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Magnetic force microscopy imaging of in-plane magnetic field gradient using transient oscillation

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A new imaging method of the in-plane magnetic field gradient using the transient oscillation of a magnetic force microscopy (MFM) tip was demonstrated by detecting the frequency shift of a MFM tip which was driven at a constant frequency. The gradient of the in-plane magnetic field along the in-plane scanning direction was measured by using a MFM tip which was magnetized in the direction normal to the sample plane. The image contrast of the in-plane magnetic field gradients reversed by scanning the same line in opposite direction. Two-dimensional vector imaging was possible by using this method together with the conventional phase detection method which detects the perpendicular magnetic field gradients. From theoretical analysis, the signal of the present method was thought to correspond to the in-plane magnetic field gradient and the present method was expected to have a higher spatial resolution because the higher-order field gradient was detected by the presented method compared to the conventional phase detection method. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2844709]

I. INTRODUCTION

Magnetic force microscopy (MFM) is a powerful tool to investigate microscopic magnetic domain structures of high density magnetic recording media and nanoscale magnetism. MFM can detect the gradient of a vector component of the magnetic field determined by the direction of the tip magnetization,[1] and it is difficult to vary the measuring direction of the magnetic field at the same sample position for precise analysis. In this study, we propose a new MFM imaging method of the in-plane magnetic field gradient using the transient oscillation of a tip whose magnetization direction is perpendicular to the sample plane. The transient oscillation occurs in high Q conditions during the MFM tip scan due to the change of the magnetic force between the sample and the tip. Here, Q is the mechanical quality factor of the tip at resonance. The transient oscillation causes a decrease in the bandwidth of the MFM measurement because it takes some time to settle the amplitude and the phase of the tip oscillation. Therefore, a frequency modulation detection method was proposed in high Q conditions for sensitive imaging with a wide bandwidth.[2] In contrast, we used the transient oscillation for magnetic imaging. When a tip moves to a next measuring position in high Q conditions, the oscillation frequency of the tip changes from the driven frequency of the tip because of the transient oscillation. We demonstrated imaging of the in-plane magnetic field gradient by measuring the frequency shift. The characteristics and the imaging mechanism of the presented method are discussed in this paper.

II. EXPERIMENT

Figure 1 shows the block diagram of the MFM measurement of the in-plane magnetic field gradient. We added a frequency measurement apparatus (easyPLL, Nanosurf®) which uses a phase locked loop (PLL) circuit to a conventional phase detection MFM (JSPM-5400, JEOL Ltd.). Here, the tip was driven at a constant frequency near the resonant frequency of the tip. The frequency and phase of the oscillating tip were measured at the same scan under a constant tip-sample distance (≈15 nm) after the topographic scan by using the so-called "lift mode" measurement. We used a

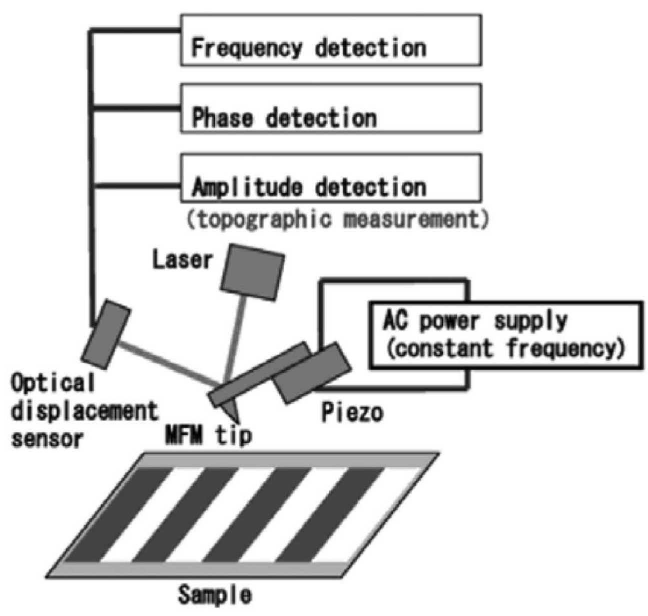

FIG. 1. Block diagram of MFM measurement.

