Possibility to form nanometer-sized optical probe in an atomic force cantilevered SNOM

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Abstract. We have studied a possibility to form nanometer-sized optical probe using prototype atomic force cantilevered SNOM and some fine structure samples. The system has an ability to obtain both atomic force microscope (AFM) and scanning near-field microscope (SNOM) images simultaneously. The fine optical probe was studied using the outside and inside Au coated SNOM probe. As experimental results, we have obtained a 10 nm-sized optical probe by observations of magneto-optical (MO) disc and Au thin film with many fine cracks.

1. Introduction
Since a scanning near-field optical microscope (SNOM) or near-field scanning optical microscope (NSOM) has been introduced, we are very interested in its optical probe [1]. So far, a lot of researchers have reported only very fine optical images. We have already measured the optical probe size of the SNOM. Although the near-field probe size is very small, the optical probe has both far-field and near-field lights [2]. We should separate the near-field light from the detected light because a power of the reflected far-field light is too stronger than that of the near-field light. Then, we have succeeded to obtain only near-field light by adopting a depolarization optics, which was very useful to eliminate the far-field light from the reflected light from the inside wall of the optical probe [3, 4]. Furthermore, we have improved the fiber probe system to an atomic force cantilevered SNOM (ANOM) system [5]. The improvement provided the stable operation of SNOM system because the atomic force is controlled constant by detecting a Z-component repulsive force instead of shear force. The AFM cantilever used here can protect from breaking the tip due to a tip crash against the sample. We have also developed a through the lens (TTL) type optical lever for atomic force detection [6].

In a near-field optical recording, the SNOM detection is expected to read the recorded bits. For example, S. Hosaka et al. have reported that the electron beam (EB) written small pits could be read out by an illumination-collection mode SNOM using an optical fiber probe [3, 4]. They succeeded in reading the 30 nm x 160 nm small pits by using the polarized near-field light as the illuminating and detected light. Furthermore, they reported that SNOM has a potential to achieve an ultrahigh density phase-change near-field optical recording with 170 Gbit/in^2 and the high speed readout [6, 7].

In this paper, we have described the ANOM system with the TTL type optical lever for repulsive atomic force detection, the illumination and detection system with a polarized light, and Au inside sputtered AFM probe. We also demonstrate AFM and SNOM images of magneto-optical (MO) disc and very fine structures in Au thin film.
2. Prototype ANOM system [5]

The ANOM system has 5 functions; (1) to generate near-field light passed through the optical probe by illuminating the laser beam into the probe (illumination SNOM), (2) to detect only near-field light reflected from the sample surface using a polarization (depolarization of far-field light), (3) to detect the deflection of cantilever (TTL type optical lever), (4) to control the cantilever to keep the gap between the probe and the sample constant (AFM function), and (5) to adjust the laser beams incident on the cantilever using a charge-coupled device (CCD) camera (laser beam alignment). In order to achieve these functions, we have developed multi-beam optics with polarization optics for near-field light generation and detection, repulsive atomic force detection optics, and observation optics with CCD camera. These optical axes coincide on the object lens as shown in Fig. 1. We use a He-Ne laser beam with a wavelength of 632.8 nm (red laser) for near-field light and a semiconductor laser beam with 532 nm (green laser) for the atomic force detection. For high efficiency to detect the lights in near-field optics and the atomic force detection as much as possible, we use 2 dichroic mirrors in the optics. We can observe the sample surface to obtain both AFM and SNOM images simultaneously.

2.1 Near-field light generation and detection

The optics consists of a He-Ne laser source, a half wave \((\lambda/2)\) plate, quarter wave \((\lambda/4)\) plates, objective lens, AFM cantilever with a small pyramidal tip, a Glan-Thompson (G-T) analyzer, and a photomultiplier tube (PMT) (Fig. 1). The linearly polarized light that illuminates from the He-Ne laser is converted to circularly polarized light through the \(\lambda/4\) plate, and is focused into the pyramidal tip on the cantilever. After the circularly polarized far-field light is reflected from the inside wall of the tip or the sample surface, the polarization is no change. On the other hand, either near-field light passing the SNOM aperture or generating due to local plasmon is slightly rotated in polarization. The depolarization optics was used with the quarter wave \((\lambda/4)\) plates and the G-T analyzer to remove the far-field light with no change in polarization. The optics can detect only near-field light reflected from the sample surface.

2.2 TTL type optical lever

The TTL optics is shown in a center optics of Fig. 1. When a green laser beam is incident to a back of the cantilever through the objective lens, the reflected laser beam is back to the lens with a reflected angle and a center axis of its laser beam is shifted. The 4-divided photo diode detects the shift of laser beam position \(\Delta d\), which means the force applied against the probe. When we controlled the force...
constant, a deflection of the cantilever $\Delta z$ is kept constant. The relationship between $\Delta z$ and $\Delta d$ can be expressed by $\Delta d = 2 \Delta z f/L$, where $f$ is a focal length (working distance; WD) of the lens and $L$ is a length of the cantilever. When we used the WD of 10 mm and the cantilever length of 200 $\mu$m, the optical magnification $\Delta d / \Delta z$ is about 100. Total detection sensitivity including the optical lever and the detection amplifier was about 80 mV/nm. This is sufficient to detect a shift of $\Delta z$ with a resolution of less than 0.1 nm. This corresponds to minimum force of less than 0.02 nN.

