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Magnetization reversal dynamics in epitaxial spin-valve structures

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We report the dynamic hysteresis behavior of epitaxial single ferromagnetic NiFe, Co layers, and NiFe/Cu/Co spin-valve structures investigated as a function of field sweep rate $\dot{H}(dH/dt)$ in the range 0.01–270 kOe/sec using the magneto-optic Kerr effect. *In situ* reflection high-energy electron-diffraction images confirmed that the NiFe, Cu, and Co layers grew epitaxially in the (100) orientation where the fcc NiFe, Co$\langle 110\rangle$ in-plane directions correspond to the Si$\langle 100\rangle$ directions. For Cu/60 Å **NiFe**/Cu/Si ($H_c = 5$ Oe) and Cu/40 Å **Co**/Cu/Si ($H_c = 104$ Oe) single magnetic layer structures, the hysteresis loop area A is found to follow the scaling relation $A \propto \dot{H}^{\alpha}$ with $\alpha \sim 0.13$ and ~ 0.02 at low sweep rates and ~ 0.70 and ~ 0.30 at high sweep rates, respectively. This result indicates that the NiFe and Co layers in the spin-valve structures can be expected to show distinct scaling behavior at high sweep rate. We found that the ''double-switching'' behavior which occurs at low sweep rates transforms to ''single switching'' at ~ 154 kOe/sec and ~ 192 kOe/sec, respectively, for the single and double spin valves due to the different dynamic response of the NiFe and Co layers. Our results provide direct experimental evidence that the magnetic anisotropy strength affects dynamic hysteresis scaling in ultrathin magnetic films, in contrast with the predictions of current theoretical models.

I. INTRODUCTION

The search for a universal theory[1–5,8,18] (and its experimental verification[6,7,9–17]) of magnetic hysteresis in ultrathin films continues to be of central importance in magnetism. Over the past decade the dynamics of magnetization reversal has attracted significant attention as a test of universality hypotheses and scale-invariant descriptions of the energy loss per cycle (the hysteresis loop area) as a function of external parameters, e.g., applied magnetic field strength H_0, frequency Ω, and temperature T. Recent theoretical studies based on a continuous spin system[1–3] and a mean field Ising model[2,4,5] demonstrated that the hysteresis loop area A follows the scaling relation

$$A \propto H_0^{\alpha} \Omega^{\beta} T^{-\gamma}, \tag{1}$$

where α, β, and γ are exponents that depend on the dimensionality and symmetry of the system. Phenomenological models[6,7] and Monte Carlo simulations[8] were also performed on the basis of domain wall motion and nucleation. On the other hand, comprehensive experiments[9–14] have been carried out to describe the dynamics of magnetization reversal in ultrathin and thin ferromagnetic films, e.g., Fe/Au(001),[9] Co/Cu(001),[10,12] Au/Co/Au/MoS$_2$,[7] Fe/W(110),[11] polycrystalline Ni$_{80}$Fe$_{20}$,[13] and Fe/GaAs(001).[14] In addition, a few studies have been devoted to the dynamics of magnetization reversal in small-sized systems such as Co single-domain nanoparticles,[15] Au/Co/Au dot arrays,[16] and micron-sized Ni$_{80}$Fe$_{20}$ disks[17] with a multidomain or a vortex structure. However, critical values of the dynamic scaling exponents of ultrathin ferromagnetic films obtained from *in situ*[9–12] and *ex situ*[7,13,14] experiments significantly differ for different materials and for different dynamical regimes. The discrepancies can be attributed to different measurement methods or to intrinsic differences in the dynamic response of the sample according to the magnetization reversal mechanism.[11,12,19] The reversal mechanism is known to be sensitive to growth conditions, e.g., thickness, film homogeneity, roughness, substrate or capping layer.[11,12] For instance, the values of the scaling exponents for Co/Cu(001) (Refs. 10 and 12) obtained by different groups exhibit surprisingly large differences ($\alpha = \beta \approx 0.67$ in Ref. 10, $\alpha = 0.15$, $\beta = 0.01$ in Ref. 12). In real magnetic systems, the current key issues are the universality of hysteresis scaling behavior, the values of the exponents and the possible correlation between α and β in Eq. (1). In prior experiments, dynamic scaling behavior was found to be independent of film thickness,[9–14] although thickness does affect magnetic anisotropy to some extent.[14] In order to test the universality of dynamic scaling behavior in ferromagnetic ultrathin films and to clarify the effect of magnetic anisotropy strength on the dynamic hysteresis scaling, we chose to study fcc epitaxial NiFe and Co grown on Cu/Si(001). We take advantage of the striking difference in the cubic magnetocrystalline anisotropy fields, which differ by more than 1 order of magnitude ($H_{K_1}{}^{\mathrm{Co}} = 2K_1/M_s \approx 844$ Oe, $H_{K_1}{}^{\mathrm{NiFe}} \approx 50$ Oe).[20] Here H_{K_1}, K_1, and M_s denote cubic magnetocrystalline anisotropy field, anisotropy constant, and saturation magnetization, respectively. A further motivation in studying spin-valve structures consisting of NiFe and Co layers with very different magnetic anisotropy strengths is that it allows us to compare the dynamic reversal behavior for ultrathin films deposited on the same substrate with the same fcc structure. In this way we can largely eliminate uncertainties due to intrinsic differences associated with the substrate or growth conditions.

