Quantitative and high-resolution magnetic images obtained by STM-SQUID microscope with distance modulation technique

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Abstract. We have developed an STM-SQUID microscope, in which a scanning tunnelling microscope (STM) is combined with an rf-SQUID. The issue in our STM-SQUID microscope was that the obtained magnetic image was not the same as the sample’s ideal magnetic field distribution. This was because the magnetic image could be affected not only by the sample’s local magnetic field distribution, but also by the magnetic field distribution above the sample, namely “background field”. In this work, we applied the distance modulation technique to our microscope. In this technique, the change of the SQUID output signal was detected while the distance between the sample and the probe tip was modulated in a constant amplitude. As a result, the influence of the background field was cancelled out, and the magnetic information near the sample surface was largely extracted. We successfully obtained the quantitative magnetic images in ~100 nm spatial resolution by using the distance modulation technique.

1. Introduction
Recently, many types of SQUID microscopes have been developed. In typical SQUID microscopes, small-sized dc-SQUIDs are applied to get high sensitivity and high spatial resolution[1]–[3]. However, our SQUID microscope, namely an STM-SQUID microscope, is completely different from typical SQUID microscopes[4],[5]. In our STM-SQUID microscope, an rf-SQUID is equipped because of easy fabrication and wirings[6]. Remarkably, a high permeability probe is also used as a flux guide from the sample to the SQUID. The high permeability probe plays some important roles to equivalently shorten the gap between the sample surface and the SQUID, and to equivalently miniaturize the size of SQUID[7]. Owing to the probe’s roles, we successfully observed the sample’s fine magnetic domain structures in sub-100 nm spatial resolution, as shown in figure 1(b). In this paper, the magnetic images obtained by directly mapping the output signal of the SQUID electronics are called “normal images”.

However, in the normal images obtained by our STM-SQUID microscope, image-processings were required to obtain the clear images. In the raw normal images, magnetic field distributions tended to be largely tilted, and the fine magnetic domain structures were easily hidden in the large contrast change, as shown in figure 1(c). Therefore, the STM-SQUID microscope had the issues that magnetic field distribution might be distorted by image-processings, and that the normal image was not perfectly the same as the sample’s local magnetic field distribution. It was required to resolve these issues to improve the quantitative performance of the STM-SQUID microscope.
In this work, we firstly analyzed the cause and solution of the issues by means of the electromagnetic simulations. From the analysis results, we focused on the distance modulation technique[8] for the solution, and we investigated its effect for the issues. Finally, we demonstrated the measurements of typical samples by the STM-SQUID microscope using distance modulation technique.

2. Simulation analysis

2.1. Comparison of original local flux density with flux distribution measured by STM-SQUID microscope

To consider the cause of the issues, we simulated the local magnetic field distribution over a sample and its magnetic flux distribution measured by the STM-SQUID microscope. Figure 2 shows these simulation models. A meander line, through which constant current flows, was applied to the sample model. Because the meander line generated the alternative magnetic field distribution as shown in figure 2(a), it can imitate the magnetic material having periodic domain structure. In this paper, the static distance between the probe tip and sample is defined by “h”. In the simulation, we calculated the magnetic flux density distribution over the sample. Figure 3(a) and (b): the results of figure 2(a) show the magnetic field distribution along the z-axis direction ($B_z$) at the plane of $h = 50$ nm above the sample surface, and its line profile along the A-B line, respectively. On the other hand, in the STM-SQUID microscope measurement model, we employed the typical sizes and relative permeability of the actual rf-SQUID and probe. We also adopted the same sample model as shown in figure 2(a). In the simulation, we calculated the magnetic flux inside the SQUID hole at each position. Obtaining the distribution by mapping the magnetic flux inside the SQUID hole is equivalent to obtaining the normal magnetic image by the actual STM-SQUID microscope. Similarly, figure 4(a) and (b): corresponding to the results of figure 2(b) show the magnetic flux distribution mapped by the STM-SQUID microscope at $h = 50$ nm and its line profile along A-B line, respectively.

