Measurement of trapped flux magnetic field near the superconducting film by the dependence of superconducting current through a Josephson junction sensor

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Abstract. Two-dimensional (2-D) magnetic field dependences of the Josephson current through a superconducting tunnel junction perpendicularly positioned to the sample niobium film have first been measured. Josephson tunnel junction was used as a magnetic sensor and was used to measure the magnetic field around the niobium superconducting film after adding the vertical magnetic field up to 5000 A/m. The 2-D magnetic field dependences of Ic through the junction without and with the Nb thin-film sample have been compared. Without Nb thin-film sample, the Ic-H dependence of the sensor junction showed the Fraunhofer patterns of the same sensitivity in two directions parallel to edges of the sensor junction. With sample niobium film, the Ic-H dependence of the sensor junction showed the Fraunhofer patterns of the different sensitivity, where in the direction perpendicular to the Nb thin-film sample the sensitivity becomes half because of the Meissner effect of Nb. Moreover, the magnetic field Hz perpendicular to the sample film has been added in the triangle shape as a follow sequence: (0)-(2000 A/m)-(0)-(3000)-(0)-(4000)-(0)-(5000)-(0). In this sequence, every time the Hz perpendicular field reduced to zero, 2-D Ic-H dependence of the sensor was measured. Significant changes in the measured 2-D Ic-H dependences were observed above a certain threshold value of Hz = 3000 A/m. We consider that the shift of the measured 2-D Ic-H dependences in the Hz minus direction occurred because of the flux quanta were trapped in the sample superconducting niobium film after the Hz value had been added greater than 3000 A/m.

1. Introduction
Josephson effect of a superconducting tunnel junction is important both in application of superconductive electronics and in fundamental physics. In this superconducting junction, a gauge-invariant-phase-difference across the tunnel barrier can be modulated by an external magnetic field [1, 2]. Tunnel current density is a sine function of this gauge-invariant-phase-difference at each point of the junction area. The total current that can flow without voltage drop is therefore the sum of this superconducting current over the junction area. The modulations of the total Josephson current Ic of the superconducting junctions were observed by one-dimensional scanning of the external magnetic
field [1-5]. From this modulation pattern of the Josephson current by the magnetic field, uniformity of the tunnel barrier was usually confirmed.

However, by this one-dimensional scanning method, only coarse information of the current distribution would be obtained [2, 6]. Recently, the external magnetic field has been scanned in two-dimensions and in three-dimensions, and the $I_c-H$ ($H_x, H_y$) dependence and $I_c-H$ ($H_x, H_y, H_z$) dependence have been measured [6-9]. The two-dimensional surfaces of the $I_c-H$ ($H_x, H_y$) dependence changed according to the shape of the junction area. For example, in a triangle shape junction, around the main peak in the center of the ($H_x, H_y$) plane of the $I_c-H$ ($H_x, H_y$) dependence, sub peaks were observed in six directions at 0, 60, 120, 180, 240 and 300 degree. By adding the vertical magnetic field $H_z$ to the niobium electrode, $I_c-H$ ($H_x, H_y, H_z$) dependences showed the complex characteristics with hysteresis effect [8].

In this paper, the external magnetic field dependences of the Josephson current $I_c-H$ of sensor junctions have first been measured. Measuring magnetic field using a Josephson junction is simpler method[10] than other solutions such as scanning Hall-probe microscopy[11] and ratchet effect method[12]. Especially in order to measure the magnetic field around the superconducting films, devices and circuits, matching between the sensor and the measured target are quite well because we only have to use superconducting technology.

In sec. 2, the fabrication of Nb junction and the measurement method for the $I_c-H$ dependence are described. The measured $I_c-H$ dependences are presented in sec. 3. Conclusions are presented in sec. 4.

2. Experiment

For sensor junction fabrication, niobium and aluminum thin films are deposited on a silicon substrate by magnetron sputtering in a vacuum system with a load-lock chamber. Tunnel barriers are formed by a natural oxidation of Al layer 5 nm in thickness in pure oxygen in an oxidation chamber [13]. Junction size is 50 micrometer square.

![Experimental set up](image)

Fig. 1. Experimental set up. A sample niobium film in x-y plane and a sensor junction in y-z plane (@4.2K). A magnetic field $H_z$ is perpendicular to the sample niobium film, and parallel to sensor junction. Flux quanta can penetrate into this niobium film and can be detected by the sensor junction.

This tunnel junction was used as a magnetic sensor and was used to measure the magnetic field near the sample niobium superconducting film. As shown in Fig. 1, a sample niobium film was placed in x-y plane and the sensor tunnel junction put in y-z plane (perpendicular to this Nb thin-film sample).
in liquid helium. The 2-D magnetic field dependences of $I_c$ through this sensor junction were measured by using two pairs of Helmholtz coils ($H_y$ coils and $H_z$ coils in Fig. 1.) The x-y-z axis is set as shown in Fig. 1, the changing magnetic field are $H_y$ and $H_z$ directions to measure the 2-D dependences of the sensor junction. The $I_c$-$H$ ($H_y$, $H_z$) characteristics of the sensor junction in this article correspond to the $I_c$-$H$ ($H_x$, $H_y$) characteristics in ref [6] and [9]. Two current sources for driving these Helmholtz coils have been controlled by GPIB system in order to obtain magnetic field dependences automatically [7].

3. Results and Discussion

We have measured $I_c$-$H$ dependence of a sensor junction without Nb thin-film sample and with Nb thin-film sample.

