Development of high-$T_c$ SQUID microscope with flux guide

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Abstract
We have developed a new type of superconducting interference device (SQUID) microscope. A direct-coupled SQUID magnetometer with a high-$\mu$ metal needle was used and the substrate was machined to create a dimple for the needle at the centre of the pick-up loop. One end of the needle penetrated through the superconducting pick-up loop in a vacuum; the needle was fixed in the vacuum window with the other end at room temperature in the outside atmosphere. Several kinds of simulation using a Maxwell simulator were performed and the results were applied to our system. As a demonstration, a laser-printed output was scanned by the microscope. Line bars with a line width of 100 $\mu$m and a spacing between lines of 200 $\mu$m were clearly imaged.

1. Introduction
A superconducting interference device (SQUID) microscope is a powerful tool for the investigation of flux dynamics and other studies in physics [1–6]. For a low-$T_c$ SQUID, a small transfer coil was developed and connected to the SQUID [3, 4]. However, for a high-$T_c$ SQUID, there is no technology to transfer a small magnetic field from a small area to the SQUID. Therefore, the high-$T_c$ SQUID must be sufficiently small and the separation of the SQUID and the sample must be as small as possible. Some groups have proposed a high-$T_c$ SQUID microscope using a high-$\mu$ metal tip or needle to solve the above-mentioned problems [7–10]. The advantage of this system is that magnetization of the sample by the modulation coil of the SQUID can be avoided, because the coil is far enough from the sample and it is coupled not to the pick-up coil directly, but to the SQUID. Several FEED simulations have been performed. We have designed and fabricated a new type of high-$T_c$ microscope using a fine flux guide based on the results. One end of the flux guide penetrates through the pick-up loop of the 77 K SQUID; the needle was held by the window with the other end sharpened and at room temperature. A system in which a room temperature flux guide penetrates the SQUID pick-up loop has not been reported to date. We present a design based on a computer simulation of the magnetic field distribution and the results of the microscope.

2. Simulation
First, we investigated the feasibility of this method using computer simulations. The three-dimensional FEED electrodynamic simulation program, Maxwell (supplied by Ansoft Japan), was used. We selected a perfect conductor as the material for the pick-up loop instead of a superconductor because there was no superconducting material in the library. The permeability of the needle $\mu_r$ was selected as 60 000. The details of the simulation parameters and dimensions are shown in figure 1. One set of small-field coils with a separation of 900 $\mu$m, which generates a magnetic field of 10 mA m$^{-1}$, was positioned above the pick-up loop. The relative position of the set of coils and the pick-up loop was varied by steps of 150 $\mu$m in this simulation. The field calculation at the centre of the pick-up coil was performed at each position. Figure 2 shows the results of the simulation. In the case of (a) the needle penetrates through the loop. The bottom of the needle is 500 $\mu$m below the film in this case. In the case of (b) the needle is at the same level as the loop. In the case of (c) the needle is above the loop with a space of 500 $\mu$m. Two peaks, one at the position of each field coil, were observed in all the cases. However, field density in the case of (a) is the largest and one order of magnitude larger than that in the case of (c). This
suggestions that the penetration of the needle through the pick-up loop is essential to obtaining higher sensitivity.

Next we investigated the effect of the size of the top of the needle. In this simulation the space between the coil and the needle was set at 0.1 \( \mu m \) and the separation of the coils was 10 \( \mu m \) to obtain good space resolution. The results are shown in figure 3. The peaks of the field with the needle of a diameter 1 \( \mu m \) are sharper than those with a diameter of 10 \( \mu m \). This result suggests that the needle with a smaller top shows better space resolution.

3. Structure of microscope

A schematic cross-sectional view of the microscope is shown in figure 4. Most of the parts of the cryostat are made of G-10 fibreglass and Delrin [5]. The cryostat contains a liquid \( N_2 \) copper reservoir, having a volume of 0.8 litres. The inside of the cryostat can be evacuated up to the order of 10\(^{-3}\) Pa by a vacuum pump and sealed off by an o-ring valve. The SQUID chip was attached to the top of a 12 \( \mu m \) diameter sapphire rod with GE (General Electric Co) varnish, which was thermally anchored with the liquid \( N_2 \) reservoir. The SQUID was 50 mm away from the metallic reservoir. A six-turn modulation coil and a heater were installed at the upper end of the sapphire rod. A copper wire step-up transformer was glued tightly to the top of the copper reservoir. The electrical contacts to the SQUID chip were made by applying conductive silver paint to the bonding pads and the side of the SQUID chip.