In this paper, we present the dynamic hysteresis behavior in epitaxial single ferromagnetic layers with different mag-

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netic anisotropy strengths and in epitaxial spin-valve structures as a function of field sweep rate $\dot{H}$ in the range 0.01–270 kOe/sec investigated with magneto-optic Kerr effect (MOKE). We find that the scaling exponent in the NiFe film is greater than that in the Co film at high sweep rates, illustrating that the dynamic response in the NiFe film is slower than that in the Co film. We also demonstrate that for spin-valve structures ''double-switching'' behavior which occurs at low sweep rates transforms to ''single switching'' at high sweep rates due to the different dynamic response of the NiFe and Co layers. This result indicates that NiFe and Co layers with different magnetic anisotropy strengths show distinct scaling behavior at high sweep rate.

II. EXPERIMENTS

The single ferromagnetic films (Ni$_{80}$Fe$_{20}$ and Co) with nominal structures, Cu(50 Å)/**NiFe**(60 Å)/Cu(700 Å)/Si(001) and Cu(50 Å)/**Co**(40 Å)/Cu(700 Å)/Si(001), respectively, were grown on the same HF-passivated Si(001) surface in order to remove the influence of the substrate. The sample was grown at room temperature by molecular beam epitaxy (MBE) under ultrahigh vacuum conditions (UHV) with a base pressure of $\sim 3\times 10^{-10}$ mbar. The single and the double spin-valve structures: Cu(50 Å)/**Co**(40 Å)/Cu(60 Å)/**NiFe**(60 Å)/Cu(700 Å)/Si(001) (Refs. 20 and 21) and Cu(50 Å)/**NiFe**(60 Å)/Cu(60 Å)/**Co**(40 Å)/Cu(60 Å)/**NiFe**(60 Å)/Cu(700 Å)/Si(001) (Ref. 22) were also grown under similar conditions. Prior to the deposition of the magnetic materials a 700 Å thick Cu(001) seed layer was deposited on Si(001) using a Knudsen cell with a typical evaporation rate of ~5 Å/min. The NiFe and Co layers were deposited on to the Cu(001) surface using electron beam evaporation and the typical evaporation rate was ~1 Å/min. The deposition rates were calibrated using a quartz microbalance, which has an accuracy of ~±10%. Epitaxial growth was confirmed using *in situ* reflection high energy electron diffraction (RHEED). The images obtained showed that the NiFe, Cu, and Co layers grew epitaxially in the (100) orientation where the fcc NiFe, Co⟨110⟩ in-plane directions correspond to the Si⟨100⟩ directions.

Magnetic hysteresis loops were measured *ex situ* at room temperature using MOKE magnetometry with a probing laser beam spot of diameter ~2 mm. The applied magnetic field was driven by a time-varying current at a frequency between 0.01 Hz and 1 kHz. A Hall probe in the frequency range studied was used to detect the effective magnetic field at each frequency.

