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Development of Scanning dc-SQUID system for local magnetic imaging

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Introduction

Superconducting quantum interference device (SQUID) is widely used for sensitive probe of magnetic flux in a wide variety of fields from medicine to engineerings [1]. One of the advantages of dc-SQUID is that the quantitatively accurate flux Φ penetrating the superconducting loop can be measured by detecting the SQUID critical supercurrent I_c as given by,

$$I_c=2I_0|\cos(\pi\Phi/\Phi_0)|$$

where I_0 is a critical current of a Josephson junction and Φ_0 is magnetic flux quantum. A SQUID is used as local probe of magnetic flux by reducing the radius of a SQUID loop. In order to obtain high spatial resolution, it is equally important to fabricate SQUID loop close to the edge of the probe. Weak-link Josephson junctions have advantages that fabrication by milling without lithography process and observation of the resultant loop may be performed *in situ* by a focused ion beam (FIB) [2]. This process is thus suitable for preparing small loop size of ~1 μm at the edge of substrate for a SQUID probe. In this paper, we describe fabrication process of SQUID probe with weak-link Josephson junctions and our newly built scanning SQUID microscope system. We demonstrate successful mapping of magnetic flux induced by the current distribution in a GaAs/AlGaAs Hall-bar structure.

Fabrication process for SQUID probe

We chose a two-step process for preparing a SQUID probe. First, a deep silicon etching process, called Bosch process, was used to define leads and a region to prepare a SQUID loop. Second, a mask-less fabrication by a FIB milling system was used to define fine structures for SQUID loop and weak-link Josephson junctions. These two techniques are key to realize an effective magnetic coupling and to image magnetic flux with high spatial resolution.

At the first step, we prepared a superconducting four-wire pattern in the vicinity of the edges of a Si substrate. A Nb/Au thin film was prepared on the Si substrate. After preparing a superconducting four-wire pattern, a maskless laser lithography was performed to define silicon SPM probe with a thickness of 100 μm as schematically shown in Fig. 1 (b). A successively repeated processes of a pulsed reactive ion etching (RIE) and deposition of a passivation layer was performed. Deep etching of silicon substrate with high aspect ratio was achieved. This Bosch process enables us to prepare about a hundred of silicon SPM probes at once. By the above process SQUID patterns were fabricated within several micrometers from the edges of silicon SPM probes.

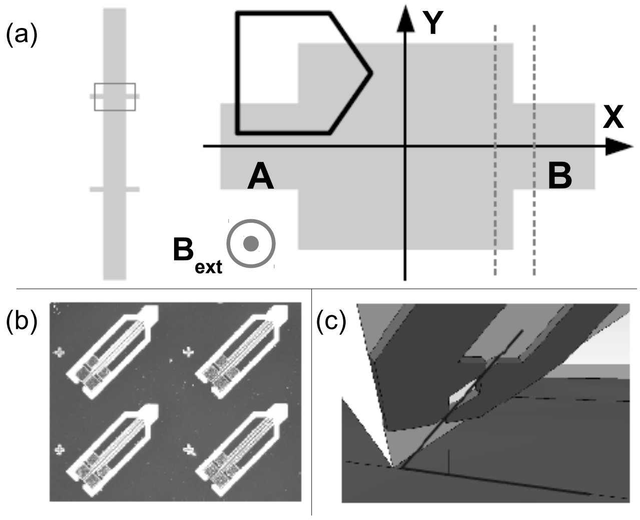

Fig. 1 (a) Schematic illustration of a GaAs/AlGaAs Hall-bar structure. The Hall-bar structure is shown on the Left panel. The Right panel shows a magnified view of the Hall-bar showing the scanned area. Black thick line indicates the SQUID probe. Magnetic flux measurements in Fig. 3 were performed along the dashed lines. The X position of the left and the right lines were 18 and 31 μm, respectively, measured from the center of the Hall-bar. (b) Optical microscope image of our SPM probes. (c) Schematic illustration of the configuration of scanning measurement.

In the second step, we fabricated a dc-SQUID in the vicinity of the edges of a silicon SPM probe by a FIB milling system. The SQUID was located within ~5 μm from the edge of a silicon SPM probe. The loop size of the dc-SQUID was 1 μm.

Scanning SQUID microscope system

We have built a scanning SQUID microscope using a SQUID probe. A sample was mounted on closed loop inertially-actuated triaxial stepping piezoelectric-stages with position encoders located in a cryogen-free Helium-4 refrigerator. The errors in the measured position of the piezoelectric states were estimated to be about 200 nm at low temperature. The base temperature was 3.4 K.