A needle made of a high-\( \mu \) metal (Fe–Ni base) was set at the centre of the pick-up loop. The length of the needle was 7 mm, its cross section at the bottom was a 300 \( \mu m \times 300 \mu m \) square shape. The top of the needle was filed so that it had a sharp edge, the shape of the top edge was not circular but oval. The size of the oval-shaped top edge was 50 \( \mu m \times 10 \mu m \) from microscopic observation. The needle penetrated a vacuum window through a hole and we found that about 100 \( \mu m \) from the top of the needle was outside the window. The hole was sealed with a silicone rubber glue after penetration. The distance between the needle and the pick-up loop was adjustable by turning 3 \( \mu m \).

A home-made XYZ translation stage was placed on the top plate of the cryostat. The stage was made of an
aluminium alloy and steel and driven by an ultrasonic linear motor. The minimum step size was 0.5 μm. The translation stage was controlled by a personal computer using signals from positioning sensors. The maximum scan range was 6 × 6 mm².

Figure 5 shows the schematic drawing of a direct-coupled dc SQUID [11]. It was made of a 200 nm thick YBa₂Cu₃Oₓ₋ᵧ (YBCO) thin film on a 500 μm thick SrTiO₃ substrate by sputtering. The junctions utilized in the SQUID were of 30° bi-crystal type. The inductance of the SQUID and the pick-up loop were 40 pH and 3 nH from calculations, respectively. The outer and inner diagonal dimensions of the pick-up loop were 6.4 and 2.2 mm respectively. The substrate at the centre of the pick-up loop was machined so that a 100–200 μm deep dimple was created for the needle space. It was not a through-hole but a dimple because the substrate was fragile.

4. Experimental details and discussion

The performance of the direct-coupled SQUID magnetometer was investigated. A needle was positioned at the centre of the pick-up loop. The needle was brought into contact once with the bottom of the dimple of the substrate by adjusting the micrometer and it was then lifted a little bit above the bottom for thermal isolation.

The SQUID was driven by a flux-locked loop with a flux modulation frequency of 256 kHz. The output signal from the SQUID was amplified by double transformers, one at 77 K and the other at room temperature. The $R_f/M_f$ is 0.5 V/φ₀, where $R_f$ is the feedback resistance and $M_f$ is the mutual inductance between the SQUID magnetometer and the modulation coil. All of the measurements were performed in a magnetically shielded room, which had a shielding factor of −50 dB. A small one-turn coil with a radius of 1 mm was prepared and put on the top end of the needle to measure the local effective area at the edge of the needle. A small coil rather than a large coil was used to avoid having the field from the coil couple directly to the pick-up loop of the SQUID. A sinusoidal current of 1 mA was used with a frequency of 100 Hz was used. We found that the effective area $A_{eff}$ of the magnetometer was 540 μm². This value corresponds to a small SQUID with a washer size of about 15 μm × 15 μm [2].

The flux noise of the magnetometer was measured. As shown in figure 6, the noise with needle was 80 μφ₀/Hz¹/₂ at 100 Hz and 30 μφ₀/Hz¹/₂ in the white noise region. Excess 1/f flux noise, which may be generated by the thermal activated hopping of vortices trapped during cooldown, was observed.

![Figure 5. Schematic drawing of a directly coupled dc SQUID. The SQUID inductance was 40 pH in the calculation. The outer and inner diagonal dimensions of the pick-up loop were 6.4 mm and 2.2 mm, respectively. The substrate at the centre of the pick-up loop was machined so that a 100–200 μm deep dimple was created for the needle space.](image)

![Figure 6. Flux noise of magnetometer with needle. The noise with needle was 80 μφ₀/Hz¹/₂ at 100 Hz and 30 μφ₀/Hz¹/₂ in the white noise region. Excess 1/f flux noise, which may be generated by the thermal activated hopping of vortices trapped during cooldown, was observed.](image)
5. Conclusion

In conclusion, we have designed and constructed a new type of magnetic microscope using a high-$T_c$ SQUID with a room temperature, high-$\mu$ metal needle. One end of the needle penetrated a superconducting pick-up loop in a vacuum; the needle was fixed in the vacuum window with the other end at room temperature in the outside atmosphere. Using a FEED electrodynamic simulation, it was found that when the needle penetrated the superconducting loop, the magnetic field density at the loop was one order of magnitude larger than that in the case of no penetration. Therefore, the substrate of a direct-coupled SQUID magnetometer was machined to create a dimple at the center of the pick-up loop to provide room for the needle. Laser-printed output was scanned by the microscope. Line bars with a line width of 100 $\mu$m and a spacing between lines of 200 $\mu$m were clearly imaged. Since the top edge of the smaller needle showed better spatial resolution in our simulations, the space resolution can be improved by using a sharper needle edge.

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References


