from typically below 10 Hz at 4.2 K to above 1 kHz at mK temperatures. This is a severe problem for MMC readout [7] and other applications below about 10 kHz where SQUID noise limits the overall signal-to-noise ratio. To address this issue, we measured a series of SQUIDs both at 4.2 K and near 10 mK. We performed a thorough analysis of these new measurements together with results obtained during the past five years to find a potential dependence of the low-frequency excess noise on the SQUID design and fabrication parameters.

II. SAMPLE SELECTION AND DATA ANALYSIS

Our SQUIDs were fabricated using a Nb-Al-AlO\(_x\)-Nb trilayer technology with Josephson junctions defined by the selective Niobium anodization process [1]. The minimum linewidth and junction dimensions were nominally 2.5 \( \mu \text{m} \). For the insulation layer, SiO\(_2\) sputtered in an Ar plasma from a stoichiometric target or Si\(_3\)N\(_4\) sputtered from a Si target in an Ar/N\(_2\) plasma were used. The resistors were made from Pd (except for wafer C602 with AuPd resistors). The devices were not passivated. The bottom Nb was patterned by wet etch, the top Nb, resistors and insulation layer(s) by lift-off. The film depositions were done in two sputter systems, our older “Alcatel” system (SCM440/174 from the French company CIT-Alcatel) and the newer “FHR” system (customer-specific cluster system MS100x4-AEO from the German company FHR).

Our noise study involves single SQUIDs as well as arrays of SQUIDs in different configurations (series or parallel) [4], [5]. Provided that all SQUIDs in an array are biased at the same working point and that there is no correlation between the noise in the individual SQUIDs, the overall flux noise density \( \Sigma_\phi \) of a SQUID array scales inversely with the number \( N \) of SQUIDs: \( \Sigma_\phi \propto 1/N \). In contrast, the energy resolution \( \xi = N\Sigma_\phi/2L \) does not depend on \( N \) (\( L \) is the SQUID inductance) [13]. Therefore, \( \xi \) in units of Planck’s constant \( h \) is a more appropriate figure of merit than \( \Sigma_\phi \) if one compares the low-frequency excess noise in SQUIDs of different designs and configurations. This is plausible if one assumes that the low-frequency excess flux noise is caused by a large number of fluctuating magnetic field sources on sub-\( \mu \text{m} \) scale rather than by a global field across the SQUID loop. In this case, the...
excess flux noise density $S_{\Phi f}$ increases with the number of contributing field sources (those nearby the Nb lines forming the SQUID loop), i.e., with the perimeter rather than the area of the SQUID loop [9]. As the loop inductance is approximately proportional to the perimeter, the ratio $S_{\Phi f}/L \propto \varepsilon_{1/f}$ should remain almost constant. This picture is consistent with our SQUID noise measurements. Furthermore, we observed that our multiloop magnetometers with stripline “spokes” [4] have a lower low-frequency noise than those with coplanar “spokes” for the same total SQUID inductance [14]. The long interconnecting striplines pick up a considerable amount of excess flux noise, but do not contribute significantly to the total loop inductance. These devices with atypically high low-frequency noise were not included in the presented study.

Table I describes the selected types of PTB SQUIDs. There are three basic categories: “regular” sensors used for practical SQUID applications, second stages of integrated two-stage arrays, and special test devices intended for noise investigations (from top to bottom). Results from other groups were also included for comparison (bottom section in Table I). We regarded SQUIDs fabricated with the Nb-Al-AlO$_x$-Nb trilayer technology, for which noise spectra at 4.2 K and mK temperatures were published in the frequency range between 10 Hz and the white noise regime [15]-[17]. In addition, a SQUID with Nb-NbO$_2$-PbIn junctions and a loop made from PbIn was considered [8].

There is a large variety of devices, ranging from small gradiometric 20 pH test SQUIDs with $\approx 10$ mm diameter loops to double-transformer sensors with 1.05 mm input inductance covering over 1 mm$^2$ chip area [4]. The PTB C1 device comprises four slotted washers with off-washer input coils to minimize stray capacitance. The bottom Nb in the test SQUIDs and SQUID arrays is $\approx 6$ mm wide to avoid flux trapping when cooling the devices in the Earth field [18].

