Making SQUIDs a practical tool for quantum detection and material characterization in the micro- and nanoscale

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Abstract. The investigation of quantum effects and materials at low and ultra-low temperature often requires very sensitive measurements of weak magnetic signals, small electric currents or voltages. Superconducting Quantum Interference Devices (SQUIDs) have been proven as very attractive tools in this field. However, well established fabrication technology and readout techniques usually fail, particularly, when going to nanoscale magnetic detection where off-the-shelf devices can rarely be used. As an alternative to elaborate nanoSQUID technology, SQUID concepts for nanoscale magnetic detection which are employing conventional, and hence, reliable technology are discussed. Magnetic coupling of nano-sized samples to conventional SQUIDs, e.g. simple gradiometers or more complex devices as fully integrated susceptometers, can be improved significantly by integrating nanoscale detection loops into these devices. Furthermore, appropriate SQUID current sensors are a prerequisite for the readout of micro- and nanoSQUIDs and small-area detection coils. The conventionally made devices are intended for fabrication in moderate numbers to make them available for a broader community.

1. Introduction

Experiments at low and very low temperature often require sensitive measurements of magnetic properties of materials e.g. magnetic susceptibility, magnetic signals as in NMR, or detection of physical quantities which are connected with a magnetic field like weak electrical currents. Superconducting quantum interference devices (SQUIDs) are extremely sensitive cryogenic detectors for magnetic signals and have been proven as very attractive tools for these experiments. Meanwhile, a variety of SQUID based detectors from magnetometers, gradiometers to sophisticated current sensors have been made available even on a commercial basis [1]. Commonly, these devices are designed with microscale dimensions and fabricated using well-established, reliable multilayer thin-film processes with niobium being the superconducting material. Typical pickup coil dimensions for magnetometers and gradiometers range from millimeters up to centimeters, where the coils can be fabricated from superconducting wire or as thin-film components integrated on the SQUID chip. Operating these devices is not straightforward, as they are very sensitive to electromagnetic interference (EMI). Magnetic shielding using superconducting encapsulations is often used for protecting the devices or the complete measuring setup. A number of state-of-the-art SQUID current sensors are designed using gradiometric sensor configurations for suppressing environmental magnetic fields or field gradients, and hence, completely unshielded operation is enabled. Magnetic flux noise levels in the order of $1 \mu \Phi_0/\sqrt{\text{Hz}}$ are achievable even in unshielded operation.
The characterization of material properties with ultimate sensitivity in the micro- and nano-scale (e.g. SQUID microscopy, micro- and nano-susceptometry), has undergone a growing interest recently and cannot be addressed by classical SQUID designs. For these applications novel SQUID designs have to be developed featuring micro- or nano-sized sensitive areas. So-called nanoSQUIDs, i.e., devices with overall loop dimension in the sub-µm regime (see, e.g., [2], [3] and references therein) have been developed enabling coupling improvement between sample and sensing loop. Furthermore, the inductance of the SQUID ring and the capacitance of the Josephson junctions are lowered to such low values that flux noise levels of the order of $10 \times 10^{-6}$ should be possible at $T = 4.2 \, \text{K}$. Unfortunately, the best noise levels obtained so far experimentally with thin-film SQUIDs fabricated on a common chip, are more than an order of magnitude higher, $0.2 \times 10^{-6}$ with $1/f$ corner frequencies above $10 \, \text{Hz}$ [4], [5]. It is worth mentioning here that the same white noise levels are achieved at $4.2 \, \text{K}$ both with conventional SQUIDs if the inductance is reduced to about $10 \, \text{pH}$ [6] and with non-dissipative SQUIDs read out in a dispersive scheme [7]. The performance and the architecture of nanoSQUIDs are mainly limited by the presently available junction technology. Sophisticated SQUID setups have been successfully tested, such as nanoSQUIDs fabricated on the apex of a sharp pulled quartz tube which are intended for nanomagnetic imaging [8]. Even nanoSQUIDs with carbon nanotube junctions have been reported [9]. Constriction junctions can be fabricated more easily by using e-beam lithography or focused ion beam techniques. Overdamped SNS and SNIS junctions have been considered as well and a number of groups have obtained promising results with these junction types as pointed out in more detail below. Furthermore, it is difficult to integrate a feedback coil on the nanoSQUID chip with a sufficiently good coupling to the SQUID loop [10]. In this case if a feedback coil is missing on chip, an external coil system is required to set the nanoSQUID working point and to operate the nanoSQUID in flux-locked-loop mode. Elaborated read-out techniques have to be applied to nanoSQUIDs in order to take full advantage of their improved thermal noise limited sensitivity.