![Figure 1](image1.png)

**Figure 1.** Example of measurement results obtained by the STM-SQUID microscope. (a) Topographic and (b) normal magnetic images of a nickel thin film sample after image-processings including flattening. (c) Its raw magnetic image.

![Figure 2](image2.png)

**Figure 2.** Schematic simulation models of (a) a meander line sample representing a magnetic domain structure and (b) measurement executed by the STM-SQUID microscope.

In figure 3(b), the flux density distribution oscillates around at 0 mT. Compared with figure 3(b), figure 3(d), illustrating the magnetic flux profile taken by the STM-SQUID microscope has large signal...
offset of ~20 aWb, superimposed on the variation of the local magnetic field. Besides, the variation of figure 3(d) is deformed from the shape of figure 3(b). It suggests that the real normal image can be affected by the same phenomena.

2.2. Discussion about the cause of issues

To consider the cause of the normal image’s issues, we analyzed the magnetic field distribution around the probe tip. Figure 4(a) shows the magnetic flux density distribution in the case of $h = 150$ nm. Each triangle marker indicates the vector direction of the magnetic flux density. The magnetic field is distributed as the probe concentrates the magnetic flux from the side surface. The field intensity becomes smaller with the distance from the sample surface longer. However, the probe length is relatively so long that the influence of the magnetic flux coming from the probe side cannot be disregarded.

Figure 3. (a) Local magnetic flux density distribution over the meander line sample, and (b) its line profile along A-B line. (c) Magnetic flux distribution measured by the STM-SQUID microscope, and (d) its line profile along A-B line.

Figure 4. (a) Magnetic flux density distribution around the probe tip ($h = 150$ nm). (b) Main contributions to the normal image taken by the STM-SQUID microscope.
This result indicated that the normal image was mainly affected by three contributions from the magnetic field: sample’s local field, background field, and environmental field. First, the sample’s local magnetic field distribution originates from the fine magnetic structure distributed on the sample’s surface. This first contribution corresponds to the flux coming from the probe tip. Next, the background field originates from magnetic field distributed over and away from the sample. This second contribution corresponds to the averaged flux coming from the upper area of the probe. Third, the environmental field originates from the external magnetic field coming to the STM-SQUID microscope instrument. This third contribution corresponds to the external magnetic flux directly coming to the instrument. The contribution of background and the environmental fields can hide the local magnetic field distribution because they are sometimes too large to ignore against the local magnetic field contribution.

2.3. Distance modulation technique

To consider the solution for cancellation of the background field influence, we analyzed the magnetic field distribution around the probe tip by changing the static distance between the probe tip and the sample: \( h \). We obtained the line profiles from simulations, and subtracted each other. One example of the results is shown in figure 5. The result shows that contribution of the magnetic field at region around the probe tip (i) is dominant, but that at region around the upper area of the probe (ii) is almost zero, as indicated in figure 5(b). Consequently, we concluded that a magnetic image obtained by detecting the signal change at different distances between the probe tip and the sample surface could be less affected by influence of the background field. It can be realized by the distance modulation technique.

![Figure 5](image1.png)

**Figure 5.** (a) Line profiles of the magnetic flux density along A-B line as shown in figure 4(a). (b) Line profile obtained by subtraction of ①-②.