III. RESULTS AND DISCUSSION

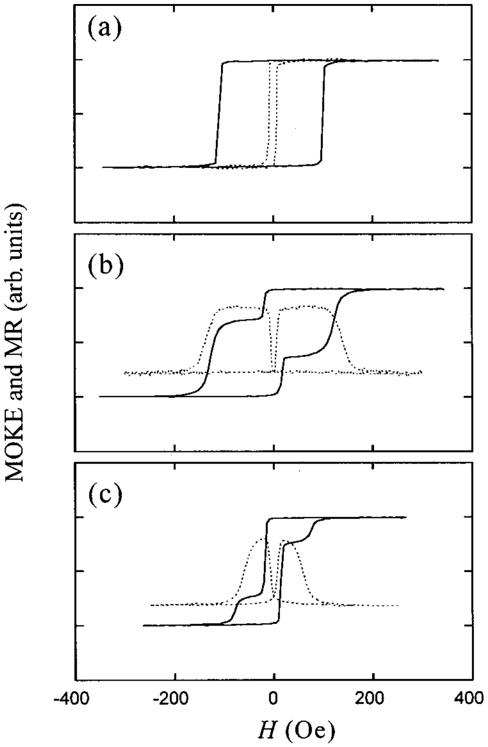

FIG. 1. MOKE hysteresis loops obtained at dc (a) for single ferromagnetic layer films (Co: solid line; NiFe: dotted line), and MOKE loops (solid) and MR curves (dot) for the single spin valve (b) and the double spin-valve structure (c). All data were obtained with magnetic fields applied parallel to the [110] axes of the Co and NiFe layers (easy axis).

In Fig. 1, we present dc MOKE hysteresis loops obtained (a) for single ferromagnetic layer samples (Co: solid line; NiFe: dotted line), and MOKE loops (solid) and MR curves (dot) for the single spin valve (b) and for the double spin-valve structure (c). All data were obtained with the magnetic field applied parallel to the [100] axis of the substrate, i.e., Co and NiFe [110] (easy axis). The fcc epitaxial NiFe film is found to exhibit a broken fourfold symmetry due to a uniaxial anisotropy induced during deposition as determined by rotary vector MOKE magnetometry. However, the anisotropy field is very weak compared with the fcc Co film. This result is in qualitative agreement with the results of Brillouin light scattering (BLS) in our previous work.[20] Very recently, Lo *et al.*[23] reported that the induced uniaxial anisotropy in the fcc epitaxial NiFe/Cu/Si(001) is ascribed to a 6% lattice mismatch. In contrast to the NiFe film, we found that the fcc epitaxial Co shows fourfold cubic anisotropy with a very weak uniaxial anisotropy, consistent with prior BLS results ($2K_1/M_s \approx -844\,\text{Oe}$, $2K_u/M_s \approx 10\,\text{Oe}$).[20] The anisotropy constants are defined such that positive values make the Co [100] axis easy. In Fig. 1(a), one can see a striking difference in the coercive field between the NiFe($H_c = 5$ Oe) and the Co films ($H_c = 104$ Oe). The two systems are thus of interest for the study of the effect of magnetic anisotropy strength on the dynamic scaling behavior.

We previously found that a Cu spacer thickness ($t_{\text{Cu}} \geqslant 60$ Å) gives rise to ''double switching'' in the single spin valve.[24] The sharp double switching is clearly seen in the single and double spin valves [Figs. 1(b) and 1(c): solid line]. For the NiFe and Co layers, the coercive fields in the single spin valve are $H_c^{\text{NiFe}} = 28$ Oe and $H_c^{\text{Co}} = 90$ Oe, while in the double spin valve they are $H_c^{\text{NiFe}} = 25$ Oe and $H_c^{\text{Co}} = 50$ Oe, respectively. Compared to H_c for the single magnetic layer films, the increase of H_c for the NiFe layer and the decrease for the Co layer in the double spin valve can probably be attributed to coupling between the magnetic layers, e.g., magnetostatic ''orange peel.''[25,26] The normalized MR curves in which the plateaux correspond to an antipar-