The low-frequency excess noise $\varepsilon_{1/f}$ was determined by fitting the measured overall noise with

$$\varepsilon(f) = \varepsilon_w + \varepsilon_{1/f}(f) = \varepsilon_w + \varepsilon_{1/f}(1\text{Hz}) \times (f/\text{Hz})^\alpha$$

and subtracting the resulting white noise level $\varepsilon_w$ from the measured noise. For simplicity, we use the notation “$1/\nu$” even if the exponent $\alpha$ differs from 1. For most of our SQUIDs, the measured noise spectra have not been stored during characterization, but rather the noise levels at selected frequencies were read out from the spectrum analyzer display and listed in the SQUID data sheets (typically at 0.1 Hz to 100 kHz in factor of ten steps). These lists of noise levels were used to determine the important quantities $\varepsilon_w$ and $\alpha$. An example of the achievable fit quality is given in Fig. 1. The fit curves obtained from six noise levels between 1 Hz and 100 kHz describe the complete spectra very well. At 4.2 K and high frequencies, $\varepsilon_{1/f}$ becomes uncertain due to the relatively high white noise level.

For our study, measurements were considered when noise data between at least 10 Hz and 100 kHz were available at mK temperatures. Only low-noise SQUIDs with $\varepsilon_{1/f} < 70 \text{ Hz}$ at 10

**Table I SQUID Types Used for the Millikelvin Noise Study**

<table>
<thead>
<tr>
<th>Type</th>
<th>Ref.</th>
<th>$N$</th>
<th>$L/\mu\text{H}$</th>
<th>$T_{\text{min}}$/mK</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>[3]</td>
<td>1</td>
<td>30</td>
<td>310</td>
<td>4-Grad, slotted-washer design</td>
</tr>
<tr>
<td>C6</td>
<td></td>
<td>1</td>
<td>33</td>
<td>16</td>
<td>8-Grad, w/o double-transformer</td>
</tr>
<tr>
<td>C3-C5</td>
<td>[4]</td>
<td>1</td>
<td>85</td>
<td>9-320</td>
<td>4-Grad, with double-transformer</td>
</tr>
<tr>
<td>C4-C5</td>
<td>[4]</td>
<td>1</td>
<td>115</td>
<td>10-300</td>
<td>4-Grad, w/o double-transformer</td>
</tr>
<tr>
<td>C4-C5</td>
<td>[4]</td>
<td>1</td>
<td>145</td>
<td>10-320</td>
<td>2-Grad, standard SQUID array</td>
</tr>
<tr>
<td>C5</td>
<td>[5]</td>
<td>16</td>
<td>180</td>
<td>10</td>
<td>2-Grad, linearized 2-stage array</td>
</tr>
<tr>
<td>C5</td>
<td>[5]</td>
<td>40</td>
<td>60</td>
<td>10</td>
<td>2-Grad, 2$^\text{nd}$ stage of 2-stage array</td>
</tr>
<tr>
<td>C4-C6</td>
<td>[4]</td>
<td>16</td>
<td>135</td>
<td>9-310</td>
<td>2-Grad, 2$^\text{nd}$ stage of 2-stage SQUID</td>
</tr>
<tr>
<td>C5</td>
<td>[5]</td>
<td>14</td>
<td>135</td>
<td>10-300</td>
<td>2-Grad, 2$^\text{nd}$ stage of 2-stage SQUID</td>
</tr>
<tr>
<td>C4</td>
<td>[4]</td>
<td>1</td>
<td>20</td>
<td>10</td>
<td>2-Grad, single current limit cell</td>
</tr>
<tr>
<td>C4-C6</td>
<td>[4]</td>
<td>1</td>
<td>50</td>
<td>10-16</td>
<td>2-Grad, opt. bottom Nb uncovered</td>
</tr>
<tr>
<td>C2</td>
<td>[3]</td>
<td>1</td>
<td>110</td>
<td>310</td>
<td>2-Grad, SQUID loop in top Nb</td>
</tr>
<tr>
<td>C5</td>
<td>[4]</td>
<td>1</td>
<td>120</td>
<td>10</td>
<td>2-Grad, similar to 2$^\text{nd}$ stage cell</td>
</tr>
<tr>
<td>We87</td>
<td>[8]</td>
<td>1</td>
<td>200</td>
<td>90</td>
<td>Magnetometer with PbIn loop $^a$</td>
</tr>
<tr>
<td>Cg98</td>
<td>[15]</td>
<td>1</td>
<td>15</td>
<td>900</td>
<td>12-Grad, multiwasher design</td>
</tr>
<tr>
<td>Me01</td>
<td>[16]</td>
<td>1</td>
<td>80</td>
<td>100</td>
<td>2-Grad, Quantum Design sensor $^b$</td>
</tr>
<tr>
<td>Bo09</td>
<td>[17]</td>
<td>1</td>
<td>270</td>
<td>53</td>
<td>2-Grad, thin-film susceptometer</td>
</tr>
</tbody>
</table>

