Research Article

High-Resolution Magnetic Force Microscopy Using Carbon Nanotube Probes Fabricated Directly by Microwave Plasma-Enhanced Chemical Vapor Deposition

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Carbon nanotubes (CNTs) have been successfully grown on the tip apex of an atomic force microscopy (AFM) cantilever by microwave plasma-enhanced chemical vapor deposition (MPECVD). Both scanning electron microscopy (SEM) and transmission electron microscopy (TEM) observations reveal that the diameter of the CNTs is ~ 30 nm and the magnetic particles with diameter of ~ 20 nm, which was used as catalyst for the CNT growth, exist on the top. This CNT probe has been applied to magnetic force microscopy (MFM) on the ultrahigh-density magnetic recording media with 1200 kilo flux change per inch (kfc).

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1. Introduction

Magnetic force microscopy (MFM) is a powerful tool to study the magnetic domain structure at a microscopic level, and is widely used in the research and development of magnetic nanodevices. Images with 50 nm resolution are routinely obtained when using commercial microscope and magnetic probes. However, higher resolution becomes more desired with increased recording density in future magnetic recording media. It is well known that the MFM resolution is limited by the tip geometry and height above the sample surface [1]. In particular, decrease in tip diameter is the most significant factor to improve the resolution.

Thus to achieve reedy tips, methods using focused ion beam (FIB) [2, 3] and the utilization of carbon nanotube (CNT) [4–9] have been proposed. There have been two methods for the fabrication of CNT-based MFM probes: a mechanical attachment of metal-filled CNTs or catalyst-attached CNTs under scanning electron microscopic (SEM) observation [7–9], and a coating of magnetic metal over a preattached CNT probe [4–6]. In the latter technique, Kuramochi et al. reported that the magnetic recording media up to 1100 kilo flux changes per inch (kfc) has been clearly observed with a resolution of approximately 10 nm

[4]. However, the methods described above require time-consuming mechanical attachment or multiple processes, and seem inadequate for the large-scale production.

In a previous work, we successfully fabricated CNT probes for scanning tunneling microscopy (STM) by microwave plasma-enhanced chemical vapor deposition (MPECVD) [10]. This direct growth is quite suitable for the mass-scaled fabrication. It should be noted that the transmission electron microscopy (TEM) observation revealed the existence of magnetic particle as a catalyst on the top of each CNT. This feature can be applicable to MFM probes. Here, we have performed a growth of CNTs on the AFM cantilever made of Si, and have evaluated the resolution in the MFM measurement of longitudinal magnetic recording media with 1200 kfc.

2. Experimental

The growth of CNTs on the Si cantilever was performed by using an MPECVD system (CVD-CN-100, Ulvac Japan, Ltd., Kanagawa, Japan). A Co thin film 20 nm thick, as the catalyst, was coated on the Si cantilever ($k = 2.8$ N/m) by vacuum deposition. It was then set into the metal holder with seat mesh on the small hole in order to avoid the electric

FIGURE 1: SEM image of CNTs on the tip apex of Si cantilever.

FIGURE 2: (a) TEM images of cocatalyzed CNT that scraped away from Si substrate. (b) and (c) are enlarged images of (a).

discharge and ion etching from the plasma [10], and was placed on the electrode in the MPECVD system. The mixed gas of CH_4 and H_2 was used for the CVD growth. The flow rate of H_2 and CH_4 was 80 and 20 sccm, respectively. Total gas pressure was set at 226 Pa. The microwave used was 2.45 GHz, 500 W and the growth time was 7 minutes. During the growth process, a voltage of 200 V was applied between the electrodes. Prior to the CNT growth, the cantilever was exposed to hydrogen plasma for cleaning as well as for activation of catalysts. During CVD process, no heater was used, but the substrate temperature was raised to approximately 600°C as measured by thermocouple. The morphology of tip apex after growth was observed by a field emission scanning electron microscope (FE-SEM, Hitachi, S4700). A high-resolution transmission electron microscope (TEM, JEOL, JEM2000EX) was used to determine the atomic structure of the CNT. In order to examine MFM performance, the surface of longitudinal magnetic recording media with densities of 600, 800, 1000, and 1200 kfc/i was

observed by Nanoscope III (Digital Instruments, NY, USA) in air.