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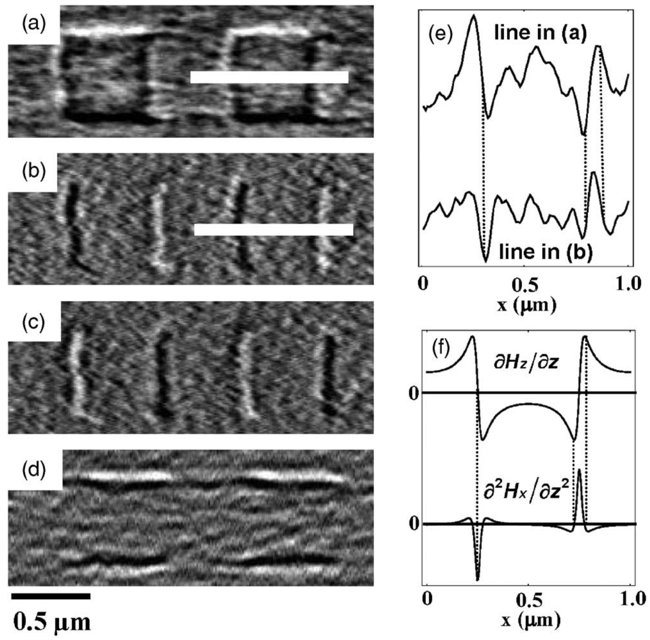

FIG. 2. Phase detection image (a) and frequency detection images [(b)–(d)] for a CoCrPt–SiO_2 perpendicular magnetic recording medium. The scanning directions are left to right [(a) and (b)] and right to left (c) in the horizontal direction. The scanning direction of (d) is top to bottom in the vertical direction. Signal profiles (e) on the line in (a) and (b) and calculated magnetic field gradients of perpendicular magnetic recording media (f).

high-coercivity MFM tip with a 20 nm $L1_0$-FePt coating made by Nitto Optical Co., Ltd. The diameter of the MFM tip was about 50 nm and the coercivity was about 8 kOe. The magnetized direction of the tip was perpendicular to the sample surface. For analysis of the MFM images, we assumed that the MFM tip behaved as a monopole type tip because the tip-sample distance was smaller than the magnetic film thickness of the tip.[3]

We observed a CoCrPt–SiO_2 perpendicular magnetic recording medium[4] which was prepared using an in-line-type magnetron sputtering system. Transmission electron microscopy shows a CoCrPt nanoparticle with a diameter of about 5.9 nm and an average interparticle distance of around 1.6 nm. Recording signals (50 kiloflux change/in.) were written using a perpendicular single-pole inductive head. The measurement was done in vacuum and air atmosphere. The value of Q was in the range from about 500 to 8000. The measuring time at each position was about 1 ms with a data acquisition interval of 1 μs.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the MFM image of a CoCrPt–SiO_2 perpendicular magnetic recording medium measured by the conventional phase detection method. Figures 2(b)–2(d) show the MFM images measured by the presented frequency detection method. These images were observed in vacuum atmosphere and the value of Q was about 2800. The images of Figs. 2(a) and 2(b) were measured at the same scan position from left to right in horizontal direction for each line. The image of Fig. 2(c) was observed during the scan in opposite direction from right to left in horizontal direction soon after the measurement in left-to-right direction in Figs. 2(a) and 2(b). The image of Fig. 2(d) was observed during the scan from top to bottom in the vertical direction of the image. Figure 2(e) shows the signal profiles of the line in image (a) and the line in image (b). The profiles were obtained by averaging ten scanning profiles on the line. Figure 2(f) shows the calculated signal profiles of the first derivative of the perpendicular magnetic field $\partial H_z/\partial z$ and the second derivative of the in-plane magnetic field $\partial^2 H_x/\partial z^2$ for an ideal perpendicular magnetic recording medium without magnetic noise. Here, the z direction is the direction perpendicular to the sample surface and the x direction is the in-plane direction which is parallel to the recording track.