All PTB sensors are designed as gradiometers; the configuration is quoted in short form, e.g., 4-Grad = 4-loop parallel gradiometer or 2-Grad = 2-loop series gradiometer. Unless otherwise noted, the SQUID loop is formed by the bottom Nb and the Nb input/feedback coils are realized on top, separated by a sputtered SiO$_x$ or Si$_x$N$_y$ insulation layer. A range for the minimum operation temperature $T_{\text{min}}$ is quoted if devices of same type were operated at different $T_{\text{min}}$. For comparison, four devices reported in literature are included in the study (bottom section of table). $^a$Operated without on-chip linearization (output current feedback). $^b$Sample C1 in [8]: 10 Hz excess noise at 4.2 K determined from 1 Hz value using the quoted frequency dependence $S_{\Phi f} \propto 1/f$. $^c$Published 100 mK noise spectrum extrapolated from 20 Hz to 10 Hz.

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Fig. 1. Noise spectra of a C2 test SQUID operated at 4.2 K and 310 mK. Black lines show the total noise $\varepsilon$, gray lines the 1/f component $\varepsilon_{1/f}$ obtained after subtracting the white noise levels which were determined by fitting the measured noise with (1) at six discrete frequencies between 1 Hz and 100 kHz. Dashed lines show the 1/f components of the fit curves.
Hz and 4.2 K were included. The SQUIDs were operated in a flux-locked loop with the XRF-1 readout electronics [19] and a single-stage or two-stage configuration [13]. In the case of single-stage readout (SQUID arrays and a few single SQUIDs), the preamplifier noise contribution was subtracted. In contrast, for two-stage setups no correction was required except for some cases where the second stages degraded the overall low-frequency noise. Here, the 1/f noise contribution from the second stage was subtracted. The second stages of the integrated two-stage devices were measured with the first stages unbiased. Nyquist noise in the bias resistor caused a high excess white noise impeding a precise determination of the 1/f noise contribution at 4.2 K (at mK temperatures there was typically no problem). All available noise data from the selected samples were used for the graphs in Section III.

III. RESULTS

The measurements at 4.2 K were done by immersing the devices directly into liquid helium. Low-temperature experiments were performed in a 3He cryostat at about 300 mK, in an adiabatic demagnetization refrigerator around 100 mK, or in a 3He-4He dilution refrigerator down to 10 mK. Environmental noise was suppressed by a superconducting shield except in the case of the dilution refrigerator. Therefore, experiments below 100 mK were restricted to magnetically very insensitive devices (test SQUIDs and SQUID arrays) and frequencies above about 10 Hz where the environmental noise drops below the intrinsic SQUID noise. We are currently designing a magnetic shield for the dilution refrigerator to extend our measuring possibilities.

Fig. 2 gives an overview of the low-frequency noise quality of our process in the past six years. At 4.2 K (open symbols in Fig. 2), there was no observable dependence of ε_{1/f} on the SQUID design or fabrication parameters. In contrast, at mK temperatures (filled symbols) the low-frequency excess noise was significantly higher when the FHR system was involved in the SQUID fabrication. There was only one SQUID with FHR involvement that achieved ε_{1/f} < 80 h at <320 mK and 10 Hz (marked by an arrow in Fig. 2), whereas all SQUIDs without FHR involvement (triangles in Fig. 2) remained below this limit. Note that the SQUID design, the number of insulation layers (vertical lines in Fig. 2), the large-area anodization of the bottom Nb, and the substrate used (cf. Table II) caused no observable effect on the mK excess noise. Possibly, the relatively low noise of the C2 devices was related to the fact that the SQUID loop was realized in the upper Nb layer.

We tested on sample basis that there was no dependence of the low-frequency excess noise on the SQUID bias point, and that the noise was not caused by critical current fluctuations (no improvement by using bias reversal [1]). The low-frequency noise did not noticeably change between 10 mK and 430 mK. In contrast, the white noise increased slightly at 430 mK compared to 10 mK, consistent with a minimum effective temperature of the shunt resistors of about 300 mK due to the hot-electron effect [20].