Whereas the manufacturing and operation of nanoSQUIDs is a challenging task, miniaturized SQUIDs and complete SQUID susceptometers can be designed and manufactured employing conventional Nb/AlO$_x$/Nb technology. In addition, these devices can be upgraded by a single nanopatterning step (e.g. e-beam-lithography, Focused Ion Beam (FIB) technique) to compete with the performance of nanoSQUIDs.

As above, the nanoSQUID still remains an object of dedicated research which has not yet reached the level of an applicable tool. So, an experimentalist not focused on the development of SQUIDs, but interested in a reasonably reliable, robust and easy-to-handle SQUID sensor as a practical instrument for his nano-scale or quantum detection experiment is facing an unsatisfactory situation. This paper is intended to shed light on the current situation and to point out what is achievable with conventional SQUID technology and what is available or will be made available in the near future. Devices manufactured utilizing a hybrid technology as mentioned above, will be introduced and compared to state-of-the-art nanoSQUIDs. Concepts of devices which have been developed mainly at PTB will be discussed in more detail.

2. State-of-the-art nanoSQUIDs

Similar to any other SQUID, a nanoSQUID consists of a superconducting ring with nanoscale dimension interrupted in the case of a dc SQUID (which will be considered in this paper) at two points by a weak link (the so-called "Josephson junction") which has a clearly reduced superconducting ampacity. Conventional SQUIDs with SIS junctions are usually employing a well established multilayer junction technology using Nb as superconductor, AlO$_x$ as insulator and a normal metal (e.g. Pd) for the shunt resistors. However, nanoSQUIDs cannot be fabricated using this technology simply by reducing the linewidth and dimension of the device components. In order to guarantee a nonhysteretic $I-V$ characteristics of the nanoSQUID, the damping parameter $\beta_c$ of the nanoSQUID junctions
\[ \beta_c = \frac{2\pi}{\Phi_0} I_0 R^2 C \]  

has to be kept low, where \( \Phi_0 \) is the flux quantum, \( R \) is the shunt resistance of the junction, \( C \) is the junction capacitance, and \( I_0 \) is the junction critical current. In conventional SQUIDs, \( \beta_c \) can be easily controlled by the shunt resistance typically consisting of a normal metal thin-film of an area of about \((10-100) \mu m^2\). Unfortunately, such resistors can hardly be implemented in a nanoSQUID, consequently another junction technology has to be considered. As mentioned above, constriction junctions are a good candidate for nanoSQUIDs and have been fabricated from various thin-films including YBCO [2, 11, 12]. Constriction junctions typically exhibit relatively large critical currents \( I_0 \) and therefore, they show hysteretic \( I-V \) characteristics. Due to the strong temperature dependence of the critical current when working near to the critical temperature \( T_c \) of the superconductor, \( \beta_c \) can be adjusted by the operating temperature of the nanoSQUID. However, this makes the operating condition and the entire nanoSQUID setup quite laborious [4]. In order to overcome this difficulty, superconductors other than Nb, with a lower critical temperature \( T_c \) may be used for nanoSQUID fabrication. If operation of the nanoSQUID at very low temperature is intended, additionally, excess heat in the junctions becomes a problem. These obstacles could be addressed by junctions based on a proximity effect bilayer. A nobel metal layer in combination with a superconducting thin-film is used, where the nobel metal acts as a thermal shunt and is used to control the \( T_c \) of the superconductor [13]. Intrinsically shunted SNS junctions could pave the way for a reproducible and mature nanoSQUID technology as it will be pointed out in more detail in section 4.3. Other approaches (such as the nanoSQUID on a capillary [8]) which are not based on a pure thin-film-on-chip technology will not be considered here.

