A scanning SQUID microscope in a dilution refrigerator

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Abstract

We have designed and built a scanning SQUID microscope in a dilution refrigerator, capable of magnetic imaging at temperatures down to 20 mK. As sensors we use susceptometer SQUIDs with two pickup loops and on-chip field coils to allow measurement of both the magnetic susceptibility of the sample and the magnetic field at the sample surface on a mesoscopic length scale. The instrument is useful for studying superconductivity and magnetic effects in novel materials and electronic coherence effects (such as persistent currents) in mesoscopic systems.

Key words: magnetic measurements; scanning probe microscopy; SQUID

1. Introduction

Scanning SQUID microscopes are useful tools for studying magnetism on a mesoscopic length scale since they provide the highest sensitivity to magnetic flux of any available sensor. The measurements are relatively straightforward to interpret since the SQUID directly measures the magnetic flux threading it. We will discuss the specifics of building a SQUID microscope for ultra-low-temperature use in a dilution refrigerator.

2. Instrument design

Our microscope utilizes a large-area piezoelectric scanner of the “S-bender” type, generally following the design of Siegel *et al.* [1] This lets us attain a relatively large scan range of approximately 80 μm $\times$ 80 μm with a compact and simple design that works well at low temperatures. Z axis motion is controlled by an additional piezo bender, on which the SQUID is mounted. A sketch of the scanner is shown in Fig. 1.

The S-bender design automatically compensates for thermal contraction of the piezos since the x and y axis piezo pairs should contract equally. This matching allows us to mount the scanner with spring-loaded screws on a copper baseplate, which is clamped directly to the mixing chamber of a dilution refrigerator, without the need for coarse motion. The sample is also attached directly to the baseplate in order to maximize the thermal contact. The general microscope design is discussed in greater detail in Ref. 2.

The susceptometers that we use are derived from an original susceptometer design by M. Ketchen *et al.* [3], but ours are modified for scanning. Apart from shunt resistor material, the ones used in the dilution refrigerator microscope are practically identical to those used at higher temperatures in our laboratory [4].

The main recent improvement over the microscope design described in Ref. 2 is that the SQUIDs are now run in a DC flux-feedback system with a low-temperature gain stage consisting of a SQUID array [5,6]. This potentially allows for much greater bandwidth than a traditional transformer-coupled readout since the bandwidth limitation due to the AC modulation is removed. Using DC feedback also makes it easier to find an optimal operating point for the susceptometer SQUID since the I–V and V–Φ characteristics of

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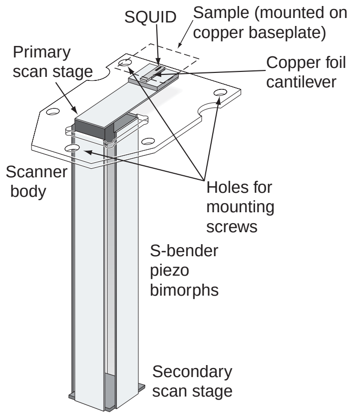

Fig. 1. S-bender scanner design. The piezo bimorphs bend in an S shape, moving the scan stage in an approximate plane. The SQUID is mounted on a piezo bender controlling the height.

the SQUID can be measured directly. While the system is not yet optimized, the noise is already typically reduced by a factor of four compared to the previously used AC readout system. The measurement system is conceptually similar to that described in Ref. 6 with the input SQUID replaced by our susceptometer.

3. Applications

The microscope can be used for making magnetic measurements on a mesoscopic length scale. This can involve both measuring local magnetic properties in bulk samples and properties of individual mesoscopic samples, typically arranged in an array so that several samples can be studied in a single cooldown.

In bulk materials, examples of interesting phenomena which are detectable by local susceptibility measurements are trace superconductivity or inhomogeneous superconducting transitions. Magnetometry measurements can be used to study local magnetization in magnetic materials and vortex characteristics and dynamics in superconductors. An example of susceptibility measurements on a tungsten thin film (actually a transition edge sensor used for astrophysics experiments [7]) with a locally applied DC background field is shown in Figure 2. On the same sample we have also looked at vortex motion as a function of temperature.

An example of a measurement on a mesoscopic system is that of persistent currents in normal-metal rings [8]. We believe that a scanning SQUID microscope is a useful tool for further investigation of this effect since it allows greater freedom in the choice of materials and substrates, background signals can easily be measured without thermal cycling, and several individual samples can be studied in the same cooldown [2].

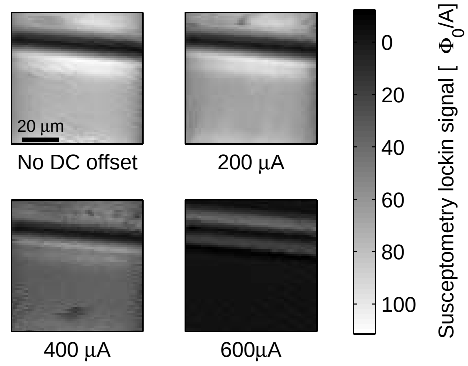

Fig. 2. 70 mK susceptometry images of a W TES sensor [7] in a locally applied background field. The AC excitation amplitude in terms of the current applied through the field coils is 50 μA. The DC field from the 600 μA DC current is larger than H_c for this sample, as it has no diamagnetic response. The bright lines at the top of the image are aluminum current rails which are superconducting throughout this field range, and the non-superconducting region between them is bare silicon.

In conclusion, our dilution refrigerator based scanning SQUID microscope provides unique opportunities for a wide range of magnetic measurements at low temperatures on a mesoscopic length scale.

Acknowledgements

We thank M. B. Ketchen and J. R. Kirtley for sharing their SQUID design with us, and B. Cabrera and A. J. Miller for providing the TES sensor. This work was supported by the NSF.

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