A SQUID probe was mounted on a quartz tuning fork. The tuning fork was driven by ac voltage, and ac currents were synchronously detected by a lock-in amplifier. In all the measurements, we set the applied voltage to be 40 mV. The Q factor of the quartz tuning fork mounted with a SQUID probe was about 10,000 at 3.4 K. The quartz tuning fork and the piezoelectric-stages were mounted in a rigid stainless cage, which was hang from the 4 K-stage by springs to reduce vibrations due to cryogen-free refrigerator.

For SQUID critical current measurement, a SQUID was driven by ac current with sawtooth waveform through a series bias resistance. We measured time difference $\Delta T = T_1 - T_0$ by a time interval counter, where T_0 is a starting time of a waveform signal and T_1 is a transition time of a SQUID from superconductor to normal conductor. T_1 is defined by the time when the SQUID voltage exceed a threshold voltage. I_c is given by $I_c = f\, I_{\max}\, \Delta T$, where f and $I_{\max}$ is the frequency of the applied ac voltage and the peak current of the sawtooth. An average of 5000 measurements of ΔT was typically performed to obtain single data point.

Mapping of magnetic flux induced by currents in a Hall-bar structure

Using the scanning SQUID microscope system, we demonstrate a local magnetic flux measurement of a Hall-bar structure of a GaAs/AlGaAs single heterojunction. The size of the Hall-bar was 25 μm×300 μm. Mappings were performed at the external magnetic field of 0.24 mT at 3.6 K. The angle between the SQUID probe and the Hall-bar sample was fixed to 45 degree. Fig. 1(a) and (c) shows a schematic image of Hall bar structure and the configuration of scanning measurements each other. We performed scanning measurements without feedback control between the probe and the surface of the sample. The distance between the SQUID loop and the Hall-bar was about 6 μm.

Fig. 2 shows a critical current modulation of a SQUID probe. The error bars were estimated from the standard deviations of ΔT. Because the angle between the SQUID probe and the external magnetic field was 45 degree, the modulation cycle was longer than the case of a perpendicular field configuration. We estimated the effective SQUID loop size of 1.3μm × 1.3μm by the modulation cycle of the critical current. The estimated loop size was about 30% larger than the device loop size, probably because of the flux focusing effect.

Fig. 3 shows a representative profile of magnetic flux across the Hall-bar at I_{sample}=200 μA between terminals A and B. With increase in y of the position of the SQUID probe as schematically shown in Fig. 3, the sign of the measured flux changed from negative to positive. It can be seen that the peak flux was larger around the narrower stem of the Hall-bar (triangle) than the peak flux around the wider stem of the Hall-bar (diamond), reflecting the current density of the underlining two-dimensional electron gas.

Conclusions

In this paper, we have described fabrication process for SQUID probe with weak-link Josephson junctions and our newly built scanning SQUID microscope system. We demonstrate mapping of magnetic flux induced by the current distribution in a GaAs/AlGaAs Hall-bar structure. We expect that our method may be applied to map the edge current of topological insulators and topological superconductors.

Acknowledgements

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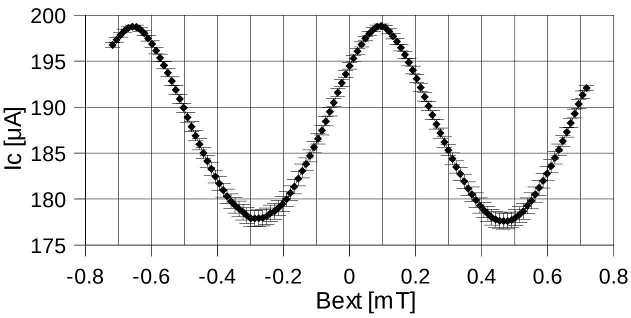

Fig. 2 Critical current modulation of SQUID probe in B_{ext}

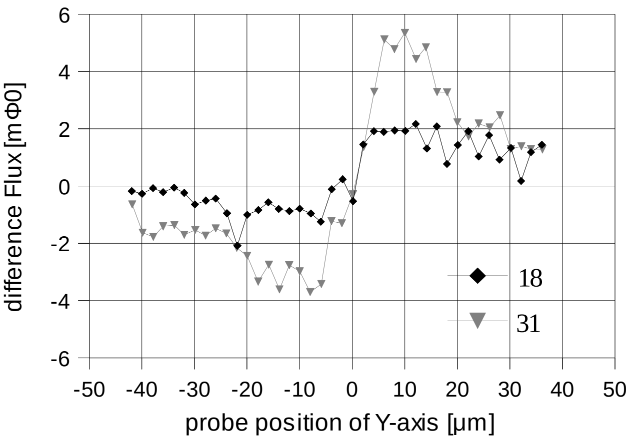

Fig. 3 Profiles of magnetic flux. Diamond and triangle marks represent the profiles on X=18 and 31 μm, respectively.