3.1. $I_c$-$H$ ($H_y$, $H_z$) dependence of a sensor junction without Nb thin-film sample

We have fabricated a Nb/AlOx/Nb square tunnel junction and used it in order to measure the magnetic field. In Fig.2, the current modulation $I_c$-$H$ ($H_y$, $H_z$) dependence of the sensor junction without the sample niobium film is shown. The $I_c$-$H$ dependence of the sensor junction showed the Fraunhofer patters in two directions (i.e. $H_y$ and $H_z$ directions) parallel to the edges of the square shape of the sensor junction. Because the corners of the sensor junction were rounded, this $I_c$-$H$ ($H_y$, $H_z$) dependence showed some ring-shape sub peaks. Numerical simulation of magnetic field dependence of the Josephson current also supported this assumption.

3.2. $I_c$-$H$ ($H_x$, $H_y$) dependence of a sensor junction with Nb thin-film sample

We have also measured the $I_c$-$H$ ($H_x$, $H_y$) dependence of the sensor junction with the sample niobium film, where the sensor junction was set 2 mm apart from the sample niobium film (10 mm square, 300 nm thickness). With this sample niobium film, the $I_c$-$H$ dependence of the sensor junction also showed the Fraunhofer patters in two directions. However, $I_c$-$H$ dependence showed different sensitivity for the external magnetic field directions, where in the direction perpendicular to the Nb thin-film sample the sensitivity becomes half because of the Meissner effect of the Nb thin-film sample.
3.3. $I_c$-$H$ ($H_y$, $H_z$) dependence after adding $H_z$ field

In this section, hysteresis effect for the magnetic field $H_z$ perpendicular to the sample film was studied. The magnetic field $H_z$ perpendicular to the sample film has been added in the triangle shape as a follow sequence: (0)-(2000[A/m])-(0)-(3000)-(0)-(4000)-(0)-(5000)-(0). In this sequence, every time the perpendicular field $H_z$ reduced to zero, 2-dimensional $I_c$-$H$ dependence of the sensor junction was measured. The measured 2-D $I_c$-$H$ dependences were shifted in the $H_z$ minus direction after the maximum value of the added $H_z$ field had been added greater than 3000 A/m. These shift values are (-200) (-160) (-500) (-900), corresponding to the added maximum $H_z$ value (2000) (3000) (4000) (5000). We consider that measured 2-D $I_c$-$H$ dependences were shifted in the $H_z$ minus direction because of the flux quanta were trapped in the sample superconducting niobium film after the $H_z$ value had been added greater than 3000 A/m. The vibration in the range from +800 to -800 A/m during the measurement of the $I_c$-$H$ dependences can be treated as a minor loop in the magnetization process of flux motion in sample superconducting Nb film. The dependence of the pattern shift values of the measured $I_c$-$H$ dependences upon the added maximum $H_z$ value ($H_{MAX}$) are shown in Fig. 5. Pattern shift values of the $I_c$-$H$ dependences shown in Fig. 5 corresponded the magnetic field in the sensor junction position that was caused by the trapped flux.
Fig. 4. $I_c-H_1(H_y, H_z)$ dependence of a sensor junction with Nb thin-film sample after adding $H_z$ field (Upper left) after adding maximum $H_z$ field 2000 A/m, (upper right) 3000 A/m, (lower left) 4000 A/m, and (lower right) 5000 A/m.

Fig. 5. Pattern shift value versus perpendicular field

3.4. Magnetic field model
Magnetic field models are shown in Fig. 6. As shown in Fig. 6(a), if the external magnetic field was applied parallel (i.e. $y$ direction) to the sample niobium film, the field was expelled from the sample, where the magnetic field lines were little disturbed. If the external magnetic field (less than 2000A/m) applied perpendicular (i.e. $z$ direction) to the sample niobium film, the field was perfectly expelled from the sample as shown in Fig. 6(b). The $I_c-H_1(H_y, H_z)$ dependence shown in Fig. 3 of the sensor.
junction with sample niobium film is twice extended in the $H_z$ direction, comparing with the dependence of Fig. 2 without sample niobium film. By this comparison, at the sensor position $P_1$ in Fig. 6(b) the magnetic field becomes about half due to Meissner effect of the sample niobium film. Meissner effect of the electrode films of the sensor junctions themselves can be ignored in this experiment, because $y$ direction and $z$ direction fields are parallel to these electrodes. Therefore, this tunnel junction set perpendicular to the sample film can be used as a magnetic sensor and be used in order to measure the magnetic field near the sample niobium superconducting film.

![Magnetic field model](image)

(a) Meissner state: Parallel field, (b) Meissner state: Perpendicular field to the sample film, (c) Trapped magnetic flux, (d) Sum of trapped magnetic flux field and applied perpendicular field. Magnetic field becomes zero at the sensor junction $P_1$.

In the case the external magnetic field more than 2000 A/m was applied, magnetic vortices invaded into the Nb thin-film sample. Even after this external magnetic field was removed, some magnetic vortices were still trapped in this sample niobium film as shown in Fig. 6(c). When this magnetic flux trap once occurred, the magnetic filed due to this trapped magnetic flux should also been considered. In the sensor position $P_1$, the magnetic field is produced by the external field and by the trapped flux. Figure 6(d) showed the magnetic field distribution as the field by the external field and the field by the trapped flux cancelled in the junction position $P_1$. Because the magnetic field in the position $P_1$ by the trapped flux was $z$ plus direction, so some minus external field should be applied for this cancellation.

4. Conclusions
A Josephson tunnel junction was used as a magnetic field sensor at liquid He temperature. We have measured the modulation characteristics of Josephson current $I_c - H$ without and with Nb thin-film sample using two pairs of the Helmholz coils. After the vertical field applied greater than 2000 A/m some magnetic flux quanta were trapped in superconducting film and were measured as pattern shift in the $I_c - H$ characteristics of the sensor junction.

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