Reading out a SQUID that is operated in a flux-locked loop, generally requires SQUID electronics which is operated at ambient temperature and consists of a low-noise amplifier and an integrator as schematically shown in Figure 1. The output signal of the integrator is fed back into the SQUID as a magnetic flux using a feedback coil in order to linearize the periodic flux-to-voltage characteristics of the sensor. This feedback coil is usually an integrated component of a common SQUID device. In nanoSQUIDs it is much more difficult to integrate such a feedback coil on chip due to technological difficulties and furthermore, the achievable mutual coupling of the coil to the SQUID loop is rather limited [10].

\[ \Phi_f \]

\[ WP \]

\[ \Phi \]

Figure 1. a) Schematic circuit diagram of a SQUID system (grey area: cryogenic part). The SQUID with the two Josephson junctions is symbolized by a circle with two crosses. It is directly coupled to an amplifier in a so-called flux-locked loop (FLL). The amplified output signal of the SQUID is fed back via an integrator, a resistor \( R_f \) and a feedback coil as a magnetic flux \( \Phi_f \) in such a way that the working point WP is kept stable on the periodic flux-to-voltage characteristics of the SQUID shown in b) even though the external magnetic field changes. It should be mentioned that alternatively to the readout with a directly coupled amplifier, flux modulation readout is widely used. In this case, the SQUID is coupled to the amplifier via a transformer and lock-technique is used (for more details see [14]).
It not only merits using nanoSQUIDs for the characterization of nanoscale samples, they are also attractive for achieving very low flux noise levels. Due to the small loop diameter and junction dimension, the SQUID inductance $L$ and junction capacitance $C$ are both low, in contrast to common SQUID sensors. This enables a low spectral flux noise density $S_\Phi$ according to the approximation by Tesche and Clarke [15]:

$$S_\Phi \approx 2L 16 k_B T (LC)^{1/2}$$

where $k_B$ is the Boltzmann constant and $T$ is the operating temperature.

Though this approximation is not necessarily valid for nanobridge junctions as often used in nanoSQUIDs, it gives an idea of the potential possible noise level. With inductances $L$ of a few pH and capacitances $C$ of a few hundreds of fF, spectral flux noise of levels of $\sqrt{S_\Phi} \ll 10 \text{n}\Phi_0/\text{Hz}$ could be achieved. However, the flux to voltage transfer coefficient $V_\Phi$ of a single nanoSQUID is not sufficient for direct readout with a room temperature preamplifier as shown in Figure 1. In order to benefit from the low intrinsic flux noise of a nanoSQUID, the equivalent flux noise $S_{\Phi,\text{Vpreamp}}$ generated by the voltage noise $S_{\text{V,preamp}}$ of the SQUID electronics should be well below the nanoSQUID noise:

$$S_{\Phi,\text{Nano}} \gg S_{\Phi,\text{Vpreamp}} = S_{\text{V,preamp}}/V_\Phi^2$$

Even with state-of-the-art SQUID electronics which have a voltage noise of $\sqrt{S_{\text{V,preamp}}} = 0.33 \text{nV/}\sqrt{\text{Hz}}$ this is difficult to achieve. In order to overcome this obstacle, a two-stage configuration using a SQUID preamplifier is a useful approach [16]. At PTB, a SQUID series array (SSA) with an integrated bias resistor $R_B$ and a low spectral current noise of $\sqrt{S_{I,\text{SSA}}} \ll 10 \text{pA/}\sqrt{\text{Hz}}$ at 4.2 K has been developed and used as a cryogenic amplifier for the nanoSQUID [4, 17]. This array consists of 16 SQUIDs with a total input inductance $L_{\text{in,SSA}} < 3 \text{nH}$. A schematic setup of the two-stage nanoSQUID readout configuration is shown in Figure 2.

This scheme has been successfully used for nanoSQUID readout, demonstrating a white flux noise of 0.23 $\mu\text{Φ}_0/\sqrt{\text{Hz}}$ at an operating temperature of the constriction junction type nanoSQUID of 7.8 K with a readout contribution of 0.10 $\mu\text{Φ}_0/\sqrt{\text{Hz}}$ [17].

Although appropriate SSAs are manufactured using conventional SQUID technology and commercially available together with adopted readout electronics [1], the overall setup is quite sophisticated. In order to provide optimum operating conditions for the nanoSQUID, it is operated on a variable temperature platform. The optimum working point is set up by an external superconducting wire-wound coil. In addition, a second superconducting field coil is used for exciting the sample under
investigation (e.g. magnetic nanoparticle) which is attached to the nanoSQUID. Figure 3 shows how
the probehead of the nanoSQUID dipstick intended for operation in liquid helium looks like.

Figure 3. Variable temperature platform for operating nanoSQUIDs in a LHe-dipstick.

a) A SSA is mounted on the 4 K platform for preamplifying the nanoSQUID signal according to
the scheme in Figure 2.
b) The working point of the nanoSQUID can be set up using superconducting solenoids. Another
superconducting coil providing a field perpendicular to that of the working point coil pair is
intended for exciting a sample under investigation attached to the nanoSQUID [17].