2.2 AFM and SNOM probe

We used a commercial cantilever (OMCL-400PSA-1) made by Olympus. The cantilever has been made of silicon nitride film with a thickness of 400 nm. A spring constant of the cantilever is about 0.16 N/m. The cantilever has a pyramidal probe in a top area of the cantilever. There is square aperture with a size of about 4 $\mu$m on the backside of the cantilever. The tip of the probe is formed at a top of the pyramid. The tip shape is a sharpened pyramidal and hollow tip. The tip height is 2.9 $\mu$m. The tip radius is less than 20 nm. The tip angle between face to face is 25 - 45 deg. In previous experiments using a fine aperture as a SNOM probe, we used the cantilever coated with Au thin films on both sides. On the other hand, here, we used the cantilever coated with Au thin film with a thickness of about 400 nm on only inner side of the probe.

3. Experimental results and discussion

3.1. Observations of MO disc surface

We tried to observe magnetic information of the recorded MO disc surface. We prepared 2 types of the SNOM probe. One is the small aperture formed in Au thin film on the outside of the AFM pyramidal tip. Another was used just after deposition of Au thin film on the inside of the tip. In the SNOM probe, we did not form any aperture at the inside tip.

3.1.1. Using small aperture fabricated on the outside of tip [5]

We have obtained Kerr effect SNOM image of 640MB MO recorded bit pattern as shown in Fig. 2. In the experiments, we used the small aperture, which was formed by the AFM scanning after sputtered Au thin film on the outside as shown in Fig. 3. The AFM image shows typical land and groove structure. And SNOM image shows bright and dark contrast pattern appears on the structure. We can consider that this pattern is due to Kerr effect. When we consider the optical probe size estimated

![Fig. 2 ANOM observation of 640MB MO disc(2$\mu$m x 2$\mu$m); (a) AFM image, (b) SNOM image and (c) signal profile of a’-b’ line.](image)

![Fig. 3 SEM images of the outside Au coated probe](image)
using a knife-edge method, the diameter was about 300 nm (Fig. 2(c)). This is unexpected value from the SNOM aperture size of 95 nm. We can consider the aperture on the outside tip is not suitable to generate near-field light with a diameter of <100 nm. As one of causes, it can be considered that the aperture expands by AFM scanning under the contact or tapping mode operations

3.1.2. Using the Au inside-sputtered tip
In order to overcome above technical issue, we adopt a local plasmon probe, which was made by inside-sputtered the Au film into the pyramidal probe without processing to form the aperture. Figure 4 shows AFM and SNOM images of MO disc surface with 2.3GB. Note that the AFM image shows typical land and groove pattern with a track pitch of 670 nm, and the SNOM image shows recorded bits pattern on both land and groove. The recorded bit length was about 240 nm, which coincides with designed minimum bit length. In addition, we obtained a profile of the light signal of a’-b’ line in Fig. 4 as shown in Fig. 5. When a signal contrast is estimated as broken line in the figure, we obtained an optical probe diameter of about 40 nm, which includes magnetic wall. Assuming it will be estimated about 20 nm, the diameter is about 20 nm. Thus, Kerr effect image proves that the near-field optical probe can detect not only structure dependent optical information but also no-structure dependent information such as magnetic domain.

3.2. Observation of fine structure of Au thin film with 10 nm wide cracks
Figure 6 shows AFM and SNOM of the fine structure of Au thin film. Figure 6(a) shows high resolution SEM image of the film. There are very fine cracks on the surface. The minimum width is less than 10 nm. Using the sample, we obtained the similar structure as the SEM image in AFM and SNOM images as shown in Fig. 6(b) and 6(c). The AFM and SNOM images have been observed with a constant force of about 20 nN. The AFM has a good resolution with a vertical resolution of less than...
1 nm and a lateral resolution of 5 nm or less, respectively. The AFM image shows very fine cracks with a minimum width of less than 10 nm. The SNOM image indicates that the bright parts correspond to the cracks in the AFM image. This means that we detected a lot of near-field light power in the crack. In the tendency, we have many same results in the experiments [7]. From the figure, we obtained very fine optical probe with a diameter of <10 nm assuming that we define the transient region of the profile as the diameter. Such a contrast has, however, been reported as a topographic artifact by B. Hecht et al. [8] We should study a more detail of the probe diameter estimated from Fig. 6. Therefore, we can describe that the optical probe diameter is 20-30 nm estimated from Fig. 5.

![Figure 6](image)

Fig. 6  SEM image (a), AFM image (b) and SNOM image(c) of the Au thin film

4. Conclusion
We have prototyped the atomic force cantilevered SNOM with polarized light (ANOM), which mainly has 2 functions of illumination and reflection mode SNOM and TTL optical lever type AFM. Furthermore, we adopt the local plasmon probe with the inside Au sputtered pyramidal probe as a SNOM probe. We have studied to evaluate the optical probe sizes from Kerr effect image of the MO bits and near-field light image of Au thin film. From the Kerr effect optical image, the optical probe size was about 20 nm.

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