Local hysteresis variation of Co/Pd nanomultilayers

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Local coercivity variation of Co/Pd nanomultilayers has been investigated by measuring the polar Kerr hysteresis loops of the local areas of submicron size using a magneto-optic Kerr microscope system. Interestingly, the local coercivity distribution was very sensitive to an increase in the number of repeats: the (2 Å Co/11 Å Pd)_{10} sample showed a smooth variation of the local coercivity, while (2 Å Co/11 Å Pd)_{18} showed a large fluctuation. Based on the thermally activated relaxation model, we have found that this local coercivity variation had a crucial effect on the contrasting magnetization reversal behavior observed in those samples, wall-motion dominant for the former sample and nucleation dominant for the latter one. © 2000 American Institute of Physics.

Ultrathin ferromagnetic films and nanomultilayers are of great interest in recent years due to the possibilities of the nanomagnetic applications as well as their magnetic properties.1–4 To achieve the high performance of the nanomagnetic applications, it is necessary to prepare the materials nanoscopically uniform, since the irregularity and stability of the domain formation are much affected by the nanomagnetic regularity of the film during the magnetization reversal process.5–9 Much effort has been devoted to characterizing magnetic regularity of the film during the magnetization reversal process.10–13 However, up to now, the imaging technique of magnetic dynamics under the external magnetic field has been rarely investigated due to the limited application of the external field in the imaging systems. Recently, we have developed the local hysteresis loop measurement technique within the optical resolution limit by adopting a magneto-optic Kerr microscope system. In this study, we have investigated the local coercivity distribution of the Co/Pd nanomultilayers having perpendicular anisotropy by measuring the local hysteresis loops. The contrasting domain configuration and reversal behavior of the Co/Pd nanomultilayers reported by Choe and Shin9 has been reexamined in accordance with the local coercivity distribution.

A high-performance Kerr microscope system has been developed to measure the local hysteresis of magneto-optic thin films having perpendicular magnetic anisotropy.14,15 The system mainly consists of an optical polarizing microscope capable of ×1000 magnification with spatial resolution of 0.3 μm and Kerr angle resolution of 0.2°. To measure the hysteresis, the system is equipped with an electromagnet controlled by a personal computer to sweep the external magnetic field over the range of ±5 kOe. The domain images are captured by an advanced charge coupled device (CCD) camera system which is interfaced to the computer. The images are composed of the light intensity distribution measured by the CCD array of 100×80 pixels, where a unit pixel corresponds to the area of 0.32×0.32 μm² at the film surface. Storing the domain images while sweeping the external magnetic field, it is possible to obtain the array of the local intensity function \( I_{xy}(H) \). This is done by tracing the intensity variation, while sweeping the external field \( H \) at every corresponding \((x,y)\)th CCD pixel. Figure 1(a) shows a typical dependence of the intensity variation on an applied magnetic field \( H \). The intensity \( I_{xy}(H) \) is correlated with the Kerr rotational angle \( \theta_{xy}(H) \) by

\[
I_{xy}(H) = I_{0y}^0 + C_{xy} \sin^2(\frac{\theta_{xy}(H) + \alpha_{xy} + \Delta \theta_{xy}}{2}),
\]

where \( I_{0y}^0 \) is the intensity offset of the corresponding CCD pixel, \( C_{xy} \) is the proportional coefficient between the intensity and the Kerr rotational angle, \( \alpha_{xy} \) is the Faraday coefficient incurred at the objective lens of the microscope, and \( \Delta \theta_{xy} \) is the angle between the polarizer and the analyzer. Fitting the measured \( I_{xy}(H) \) vs \( H \) with Eq. (1) for the two saturated states of \( \theta_{xy}(H) = \pm \theta_{M}^{\alpha_{xy}} \), as shown by the solid lines in Fig. 1(a), one can determine the values of \( I_{0y}^0, C_{xy}, \alpha_{xy}^2, \Delta \theta_{xy}/\alpha_{xy}, \) and \( \theta_{M}^{\alpha_{xy}}/\alpha_{xy} \) under an approximation of \( \sin \theta \sim \theta \) for small \( \theta \). Then, the normalized Kerr hysteresis loop can be generated from the intensity variation with the fitting quantities by