![Figure 6](image2.png)

**Figure 6.** Schematic illustration of the distance modulation technique.

In the distance modulation technique, the change of SQUID signal synchronized to the modulation frequency was detected while the distance between the probe tip and the sample surface was modulated in a constant amplitude, as shown in figure 6. It is expected that the sample’s local magnetic field is largely extracted and the background field is cancelled out. We simulated the STM-SQUID microscope using the distance modulation technique. For this simulation, we calculated the profiles of the flux change by subtracting the magnetic flux obtained at two different \( h \) conditions at each position. Figure 7(a) shows an example of the simulation result, where the modulation amplitude and \( h \) were set at 40 nm \(_p-p\) and 50 nm, respectively. The simulation result indicates that the signal offsets obtained by the distance modulation was reduced to 0.16 aWb, which was about 100 times smaller than the normal result as shown in figure 7(b). In addition, distribution of the magnetic flux obtained by the distance modulation becomes similar to the sample’s local magnetic field distribution, as shown in figure 3(b). Thus, the distance modulation technique could reduce the background field influence.
We also investigated the dependence of the signal offsets and amplitudes on the modulation amplitude. We calculated the signal offsets and amplitudes while changing the modulation amplitude, as shown in figure 8(a) and (b), respectively. The result shows that the signal offset becomes smaller as the modulation amplitude is decreased, as shown in figure 8(a). From this result, we concluded the modulation amplitude should be small to cancel out the background field effect ideally. However, the signal amplitude becomes smaller as the modulation amplitude is decreased, as shown in figure 8(b). In other words, the signal amplitude may become so small to be hidden by noises, if the modulation amplitude is too small.

3. Experimental results

3.1. Setup of STM-SQUID microscope
Our STM-SQUID microscope was based on a commercially available STM-microscope system (JSPM-5410, JEOL). Figure 9 shows the basic setup of the STM-SQUID microscope. A laboratory-made cryostat head was mounted instead of the default STM head. An rf-SQUID made of YBCO film with 120 nm thickness, as shown in figure 9(b), was fixed inside the cryostat. The high-permeability probe, as shown in figure 9(c), was also fixed just under the the SQUID hole of the rf-SQUID. The probe was made of a permalloy (alloy of iron and nickel) wire with 90 \( \mu \)m diameter and ~5 mm length. The probe tip was sharpened with its curvature radius from 50 to 150 nm. The STM feedback-system controlled the probe tip-sample distance at ~1 nm by measuring the tunnelling current between the probe tip and sample surface. From the STM-feedback signal, the sample’s topographic image was obtained. We used a commercially available SQUID electronics, supporting the flux-locked loop (FLL) control to detect the magnetic field intensity quantitatively. From the FLL output, normal magnetic images were obtained.

![Figure 7](image7.png)  
*Figure 7.* Profile comparison between the distance modulation and the normal results. (a) Magnetic flux distribution obtained by the distance modulation technique, assuming the modulation amplitude of 40 nm \(_{p-p}\). (b) Magnetic flux distribution taken from the meshed area in Figure 3(d).

![Figure 8](image8.png)  
*Figure 8.* Dependence of (a) the signal offset and (b) the signal amplitude on modulation amplitude (h=50 nm).

![Figure 9](image9.png)  
*Figure 9.* (a) Setup of the STM-SQUID microscope, consisting of (b) an rf-SQUID and (c) a high-permeability probe.
3.2. Signal flows of for distance modulation technique

Figure 10 shows the signal flows for obtaining the magnetic images by the STM-SQUID microscope using the distance modulation technique. We adopted the two-pass method for obtaining the normal image and the modulation image in the same condition. In this method, the probe scanned every line twice. In the first pass, the STM feedback control was executed to keep the probe tip-sample distance and obtain the topographic image. At this timing, the normal image was obtained by directly mapping the FLL output as shown in figure 10(a). The image-processings were performed after the measurement, as shown in figure 10(a). In the second pass, the distance modulation technique was executed. For the application of the distance modulation technique, we used a lock-in amplifier to detect the change of the SQUID output signal while the distance between the probe tip and the sample was modulated at the frequency of ~8 kHz. From the lock-in amplifier, we obtained two images: the amplitude image corresponding to the intensity of the magnetic field (figure 10(b)) and the phase image corresponding to the polarity of the magnetic field (figure 10(c)). After the measurement, the modulation image (figure 10(d)) was reconstructed by combining the amplitude and phase images.