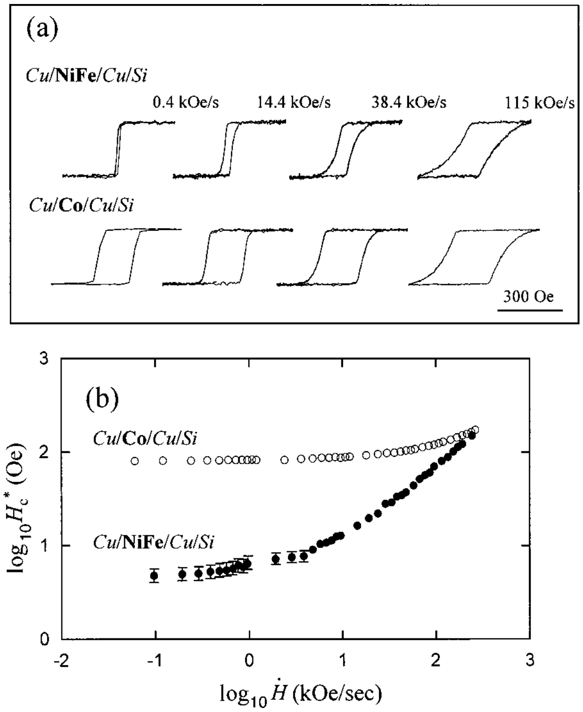

FIG. 2. (a) Evolution of sweep-rate dependent hysteresis loops and (b) log-log plots of dynamic coercive field (H_c^*) against field sweep rate $\dot{H}$ for the NiFe and Co single magnetic layer films.

allel configuration of the two magnetic layer magnetizations are in good agreement with the M-H loops for the single and double spin valves [Figs. 1(b) and 1(c): dotted line]. The MR ratios are 0.3% and 1.2%, respectively, for the single and double spin valves.

Zhong and Zhang[3] proposed that, in the limit of low H_0 and Ω in Eq. (1), the field is a linear function of time t with a proportionality coefficient $H_0\Omega$ and thus $\alpha=\beta$. In this case, for a sweep rate $\dot{H}(dH/dt)$,[3,19]

$$H_0=\dot{H}t, \tag{2}$$

$$A\propto\dot{H}^{\alpha}. \tag{3}$$

Previous experimental work[10,14] has demonstrated that the exponent α is identical to β from Eq. (1). We used the fact that dynamic coercive field (H_c^*) is proportional to the M-H loop area A in this case for the determination of the exponents in Eq. (1).[1,9,13,14] The dynamic coercive fields (H_c^*) were determined for varying frequencies and fixed field amplitudes at which the hysteresis loops are saturated.

Figure 2 displays (a) the evolution of the hysteresis loops and (b) log-log plots of the dynamic coercivity (H_c^*) against field sweep rate $\dot{H}$ for the NiFe and Co single magnetic layer films. The M-H loop area A increases with increasing sweep rate until it reaches a maximum. As the sweep rate increases further, the M-H loops eventually can no longer be saturated with the available field, and then collapse gradually (not shown in Fig. 2) as predicted in theoretical work[1,2,4] and demonstrated experimentally.[9,10,13,14,17] The magnetizations of the NiFe and Co films are unable to respond immediately to the rapidly varying field and this effect becomes progressively more pronounced as the sweep rate increases. However, it is noticeable that there is a significant difference in the dynamic response to the sweep rate between the NiFe and Co films. At 0.4 kOe/sec, H_c^* of the NiFe film is much smaller than that of the Co film, but H_c^* of the NiFe film gets close to that of the Co film with increasing sweep rate as seen in Fig. 2(a). Distinct dynamic reversal behavior in both films is clearly observed in the log-log plot of H_c^* against the sweep rate $\dot{H}$ [Fig. 2(b)]. We found that the exponent α in Eq. (3) varies with the sweep rate, but two distinct regions are seen in which approximately linear behavior occurs but with different values of α for the NiFe and the Co films. This behavior is qualitatively compatible with previous work,[7,14] where differing values of α are attributed to a change of the magnetization reversal process with increasing field sweep rate. Domain wall motion dominates the magnetization reversal at low sweep rates, but becomes less significant with increasing sweep rate. Very recently, Lyuksyutov *et al.*[8] carried out numerical Monte Carlo simulations of dynamic hysteresis scaling based on domain wall motion, nucleation, and retardation of the magnetization, showing that the theory is compatible with available experimental data. However, the critical transition from low to high values of α reported in previous work[7,14] and observed in the present work is believed to result from the competition between domain wall motion and nucleation processes but is not currently well understood. For the NiFe and Co films, the hysteresis loop area A is found to follow the scaling relation with $\alpha\sim0.13$ and ~0.02 at low sweep rates and ~0.70 and ~0.30 at high sweep rates, respectively (see Table I). Consequently, a crossover at which the dynamic coercive fields of the NiFe and Co films are identical is found to occur at 245 kOe/sec [see Fig. 2(b)]. The corresponding transitions from low to high values of α are found to occur at ~3 kOe/sec and 40 kOe/sec, respectively, for the NiFe and Co films. The values of the exponent α for the NiFe and the Co films at high sweep rates are comparable with that of polycrystalline NiFe films[13] [$\alpha\approx0.9$, $\beta\approx0.8$ in Eq. (1)] and that of Fe/GaAs(001) films[14] ($\alpha\approx0.33$–0.40), respectively, observed in our previous work.[13,14]