![FIG. 1. (a) Typical value of the local intensity variation \( I_{xy}(H) \) measured by the \((x,y)\)th CCD pixel as a function of an applied magnetic field \( H \). The solid lines are the fitting curves given by Eq. (1) for the two saturated states of \( \theta_{xy}(H) = \pm \theta_{M}^{\alpha_{xy}} \). (b) The normalized Kerr hysteresis loop \( \theta_{xy}(H) \) generated from the intensity variation shown in (a).](image-url)
Figure 1(b) shows the normalized Kerr hysteresis loop generated from the intensity variation shown in Fig. 1(a). It should be stressed here that the Kerr hysteresis loop can be obtained for every corresponding CCD pixel and thus, one can generate the microscopic map of the local coercivity distribution $H_C(x,y)$ by measuring the coercivity from the corresponding hysteresis loop of the every CCD pixel at $(x,y)$. The local coercivity distribution $H_C(x,y)$ is further deconvoluted by $H_C(x,y)=H^0_C+\delta H_C(x,y)$, where $H^0_C$ is the mean value of the local coercivity and $\delta H_C(x,y)$ is the local variation of the coercivity.

The local coercivity distribution of Co/Pd nanomultilayers has been investigated. Samples of (2 Å Co/11 Å Pd)$_n$ with varying number of repeats $n$, were prepared on glass substrates by e-beam evaporation under base pressure of $1.0 \times 10^{-6}$ Torr at ambient temperature. The nanomultilayered structure was achieved by alternatively exposing the substrate to the two e-beam sources with typical deposition rates of 0.3 Å/s for Co and 0.5 Å/s for Pd. The layer thickness was controlled within a 4% accuracy by a thickness-control technique using real-time thickness measurement.

The samples of $n=10$ and 18 were extensively examined. Both samples had perpendicular magnetic anisotropy and showed the $MH$ hysteresis loops of unit squareness. The coercivities measured by vibrating sample magnetometer (VSM) were 1.3 and 2.4 kOe for the samples of $n=10$ and 18, respectively.

Interestingly, the local coercivity distribution was found to be very sensitive to an increase in the number of repeats $n$. In Fig. 2, we illustrate the local coercivity distribution of (a) $n=10$ and (b) 18, respectively, by mapping $\delta H_C(x,y)$ in gray level on the two-dimensional $XY$ plane where the area of the maps corresponds to $32.8 \times 26.2 \, \mu m^2$ at the sample surface. It is surprising that the local coercivity distribution is so dependent on the number of repeats $n$: the thinner film with $n=10$ shows a smooth variation of the local coercivity as shown in Fig. 2(a), while the thicker film with $n=18$ shows a large fluctuation of the local coercivity as shown in Fig. 2(b). The standard deviation $\Delta H_C$ of the local coercivity distribution was found to be increased from 22 to 34 Oe with an increase in $n$ from 10 to 18. The large fluctuation of the local coercivity of the thicker film is possibly ascribed to a larger amount of structural irregularity, because the local structural irregularity such as atomic misfit, defects, and dislocations, may be accumulative during the film deposition. The local structural irregularity is known to cause magnetic inhomogeneity such as the misorientation of the polycrystalline axis, the reduction of the nucleation field, and the domain-wall pinning effect.