Using a constriction type nanoSQUID with $L \sim 1 \mu\text{H}$, and $C \sim 0.1 \text{pF}$ in the setup depicted in Figure 3,
a white flux noise of $\sqrt{S_\Phi} = 230 \text{n}\Phi_0/\sqrt{\text{Hz}}$ @ 10 Hz has been obtained at an operation temperature of
$T = 7.8 \text{K}$. This is more than an order of magnitude higher than the theoretically predicted value of
$\sqrt{S_\Phi} = 16 \text{n}\Phi_0/\sqrt{\text{Hz}}$ [17].

3. Conventional SQUIDs with reduced dimensions
As pointed out in the previous section, nanoSQUID technology is not yet mature and requires further
development. Fortunately, the main objectives pursued with nanoSQUIDs can be partly achieved by
conventionally manufactured micro-sized SQUID sensors. Although the reduced SQUID dimension of
a micro-sized SQUID leads only to a slightly improved noise performance according to relation (2),
practical nanoSQUIDs do not perform much better than state-of-the-art microSQUIDs. A more
difficult task is to couple the microSQUID to a nanoscale sample, which will be considered in more
detail in this chapter.

3.1. Miniature pickup coils
A very simple way to detect magnetic signals from a sample is to use a wire wound pickup coil
connected to a sensitive (commercially available) SQUID current sensor. This works even if the
sample has nanoscale dimensions as it has been demonstrated in NMR experiments [18]. However, for
nano-sized samples it is more appropriate to use a thin-film miniature pickup coil. This approach is in
particular useful for experiments at ultralow temperature, if the SQUID can be operated remotely from
the coil, and hence, parasitic heat input to the sample by the dissipative SQUID can be avoided. It has
been demonstrated in [19] that such a configuration can be used for the detection of NMR signals from
a $^3\text{He}$ gas sample. To obtain a high energy resolution of the NMR setup, a very sensitive two-stage
SQUID current sensor consisting of a front end SQUID and a SQUID array has been used in this
experiment. The SQUID current sensors fabricated at PTB are available with various inductances of
the input coil. This allows one to select a sensor that provides a good match between the microcoil and
the input coil of the current sensor [16 ]. In this particular case a sensor with an input coil inductance
of $L_i = 29 \, \text{nH}$ has been used in combination with the microcoil shown in Figure 4. The intention is to apply the microcoil setup for NMR experiments on nanofluidic samples.

Setups like this can be effectively used for other experiments as well, where microcoils are adopted to the experimental requirements and connected to an appropriate SQUID current sensor. Auxiliary components are already integrated on the current sensor chip, like filters and input current limiters, which makes it more convenient to use these sensors.

### 3.2. Micro-SQUID gradiometers

Conventional Nb/AlO$_x$/Nb tunnel junction technology can be employed for manufacturing SQUIDs with a very small sensing area. The idea is to reduce the sensing area of the SQUID by covering the SQUID loop partly by a superconducting layer, while the other device components (junctions, shunt resistors) still remain their normal size. The microSQUID gradiometer presented in Figure 5 has made use of this idea. It can be clearly seen, that the areas of the Josephson junctions (4 $\mu$m $\times$ 4 $\mu$m) are much larger than the sensing area of the SQUID gradiometer. The diameter of the sensing area of about 3 $\mu$m equals approximately the linewidth of the superconducting lines. Two integrated lines enable feedback and magnetic sample excitation. With this device, a minimum intrinsic flux noise of $\sqrt{\Delta \Phi} = 122 \, \text{n}\Phi_0/\sqrt{\text{Hz}}$ @ 10 kHz has been measured at an operational temperature of 4 K. With a two-stage readout an overall white noise of $\sqrt{\Delta \Phi} = 163 \, \text{n}\Phi_0/\sqrt{\text{Hz}}$ @ 10 kHz was obtained which is comparable to the practically achieved noise levels of nanoSQUIDs [6].