3. Results and Discussion

Figure 1 shows an SEM image of CNTs grown on the tip apex of the Si cantilever. The CNTs ~ 30 nm in diameter are clearly observed at the tip apex. Figure 2 shows a TEM image of a typical CNT similarly grown on an Si wafer. The catalyst particle exists on the top of CNT. This suggests that CNTs grew via the so-called tip growth mechanism [11]. The CNT shows tubular structure with graphene layers (lattice spacing of 0.34 nm) as resolved in the enlarged TEM image (Figure 2(b)). The magnified image of catalyst particle is shown in Figure 2(c), where the lattice of 0.19 nm is thoroughly observed. The lattice spacing corresponds to $\text{Co}_3\text{C}(103)$, suggesting that the CNT is grown with a nanoparticle of single crystalline Co_3C at its top [12].

FIGURE 3: MFM images of ultrahigh-density recording media of 1000 and 1200 kfci using conventional and CNT probes. (a), (c) show MFM image obtained by conventional probe. (b), (d) show MFM image obtained by CNT probe. The recording densities were (a) and (b) 1000 kfci, (c) and (d) 1200 kfci.

FIGURE 4: Power spectra corresponding to Figures 3(b) and 3(d). We have averaged twenty power spectra after performing a Fourier transform on a single-line profile obtained from MFM image.

Using this fabricated CNT probe and a conventional probe, MFM observation is performed for the ultrahigh-density recording media of 1000 and 1200 kfci, as shown in Figure 3. In the case of conventional probe, a stripe pattern of magnetic domain structure is observed up to 1000 kfci (Figure 3(a)), though the periodicity is not so clear. Irregular pattern appears appreciably comparable to the periodicity. In the case of 1200 kfci, no stripe magnetic domain structure is observed, as shown in Figure 3(c). In contrast, the recording period is clearly resolved up to 1000 kfci using the present CNT probe (Figure 3(b)), and even for 1200 kfci, the periodicity is visible on the background of the irregular pattern due to the limitation in the resolution and/or sample preparation.

Figure 4 shows the power spectra corresponding to Figures 3(b) and 3(d). These spectra were obtained by averaging twenty spectra after performing a Fourier transform of a

single-line profile of the cross-section in MFM image. As shown in Figure 4, peaks at 55.1 and 45.2 nm are recognized (which is double the recording bit size). These values are larger than the calculated values of 50.8 and 43.2 nm for 1000 and 1200 kfci. This may be due to inaccuracies in the recording process [2]. In these power spectra, strong background is observed on the low-frequency side. The inverse Fourier analysis indicates that this is caused by an irregular period due to disorder of the longitudinal recording. The writing of 1200 kfci is known to be difficult in the case of the longitudinal recording.

In order to estimate attainable resolution, we follow analysis procedure reported by Kuramochi et al. [4]. Figure 5(a) shows normalized intensity of power spectrum as a function of recording density. It is observed that the intensity decreases with increase in recording density. The intensity decreases with the increase of recording density.

FIGURE 5: Plot of normalized intensity of power spectrum at the various recording bit length. The solid line was obtained by linear fitting for experimental plot. The sloping dashed line was obtained by extrapolating of solid line. The noise level was obtained from DC-erased area in (b) MFM image.

The attainable resolution in the observation of recording media is obtained from intersecting point of extrapolation of solid line and noise level line in Figure 5 [4]. The noise level was obtained from DC-erased area in MFM image as shown in Figure 5(b). The intersecting point corresponding to attainable resolution is around 7.6 nm, which is comparable to the value reported in [4]. It should be noted that in spite of the CNT-MFM probe by the present simple fabrication process without coating of magnetic materials, the resolution has been improved compared with conventional probe. The mass-scale fabrication of high-resolution CNT-MFM probes is also expected by this direct growth method.

4. Conclusion

In conclusion, we have successfully fabricated the CNT probes for MFM by direct growth using MPECVD. The CNTs of ~ 30 nm in diameter have been grown on the tip apex of Si cantilever, and the magnetic particle (~ 20 nm) is located at the end. The MFM observation using the fabricated CNT probe for magnetic recording media is demonstrated. The CNT probe resolves a stripe magnetic domain structure of ultrahigh-density recording media of 1000 and 1200 kfci much clearer than the conventional probe.

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