The phase detection image (a) and its corresponding signal profile in Fig. 2(e) are well characterized as those of the perpendicular magnetic field gradient. The areas of up and down magnetizations with respect to the sample plane show the bright and dark contrasts. The boundaries between up and down magnetization areas show the neighboring bright-dark contrast. On the other hand, the frequency detection image (b) and its corresponding signal profile in Fig. 2(e) show the neighboring bright-dark-bright and dark-bright-dark contrasts at the boundaries. In the case of perpendicular magnetic recording media, the maximum and minimum intensities of the in-plane field gradient are obtained at the boundaries of neighboring recorded bits where the intensities of the perpendicular field gradient is zero. The maximum and minimum intensities of the perpendicular field gradient are obtained at the positions where the intensity of higher-order in-plane field gradient is zero, as seen in Fig. 2(f). The characteristics of the signal profiles in Fig. 2(e) are similar to those of the calculated perpendicular and in-plane magnetic field gradient in Fig. 2(f). From these results, it was found that two-dimensional vector imaging is possible by using this method together with the conventional phase detection method which detects the perpendicular magnetic field gradients. Furthermore, the dark and bright contrasts of the in-plane field image were found to be reversed when the direction of scanning was opposite as seen in image (c). This characteristic is useful to reduce noise from a MFM image by image subtraction. The image of Fig. 2(d) was observed during the scanning from top to bottom in the vertical direction of the image. The neighboring bright-dark-bright and dark-bright-dark contrasts which are the characteristics of the in-plane magnetic field gradient are clearly observed at the bit boundaries. By using the presented method, we can easily select the measuring direction of the in-plane magnetic field in a sample plane. In this measurement, the in-plane magnetic field image was found to be independent of the speed of the tip motion within our experimental conditions which enabled us to observe a topographic image. Furthermore, the observation in air atmosphere where the value of Q was about 500 was also found to be possible.

The above-mentioned characteristic of this method can be well explained by a following simple model. A cantilever with a MFM tip is driven at the sinusoidal force with a constant frequency ω_d,

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$$m\frac{d^2z(x)}{dt^2}+m\gamma\frac{dz(x)}{dt}+\left(k_0+\frac{\partial F(x)}{\partial z}\right)z(x)=F_0\cos(\omega_d t), \tag{1}$$

where z is the displacement of the tip, m is the effective mass of the tip, γ is the damping factor of the oscillation and is equal to Q/ω_0 (ω_0 is the resonant frequency of a tip), k_0 is the spring constant of the cantilever, and $\partial F(x)/\partial z$ is the force gradient acting on the MFM tip.

Now, we consider the movement of a MFM tip from $x=x_0$ to $x=x_0+\Delta x$. At $x=x_0$, the cantilever is assumed to be in a steady state given by

$$z(x_0)=A_0\cos(\omega_d t+\theta_0), \tag{2}$$

where A_0 and θ_0 are the steady-state amplitude and phase. After the tip movement, the cantilever comes into a transient state due to the change of $\partial F(x)/\partial z$. The displacement of the cantilever is given by

$$\begin{aligned}z(x_0+\Delta x)&=A_0'\cos(\omega_d t+\theta_0')\\&\quad+A_t\exp(-\gamma t/2)\cos(\omega_t t+\theta_t),\end{aligned} \tag{3}$$

where A_0' and θ_0' are the new steady-state amplitude and phase.[2] The second term is the transient term and ω_t is the resonant frequency for free oscillations, and is given by

$$\begin{aligned}\omega_t&=\sqrt{\frac{1}{m}\left(k_0+\frac{\partial F(x_0+\Delta x)}{\partial z}\right)-\frac{\gamma^2}{4}}\\&\cong\sqrt{\frac{k_0}{m}-\frac{\gamma^2}{4}}+\frac{\omega_0}{2k_0}\frac{\partial F(x_0+\Delta x)}{\partial z}=\omega_0'+\Delta\omega.\end{aligned} \tag{4}$$

Here, $\omega_0'=\sqrt{(k_0/m)-(\gamma^2/4)}$ and $\Delta\omega=(\omega_0/2k_0)[\partial F(x_0+\Delta x)/\partial z]$. $\Delta\omega$ depends on the gradient of the perpendicular magnetic force.