Magnetization reversal behavior of the Co/Pd nanomultilayer samples have been investigated by time-resolved observation of domain evolution from the saturated state under a reversed applied field. The reversal phenomena in this system was found to change from wall-motion dominant to nucleation dominant with increasing the number of repeats $n$. Figure 3 shows the typical domain patterns of the samples with (a) $n=10$ and (b) 18, respectively, during the magnetization reversal. The figures were grabbed from the same positions of the corresponding samples shown in Fig. 2 using the same CCD camera attached to the microscopic system and subsequently, the figures were intensified by noise filtering and brightness-contrast adjustment. The black regions in figures illustrate the reversed domain patterns at 20% reversal from the saturated state. A large domain is clearly observed in Fig. 3(a), while a number of small domains are seen in Fig. 3(b). These contrasting reversal patterns are occurred by the counterbalance between the nucleation process and the wall-motion process: the large domain shown in Fig. 3(a) is formed by the wall-motion process from a single nucleation site, while the small domains in Fig. 3(b) are nucleated by the nucleation process irrespectively to existing domains.

It is very interesting to note that these contrasting reversal patterns coincide with the local coercivity distributions for each corresponding sample. The reversal mechanism under the local coercivity variation has been analyzed based on the thermally activated relaxation process. The half reversal time $\tau$, which is the time needed to reverse half the volume of the sample, has been experimentally determined to be exponentially dependent on the applied field $H$. By considering the local coercivity distribution $H_C(x,y)$, the half rever-
sal time \( \tau(x,y) \) of magnetization \( M_s \) of a volume \( V_A \) located at \( (x,y) \) is given by

\[
\tau(x,y) = \tau_0 \exp \left[ \frac{V_A M_s}{k_B T} \left( H_C(x,y) - H \right) \right],
\]

where \( \tau_0 \) is the characteristic reversal time for \( H = H_C(x,y) \), \( k_B \) is the Boltzmann constant, and \( T \) is the temperature.\(^7\) Then, the half reversal time \( \tau(x,y) \) is locally irregular even under a spatially uniform applied field \( H \), because \( \tau(x,y) \) is proportional to the value of \( \exp[V_A M_s \Delta H_C(x,y)/k_B T] \). Since the magnetization reversal primarily happens in regions of faster \( \tau(x,y) \) while the reversal process is impeded at the regions of slower \( \tau(x,y) \), the domain reversal pattern is sensitive to the local reversal time variation. As the local coercivity variation is increased, the wall motion is pinned at the regions of slower reversal speed and then, the reversal proceeds by the nucleation at the regions of faster reversal speed irrespectively to the existing domains. This type of reversal behavior is empirically perceived as a nucleation dominant reversal. On the other hand, the reversal behavior under a smooth coercivity distribution is dominated by the wall motion overcoming the smaller wall-pinning effect.

Measuring the magnetization viscosity curves with changing the reversed applied field \( H \), the values of \( (V_A M_s/k_B T) \) were determined to be \( 3.0 \times 10^{-2} \) and \( 2.5 \times 10^{-2} \) Oe\(^{-1}\) for the samples of \( n = 10 \) and \( 18 \), respectively, and then, the reversal time variation \( \exp(V_A M_s \Delta H_C/k_B T) \) was estimated to be 1.9 and 2.3 for the samples of \( n = 10 \) and \( 18 \), respectively. Thus, it could be well explained that the reversal behavior of the sample of \( n = 10 \) is wall-motion dominant with the smooth coercivity variation as shown in Fig. 2(a), while the reversal of the sample of \( n = 18 \) is nucleation dominant with the large coercivity fluctuation as shown in Fig. 2(b).

In summary, we have investigated the local coercivity distribution of the Co/Pd nanomultilayers having perpendicular anisotropy by measuring the local hysteresis loops of the local areas of submicron size using a magneto-optic Kerr microscopic system. The local coercivity distribution was very sensitively increased with increasing the number of repeats: the (2 Å Co/11 Å Pd)\(_{10}\) sample showed a smooth variation of the local coercivity, while (2 Å Co/11 Å Pd)\(_{18}\) showed a large fluctuation. Based on the thermally activated relaxation model, we have found that this local coercivity variation had a crucial effect on the contrasting magnetization reversal behavior observed in those samples; wall-motion dominant for the former sample and nucleation dominant for the latter one.

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