# Investigation of all niobium Nano-SQUIDs based on sub-micrometer cross-type Josephson junctions

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During the last years there has been growing interest in the investigation of small spin systems and in SQUID microscopy. Although SQUID sensors are known to be one of the most sensitive devices for measuring magnetic flux, they usually have dimensions of several µm to mm and are therefore not well adapted to this task.

To improve the spin sensitivity $S_\mu^{1/2} = S_\Phi^{1/2}/\Phi_\mu$ of SQUIDs, both their flux noise spectral density $S_\Phi$ and the coupling $\Phi_\mu$ between a particle with magnetic moment µ to the SQUID have to be improved. Both can be achieved by reducing the physical dimensions of the SQUID. Nowadays, miniaturized SQUIDs are typically based on constriction type Josephson junctions, since desired standard SIS window-type junctions in the micrometer size range do not allow the implementation into SQUIDs with sub-micrometer loop dimensions. Therefore, we recently introduced a new technology for the fabrication of miniaturized SQUIDs based on cross-type SIS Nb/AlO$_x$/Nb Josephson tunnel junctions [2, 3].

Here we describe ongoing work towards highly sensitive NanoSQUIDs based on these cross-type junctions. Figure 1 (left) shows a scanning electron microscope image of such a device with (0.8 × 0.8) µm$^2$ Josephson junctions and an inner loop diameter of about $w$ = 1.5 µm.

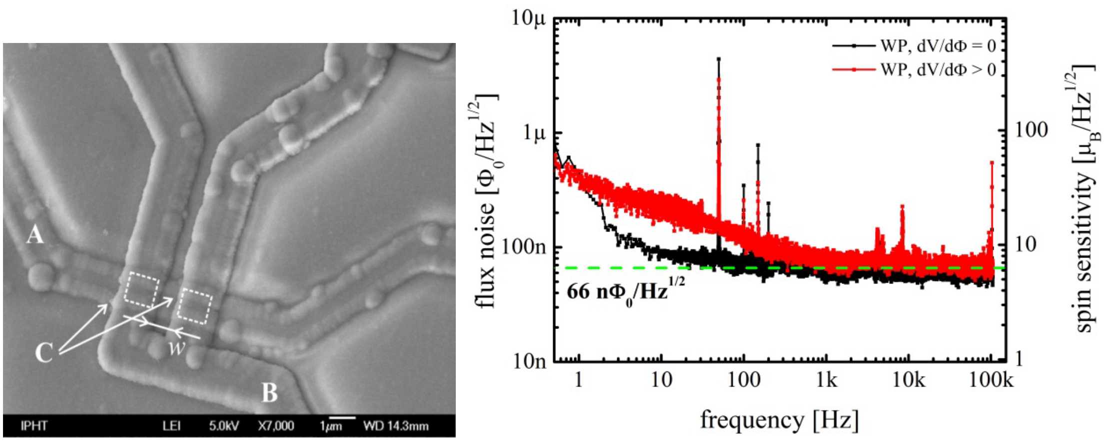


**Fig. 1.** Left: scanning electron microscope image of a SQUID with (0.8 × 0.8) µm$^2$ sized Josephson junctions and an inner loop dimension $w$ of 1.5 µm. Areas C denote the Josephson junctions formed by the overlap of trilayer (A) and wiring layer (B). Right: equivalent flux noise spectrum for SQUID #9. The red and black curves correspond to working points (WP) on the slope of the flux-voltage characteristics with $\partial V/\partial\Phi > 0$ and $\partial V/\partial\Phi = 0$, respectively, where the SQUID is insensitive to magnetic flux noise. The equivalent white flux noise corresponds to 66 n$\Phi_0$/Hz$^{1/2}$.