Here, we can expand Eq. (3) as

$$\begin{aligned}z(x_0+\Delta x)&=\left[A_0'+A_t\exp\left(-\frac{\gamma}{2}t\right)\right]\cos\left(\frac{\omega_d-\omega_t}{2}t+\frac{\theta_0'-\theta_t}{2}\right)\\&\quad\times\cos\left(\frac{\omega_d+\omega_t}{2}t+\frac{\theta_0'+\theta_t}{2}\right)\\&\quad-\left[A_0'-A_t\exp\left(-\frac{\gamma}{2}t\right)\right]\sin\left(\frac{\omega_d-\omega_t}{2}t+\frac{\theta_0'-\theta_t}{2}\right)\\&\quad\times\sin\left(\frac{\omega_d+\omega_t}{2}t+\frac{\theta_0'+\theta_t}{2}\right).\end{aligned} \tag{5}$$

Equation (5) shows that the carrier frequency ω_c of the oscillation after the movement of the tip is given by $\omega_c=(\omega_d+\omega_t)/2=(\omega_d+\omega_0'+\Delta\omega)/2$. The carrier frequency shift of the amplitude modulated oscillation in the transient state can be detected by the PLL technique, as seen in Figs. 2(b)–2(d). The PLL tracks the frequency shift during the scan. When the frequency increases or decreases by the scan, the PLL generates a plus or minus output signal. This is the reason for the change of MFM contrast by the reversion of the scan direction in Fig. 2(c). Therefore, the PLL apparatus can detect the differential of the carrier frequency with respect to the sample position given by $\partial\omega_c/\partial x=1/2\partial\Delta\omega/\partial x$. When a MFM tip behaves as a monopole type tip,[3] the magnetic force is given by $F=q_mH_z$, where q_m is the magnetic charge at the MFM tip end and H_z is the perpendicular component of magnetic field with respect to the sample plane. Therefore, the differential of the carrier frequency is given by $\partial\omega_c/\partial x=\partial\Delta\omega/\partial x=(\omega_0q_m/4k_0)\partial^2H_x(x)/\partial z^2$. Here, we use the relation of $\partial H_z(x)/\partial x=\partial H_x(x)/\partial z$, which is the characteristic of the vortex-free magnetic field generated from magnetic charges. Therefore, it was concluded that the presented method enables the imaging of the in-plane magnetic field gradient. It should be noted that the presented method detects the higher-order derivative of the magnetic field with compared to conventional methods. By using a monopole type tip, the presented method detects the second derivative of magnetic field, $\partial^2H_x/\partial z^2$, while the conventional phase detection method detects the first derivative of magnetic field, $\partial H_z/\partial z$. The suggested method is expected to have a higher spatial resolution because of the detection of the higher-order field gradient, as seen in Fig. 2(f). The time constant τ of the transient oscillation in this experiment can be estimated as $\tau=2/\gamma=2Q/\omega_0\approx500-8500$ μs [the resonant frequency $\omega_0\approx2\pi\times300\,000$ and $Q\approx500-8000$ (in air and vacuum)]. Therefore, the large value of τ is thought to be the reason that the in-plane magnetic field images were independent of the speed of tip motion. From the above mentioned unique characteristics of the suggested method, this method is thought to be a powerful tool to investigate microscopic magnetic domain structures of high density magnetic recording media and nanoscale magnetism.

IV. CONCLUSION

A new imaging method of the in-plane magnetic field gradient using the transient oscillation of a MFM tip was demonstrated. This method detects the frequency shift of a MFM tip which was driven at a constant frequency. The gradients of the in-plane magnetic field along the in-plane scanning direction were measured, and the image contrast of the in-plane magnetic field gradients reversed by scanning the same line in opposite direction. Two-dimensional vector imaging is possible by using this method together with the conventional phase detection method which detects the perpendicular magnetic field gradients. Theoretical analysis revealed that the signal of this method corresponds to the in-plane magnetic field gradient and that this method detects the higher-order field gradient compared to the conventional phase detection method.

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