![Figure 10. Signal acquisition flows of the magnetic images taken by the STM-SQUID microscope using the distance modulation technique.](image)

3.3. Demonstration of measurements using distance modulation technique

We measured an iron garnet film and a nickel thin film samples by the STM-SQUID microscope using the distance modulation technique. Magnetic domain structures of the both samples show the maze patterns[9],[10]. The magnetic domain sizes of the garnet and the nickel samples are tens of μm and a few hundreds of nm, respectively. We measured the garnet and the nickel samples to confirm the effect of distance modulation technique and to confirm the spatial resolution of our microscope, respectively. The iron garnet surface was coated by gold thin films in order to detect the tunnelling current because it was an insulator.

Figure 11 shows the magnetic images of the garnet sample. In figure 11(a), the normal image has large offset and the sample’s magnetic domain structure is blurred. In figure 11(b), the magnetic field intensity is almost constant, but is close to zero at the boundary of magnetic domain. In figure 11(c), the phase of the magnetic field changes by 180 degrees, domain by domain. Compared with figure 11(a) illustrating the normal image, figure 11(d), illustrating the modulation image shows the magnetic
domain structure clearly even though any image-processings were not carried out. Judging from the amplitude and phase images, we supposed that the sample had a perpendicular domain structure. Moreover, judging from the modulation image, we conclude that distance modulation technique could reduce the background field influence.

On the other hand, figure 12 shows the magnetic images of the nickel sample. Figure 12(a), illustrating the normal image is distributed by noises even after the image-processings carried out. In figure 12(b), the magnetic field intensity is weak at the boundary. In figure 12(c), the phase of magnetic field is almost constant. In the same manner of the garnet result, the modulation image reveals the fine magnetic domain structure clearly without any image-processings, as shown in figure 12(d). Fewer noises are observed in the modulation image than the normal image. Judging from the amplitude and phase images, we supposed that the sample had a horizontal domain structure. Moreover, according to the modulation image, the domain size is approximately 200 nm. Thus, the spatial resolution of the STM-SQUID microscope is estimated at ~100 nm.

4. Summary
The background field over the sample strongly affects the normal magnetic image obtained by the STM-SQUID microscope. It causes the issue that the normal image is not completely same as the ideal magnetic field distribution of the sample because the high permeability probe transfers the magnetic flux not only from the probe tip but also from the upper side of the probe. The distance modulation technique is very effective to cancel out the background field influence. We successfully obtained the local magnetic field distribution of the nickel sample in ~100 nm spatial resolution by the STM-SQUID microscope by using the distance modulation technique.

Figure 11. (a) Normal (inset: its raw image), (b) amplitude, (c) phase, and (d) modulation images of an iron garnet sample obtained by the STM-SQUID microscope using the distance modulation technique.
Figure 12. (a) Normal (inset: its raw image), (b) amplitude, (c) phase, and (d) modulation images of a Ni thin film sample obtained by the STM-SQUID microscope using the distance modulation technique.

References
[1] Finkler A et al. 2010 Nano Letters 10 pp.1046–9
[2] Anahory Y et al. 2014 Nano Letters 14 pp.6481–7
[3] Shibata Y et al. 2016 Superconductor Science and Technology IOP Publishing 29 pp.104004
[4] Hayashi T et al. 2007 IEEE Transactions on Applied Superconductivity 17 pp.792–5
[5] Watanabe N et al. 2013 Journal of the Magnetics Society of Japan 37 pp.235–8
[6] Hisayama K et al. 2015 Physics Procedia Elsevier B.V. 65 pp.189–92
[7] Watanabe N et al. 2013 IEEE Transactions on Applied Superconductivity 23 pp.3–6
[8] Hayashi T et al. 2007 Superconductor Science and Technology 20 pp.8374–9
[9] Xia WX et al. 2010 Journal of Applied Physics 108 pp.3–7
[10] Mishina H et al. 2009 Journal of Applied Physics 105 pp.093911-1–093911-5