SQUIPT – a Quantum Interference Detector of Magnetic Flux with Low Power Dissipation

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February 19, 2014 (HP70). SQUID (superconducting quantum interference device) sensors are widely used in applications such as detection of ultra-small magnetic fields, for instance to monitor the spatially resolved electromagnetic activity within the human brain. Generally, the performance of these sensors depends on their response to external magnetic flux and, considering the signal to noise ratio, the achievable lowest noise level. The latter depends, if the Johnson noise is the limiting factor, on the operation temperature of the device. Indeed, SQUIDs show enhanced noise performance when the temperature is lowered further, *e.g.*, below 4 kelvin, but ultimately, due to dissipation and weak intrinsic thermalization in the superconductor, further reduction of the lattice temperature below about 0.3 kelvin does no longer yield reduced noise levels. At this point, a new concept, the SQUIPT (Superconducting Quantum Interference Proximity Transistor) [1] promises advantages: the intrinsic dissipation of this device is predicted to be two to three orders of magnitude lower and consequently, the achievable effective noise temperature and noise level are lower.

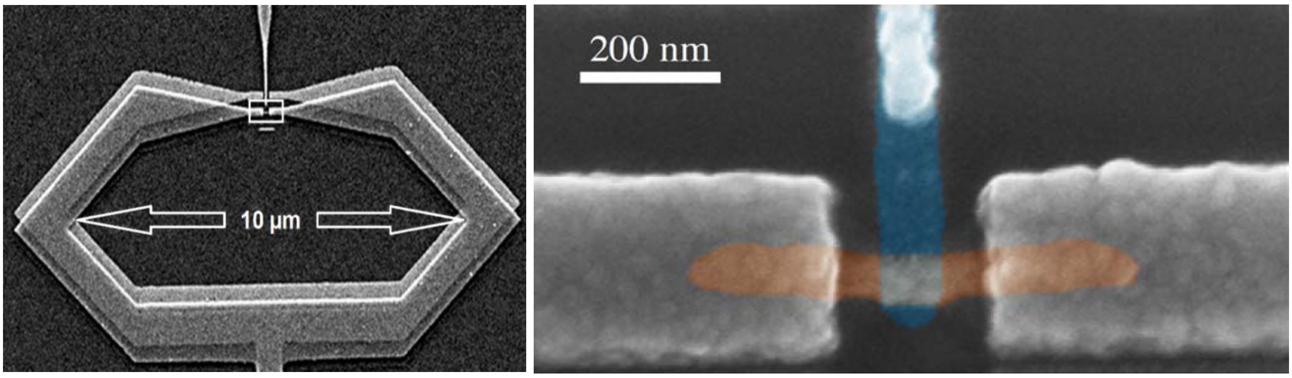

Fig. 1. (left) Scanning electron micrograph of the SQUIPT loop geometry with the weak link inserted in the top of the ring. The ring itself is made out of three layers in the EBL fabrication process involving three angle shadow evaporation through a suspended mask: at first, a thin layer of aluminum (15 nm) is deposited with an oxide tunnel barrier on top, then the copper film (20 nm) and finally a thick (100 nm) aluminum layer. The box around this weak link marks the extent of the area depicted on the right (colored SEM image): a small normal conducting copper strip interrupts the thick superconductor. In addition, a superconducting (blue) contact is attached via a tunnel barrier to the middle of the weak link.

Figure 1 depicts the main concept of a SQUIPT: a superconducting ring is interrupted by *one* weak link, a lateral Josephson junction, forming an Andreev interferometer [2]. The weak link is a small copper island (see Fig. 1 right) in direct and clean contact with the superconducting material (aluminum). The island is about 150 nm long and has a small cross section. A similar setup is well known and has been widely used in the past for rf-SQUIDs, but there the readout requires a radio-frequency tank circuit. In the SQUIPT, the key idea is to place the probe on the weak link such that it allows for a simple read-out as described next. It is realized independently from the ring itself using a tiny tunnel junction attached to the middle of this weak link. Such a setup allows performing tunnel spectroscopy [3] of the density of states within the weak link. The superconducting coherence length in the aluminum (about 200 nm) is here of the same order as the weak link length. As a consequence, the properties of the normal metal are strongly modified due to the superconducting proximity effect.

The density of states is altered by the magnetic flux penetrating through the superconducting ring. Two extreme cases are: (1) an integer number of flux quanta (Φ_0) leads to a phase difference of an integer multiple of 2π across the weak link. An induced energy gap within the density of states in the normal conductor is then observed. On the other hand, for half Φ_0 modulo 2π through the loop, the density of states in the copper conductor is not altered at the location of the tunnel probe [3]. Consequently, the current through the tunnel junction varies with the periodicity of Φ_0 from zero to its maximum value governed by the tunnel resistance of the probe, sensitively probing the magnetic flux threading the loop. The device allows for a very simple and effective measurement setup. It is sufficient to apply current or voltage bias and read the resulting voltage across or current through the device with a single low-noise amplifier at cryogenic temperatures, or for less demanding measurements even at room temperature.

The device offers a series of advantages: first of all, the power dissipation as low as 1 fW, due to the high impedance (about 100 kΩ) of the tunnel probe, allowed us to effectively operate our SQUIPT at 50 mK [4] as normal conducting materials thermalize efficiently compared to superconductors at these temperatures. This is the key factor in the inferred enhanced noise performance of the SQUIPT. Furthermore, the simplicity of the readout scheme makes the device suitable for various experimental setups, for instance scanning field microscopes, and sensor arrays. In addition, it is advantageous for the readout of the device that the probe junction can be engineered independently from the SQUIPT loop itself: the device can then be perfectly matched to the input impedance of the readout amplifier. Finally, fabricating the ring of superconducting materials with a larger gap, like niobium or vanadium, should enhance the responsivity of the device in future realizations[1]. Altogether, an optimized device as described above should be able to reach flux sensitivity well below $10^{-7}\ \Phi_0\mathrm{Hz}^{-1/2}$, which is the best figure of merit of SQUID devices. Recently [4], device responsivities on the order of 20 nA/Φ_0 were experimentally realized corresponding to a flux resolution of $2\mathrm{x}10^{-7}\ \Phi_0\mathrm{Hz}^{-1/2}$, using just a room temperature amplifier.

References

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[1] By responsivity we understand here the change in the current through the device corresponding to one Φ_0 change in the magnetic flux threading the SQUIPT loop.