### 3.3. MicroSQUID susceptometers

Already 30 years ago, integrated SQUID susceptometers have been designed and successfully operated [20]. For scanning SQUID microscopy, fully integrated devices have been reported recently [21]. At PTB, we have developed integrated susceptometers with various pickup loop dimensions [6, 22]. In addition to a first-order SQUID gradiometer consisting of two circular loops, an excitation field...
coil is integrated on-chip as shown in Figure 6. It provides an excitation field with a sensitivity of about 100 mT/A at the sample position in the pickup loops, whereas the Josephson junctions are just exposed to a reduced field. Devices with pickup loop diameters of 30 µm, 60 µm and 100 µm are available. Compared with the microSQUID gradiometer depicted in 3.2, the micro-sized susceptometer have higher SQUID inductances which leads to higher white flux noise levels, e.g. $1.3 \mu \Phi_0/\sqrt{\text{Hz}}$ for the 30 µm device. These susceptometers enable measurements of both the real and the imaginary part of the magnetic susceptibility in a wide frequency range up to 1 MHz at temperatures down to the mK range. Preferably, the susceptometers should be read out as well with an SSA in a two-stage configuration.

4. Advanced device concepts

The devices described in section 3 are manufactured utilizing conventional optical lithography only. Their operation is quite straightforward by making use of state-of-the-art SQUID current sensors in a two-stage configuration in combination with conventional FLL electronics. Nevertheless, the coupling of the devices to real nanoscale samples can be significantly improved. This can be achieved if nanopatterning is applied to parts of the SQUID pickup loops after the basic device has been manufactured in a conventional way. Furthermore, the readout configuration can be simplified.

4.1. Micro-sized SQUIDs with integrated nanoloops

The basic idea to improve the coupling of a nanoscale sample to a micro-sized SQUID is to connect a nanoloop in series to the common SQUID pickup loop (see Figure 7). This can be done by removing material from the SQUID pickup loop which has typically a linewidth $\geq 1.5$ µm. Focused Ion Beam (FIB) patterning or e-beam-lithography in combination with plasma etching are appropriate techniques for this fabrication step.

From FEM simulations a ten-fold improvement of the coupling between a magnetic dipole and the pickup loop was predicted for an optimum design. In order to verify this prediction, a microsusceptometer as shown in Figure 5 with a 30 µm pickup loop has been used to implement a nanoloop with an inner diameter of 450 nm and a linewidth of 250 nm. Test measurements with this device have been successfully performed on a Permalloy sample covering the nanoloop. Both, the in-phase signal and the out-of-phase signal from the sample have been observed in a frequency range up to 100 kHz. The sample was excited with an ac magnetic flux density of about 250 µT rms by using the integrated excitation coils of the susceptometer [22].

Figure 6. Fully integrated microSQUID susceptometer with gradiometric SQUID loop and excitation coils around the pickup loops (SEM picture). Dummy structures are added for maximum balance of the gradiometer type susceptometer.
4.2. MicroSQUIDs with on-chip preamplifier

As described in section 2, the low-noise SQUID devices have to be read out in a two-stage configuration, where the signal from the front-end SQUID is preamplified by a SQUID current sensor (in most cases a SSA). This configuration allows flexibility for the placement of the devices in a certain setup, e.g. if the SSA has to be advantageously mounted far from a magnetic excitation field. If the SSA can be operated near to the front-end SQUID, it is reasonable to integrate both devices on the same chip. It makes the entire setup much more robust and easy-to-handle and can avoid interferences due to poor wiring. Auxiliary elements like pads for heat sinking and filters are on chip as well. Figure 8 shows a chip design with the latest version of the susceptometer presented in subsection 3.3 integrated on chip with a 24-SQUID series array current sensor. Three variants with different pickup loop diameters are available [23].

Figure 7. SQUID pickup loop with integrated nanoloop.

a) Scheme of nanoloop implementation. The minimum pickup loop linewidth d of a conventional SQUID is typically about 1.5 µm
b) REM picture of a nanoloop with an inner loop diameter of 450 nm integrated in a pickup loop of a susceptometer depicted in Figure 6. [22].

Figure 8. Chip layout of a SQUID micro-susceptometer with on-chip SSA. The chip size is 3.3 mm × 3.3 mm. The susceptometer is located in the lower right corner of the chip and the 24-SQUID series array is positioned in the upper chip part. On the left hand side are the bonding pads and filters [23].