**Table 1:** Device parameters of the investigated SQUIDs: $w$ denotes the inner diameter of the SQUID loop shown in Figure 1, $L_{SQ}$ the total SQUID inductance, $\beta_L = 2I_C L_{SQ}/\Phi_0$ the screening factor. The equivalent white flux noise levels were measures at 4.2 K; estimations are based on relation (1) as explained in the text.

| SQUID # | loop diameter $w$ [μm] | total SQUID inductance $L_{SQ}$ [pH] | $\beta_L$ | white flux noise [$n\Phi_0/Hz^{1/2}$] measured | white flux noise [$n\Phi_0/Hz^{1/2}$] estimated (1) |
|---|---|---|---|---|---|
| 1 | 10.0 | 40.9 | 0.61 | 230 | 207 |
| 2 | 10.0 | 40.9 | 0.59 | 200 | 207 |
| 3 | 5.5 | 21.7 | 0.31 | 160 | 119 |
| 4 | 5.5 | 21.7 | 0.28 | 125 | 119 |
| 5 | 3.0 | 12.1 | 0.19 | 127 | 89.1 |
| 6 | 3.0 | 12.1 | 0.18 | 106 | 89.1 |
| 7 | 1.5 | 6.93 | 0.09 | 90 | 67.4 |
| 8 | 1.5 | 6.93 | 0.10 | 76 | 67.4 |
| 9 | 0.5 | 3.84 | 0.06 | 66 | 50.2 |
| 10 | 0.5 | 3.84 | 0.07 | 66 | 50.2 |

SQUIDs have been investigated with $w$ ranging from 10 μm down to 0.5 μm, as listed in Table 1. For these optimized sensors with McCumber parameters $\beta_C = 2\pi I_C R^2 C/\Phi_0$ of about unity, white flux noise levels of down to 66 $n\Phi_0/Hz^{1/2}$ have been measured using a SQUID preamplifier. Figure 1 (right) shows the measured flux noise spectrum of SQUID #9. Besides the very low white flux noise it is worth to note that the measured magnitude of flux noise at 1 Hz amounts to only 0.4 $\mu\Phi_0/Hz^{1/2}$, corresponding to an energy resolution $\varepsilon = S_\Phi/(2L_{SQ})$ of about 3.4 $h$ in the white noise region and up to 126 $h$ at 1 Hz, with $h$ being Planck's constant. According to the relation given in [3], the measured flux noise corresponds to a white spin sensitivity of better than 7 $\mu_B/Hz^{1/2}$.

As device dimensions vary by more than an order of magnitude, theoretical predictions of the white flux noise based on the well-known relation $\varepsilon = 16\, k_B T\, (L_{SQ}C)^{1/2}$ yield values that are too small, since the assumption $\beta_L = 2I_C L_{SQ}/\Phi_0 = 1$ cannot be fulfilled for all devices. To accommodate in this concern, we suggest discussing the noise behavior of non-optimized SQUIDs as follows. The relation mentioned above can be treated as the thermal energy $k_B T$ distributed in the frequency range limited by the SQUID time constant $\tau_{LC} = (L_{SQ}C/2)^{1/2}$. In the SQUIDs presented herein, the longest time constant limiting the SQUID bandwidth is, however, given by $t_{RC} = RC$. This substitution yields

$$\varepsilon = 16\, \sqrt{2}\, k_B T\, (RC) \text{ and } S_\Phi^{1/2} = (32\, \sqrt{2}\, L_{SQ} RC\, k_B T)^{1/2} \quad (1)$$

for SQUIDs with non-optimized screening factor $\beta_L$, and shows reasonable agreement with measurements results (see Table 1), allowing for more reliable estimations of noise figures for future Nano-SQUID sensor designs.

Besides a further reduction in SQUID loop dimensions, the optimization of $\beta_L$ to about unity still leaves room for further improvements, which may push the sensitivity of such devices even to single spin resolution. Moreover, the expected feasibility of fabrication of homogenous sensor arrays offering a continuous operation over a broad temperature range, down to mK, represents a unique feature of our approach.

## References

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