The influence of the FHR sputter steps is clearly visible in the distribution of the 10 Hz 1/f noise components (Fig. 3). At 4.2 K, no systematic effect is visible, whereas at <320 mK the distributions move to higher excess noise levels with increasing number of FHR sputter steps. Note that for the last C5 wafer we directly checked that the noise degrades with the number of FHR steps: the 50 pH test SQUIDs without material on the SQUID loop showed a substantially lower mK 1/f noise than the other devices from the same wafer with SiO$_2$ (two FHR steps).
the approximation for the $1/f$ plot, the dependence may be fitted by straight line(s), yielding

\[ \varepsilon_{1/f} = \alpha \varepsilon \]  \hspace{1cm} (1)

The denotation of symbols is given in Table II, details of literature devices in Table I. Dashed lines show approximation (2). Arrows help to relate outlier data points to the corresponding frequency.

The increase in the excess low-frequency noise is accompanied with a rise in the exponent $\alpha$ (see Fig. 4). In semi-log plot, the dependence may be fitted by straight lines, yielding the approximation for the $1/f$ noise in our SQUIDs

\[ \varepsilon_{1/f} \approx 0.09 \times (f/200 \text{kHz})^\alpha . \]  \hspace{1cm} (2)

Equation (2) is depicted in Fig. 4 by dashed lines; most of the data points lie within a factor of 2 around them. The literature values (stars in Fig. 4) are roughly consistent with our measurements except for “Me01” [16] with $\alpha = 1$; possibly, other low-frequency noise sources were involved here.

The excess noise ratio (ENR) is defined here as the ratio of the $1/f$ noise components at mK temperatures and 4.2 K: ENR = $\varepsilon_{1/f}(T_{\text{mK}})/\varepsilon_{1/f}(4.2 \text{K})$. We use it to estimate the mK noise quality of our wafers from SQUID characterization at 4.2 K. Fig. 5 shows that the measured ENRs were below or above 2.8 (dashed lines) for devices fabricated without or with FHR sputtering, respectively. A reasonable agreement between our “all Alcatel” devices and those reported in literature is found. We could not observe a systematic dependence of the ENR on the absolute $1/f$ noise level or the SQUID inductance $L$. There is a trend that the low-frequency noise in SQUID arrays (filled symbols in Fig. 5) is slightly higher than in single SQUIDs (open symbols), presumably caused by variations of the low-frequency noise performance along the array. The lower limit for our currently achievable mK noise is set by a 50 MHz test SQUID of type C6 operated at 16 mK; $\varepsilon = 0.62 \, h$ at 100 kHz, increasing to 1.64 $h$ at 1 kHz and 14 $h$ at 10 Hz.

IV. DISCUSSION

The noise behavior of our SQUIDs at mK temperatures is generally consistent with the study by Wellstood et al. [8]. For low-noise devices, similar $\alpha$ values below $\approx 1/3$ were observed. At 4.2 K, however, Wellstood et al. found “true” $1/f$ noise ($\alpha = 1$) which originated from other sources than the mK noise and decreased with temperature [21]. This 4.2 K excess noise is typically not present in our SQUIDs, and $\alpha = 0.6$ is found at 4.2 K as well. Such weak frequency dependences of the $1/f$ noise above $\approx 10$ Hz were also observed in literature [22]-[24].

The ENRs of our SQUIDs were above or below 2.8 depending on whether the bottom Nb or insulation layer were fabricated in the FHR instead of the Alcatel system. In the case of the insulation layer, the material involved (SiO$_2$ vs. Si$_3$N$_4$) could be of importance; however, the mK noise level observed with SiO [15] or SiO$_2$ [17] insulation is comparable to that of our SQUIDs with Si$_3$N$_4$ insulation. There are two main differences between our sputter systems: (1) the Alcatel system uses a diffusion oil pump with a liquid Nitrogen trap, whereas the FHR system is equipped with a turbo molecular pump resulting in a higher water content in the sputter chamber, and (2) the FHR system is dimensioned for substantially higher deposition rates than the Alcatel system. We are currently modifying the FHR system to obtain lower deposition rates. Further noise investigations are planned. Our hope is to find the reason for the increase in the low-frequency noise caused by the FHR system, and to learn from that how to modify the fabrication process for minimum noise at mK temperatures.

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