Stimulated by the promising results obtained from the nanoloop experiments described in the previous subsection, optimized susceptometers for nanoloop integration have been developed. The large pickup loops of the susceptometer depicted in Figure 6 have shrunken to a minimum and the multi-turn excitation coils have been replaced by single lines surrounding the pickup loops. The susceptometer is integrated on a 3.3 mm × 3.3 mm chip together with an SSA in two-stage configuration as well (see Figure 9). A design with galvanically separated feedback and excitation lines by coupling transformers has also been developed and fabricated but not tested yet [22].
4.3. NanoSQUIDs with intrinsically shunted SNS junctions

As mentioned in section 2, a mature technology for nanoSQUIDs isn’t available yet, but intrinsically shunted SNS junctions have a great potential to meet upcoming needs for more complex nanoSQUID based devices. Recently, SNS junctions have been used by PTB for manufacturing nanoSQUIDs employing a chemical-mechanical-polishing process (CMP) [5]. These nanoSQUIDs are based on Nb thin films and overdamped SNS Josephson junctions with HfTi as a normal conducting barrier. The SQUIDs can be operated in nonhysteretic mode at 4 K. In these devices, the SQUID loop is perpendicular to the chip plane similar to devices with SNIS junctions reported in [25] but fabricated without using FIB patterning. A line in the bottom Nb layer forms one part of the SQUID loop. The other part is formed by a line in the top Nb layer that is separated from the bottom layer by a 225 nm thick insulating SiO₂ layer. The two stacked Nb lines are connected by the HfTi Josephson junctions with lateral dimensions of 200 nm × 200 nm. The loop geometry is determined by the distance of the junctions of 1,6 µm and the SiO₂ layer thickness. These devices can be operated in magnetic fields up to $B = \pm 50 \text{ mT}$ with a white flux noise $\sqrt{S_\Phi} = 250 \text{ n}\Phi_0/\sqrt{\text{Hz}}$ for frequencies above 1 kHz. Operation in very high magnetic fields up to 0.5 T could be also demonstrated. Even at those high fields, a flux noise of $\sqrt{S_\Phi} = 680 \text{ n}\Phi_0/\sqrt{\text{Hz}}$ has been achieved, which makes this device concept very attractive for experiments where e.g. large magnetic excitation fields are required. A practical application for SQUID magnetometry has been reported in [25].

In order to make this junction technology more flexible for practical use, several designs for our standard 3.3 mm × 3.3 mm chips have been developed. The chips contain the basic Nb wiring including bond pads, and filters similar to the chip designs in Figure 8 and 9. The HfTi junctions are implemented using CMP. After the junction fabrication step is finished, the top Nb wiring is applied. Figure 10 gives an impression of the structure of a special SQUID gradiometer with HfTi junctions. A number of designs including serial and parallel nanoSQUID gradiometers and nanoSQUID current sensors are currently under investigation.
5. Summary

The aim of this paper was to deal with an overview of micro- and nano-sized SQUID devices which are manufactured using more or less conventional fabrication technology. In contrast to nanoSQUIDs based on a sophisticated junction technology, these devices are already available or can be made available for a broader community. In order to use the micro and nanoSQUIDs to full capacity, appropriate SQUID current sensors are an essential component of the readout setup. These current sensors are operated with a common SQUID readout electronics. The requirements of a number of low-temperature experiments (e.g. NMR) can be already addressed with small wire wound or thin-film coils combined with a state-of-the-art SQUID current sensor. MicroSQUIDs with a number of auxiliary components on chip are already available, even with an integrated SSA if required. The coupling of a microSQUID fabricated in conventional technology to a nano-sized sample can be significantly improved by integrating a nanoloop in the pickup coil. However, this needs additional nano-fabrication steps using FIB or e-beam lithography. Templates made in Nb technology can be used advantageously for implementing real nanoSQUIDs. This has been shown for HfTi junction based SQUIDs but could be of interest for other junction technology as well, e.g. constriction junctions. The devices fabricated in conventional technology could be further improved by shrinking the junction dimension as it is obvious from [27]. If operation in comparatively high magnetic fields is required, real nanoSQUIDs with e.g. HfTi junctions are inevitable. Figure 11 tries to summarize these issues.

![Figure 10. Serial nanoSQUID gradiometer with HfTi junctions before CMP has applied and Nb top wiring has been deposited. The position of the Nb top line is schematically shown by the dashed bar [26].](image)

![Figure 11. Overview of micro- and nanoSQUID setups with respect to technological maturity.](image)

Acknowledgement

The author would like to thank his colleagues at PTB, especially D. Drung, J. Beyer, S. Bechstein, F. Ruede, C. Aßmann, A. Kirste, O. Kieler, J. Kohlmann and N. Kranz for helpful discussions and technical assistance. A considerable amount of the work reviewed here has been done in collaboration with groups at NPL, Royal Holloway University of London, University of Zaragoza and CSIC Zaragoza. It has been supported by the European Union in the framework of the FP7 European Microkelvin Collaboration and the European Metrology Research Programme EMRP, which is jointly funded by the participating countries within EURAMET and the EU.
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