The observed crossover in the variation of H_c^* against the sweep rate $\dot{H}$ for the NiFe and Co films supports the view that the dynamic scaling behavior at high sweep rate is dependent upon the magnetic anisotropy strength which is in contrast with the predictions of current theoretical models. In order to explore the influence of magnetic anisotropy strength on the dynamic response of the NiFe and Co films, we studied the dynamic hysteresis behavior in epitaxial single and double spin-valve structures comprising the two magnetic layers. Figure 3 shows the evolution of representative hysteresis loops against field sweep rate for the single (a) and double (b) spin valves. First, it is seen that both the spin valves show clear ‘‘double-switching’’ behavior at low sweep rates. However, the ‘‘double-switching’’ behavior which occurs at low sweep rates gradually becomes less clear as the sweep rate increases and then transforms to ‘‘single switching’’ at ~154 kOe/sec and ~192 kOe/sec, respectively, for the single and double spin valves. The ‘‘single switching’’ in the double spin valve is more pronounced than that in the single spin valve, since for the

TABLE I. Experimental dynamic scaling exponents in $A \propto H^{\alpha}$ for the single magnetic films and the single and double spin valves.

System		α		H_c (Oe) at dc	Critical transition (kOe/sec)
		At low sweep rates	At high sweep rates		
Cu/$\mathbf{Ni_{80}Fe_{20}}$/Cu/Si(001)		~0.13	~0.70	5	3
Cu/**Co**/Cu/Si(001)		~0.02	~0.30	104	40
Single spin valve	NiFe	~0.06	~0.58	28	17
Cu/**Co**/Cu/$\mathbf{Ni_{80}Fe_{20}}$/Cu/Si (001)	Co	~0.03		90	
Double spin valve	NiFe	~0.04	~0.60	25	14
Cu/$\mathbf{Ni_{80}Fe_{20}}$/Cu/**Co**/Cu/ $\mathbf{Ni_{80}Fe_{20}}$/Cu/Si(001)	Co	~0.05	~0.46	50	68

single spin valve the value of H_c^* for the Co layer exceeds the available magnetic field strength, giving rise to rounded tips of the M-H loop.

In Fig. 4, we present the log-log plots of $H_c^{*(\mathrm{NiFe})}$ and $H_c^{*(\mathrm{Co})}$ against sweep rate for the single and double spin valves. We find that for the single spin valve, $H_c^{*(\mathrm{Co})}$ increases monotonically with the sweep rate with no critical transition. This behavior is likely to be due to $H_c^{*(\mathrm{Co})}$ being greater than H_0 at high sweep rates. In contrast to the Co layer in the single spin valve, the dynamic response of the NiFe layer is comparable with that of the single NiFe film (see Fig. 2). The values of α at low and high rates are ~0.06 and 0.58, respectively, which are in good agreement with that of the single NiFe film (see Table I). A critical transition is also found to occur at 17 kOe/sec. On the other hand, for the double spin valve the dynamic response of both the NiFe and Co layers is very similar to that of the single NiFe and Co films (see Table I). Dynamic magnetoresistance (MR) measurements for the spin valves are in progress.

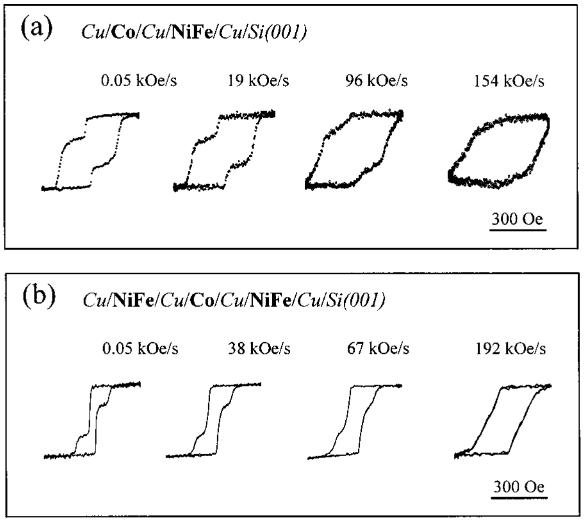

FIG. 3. Evolution of sweep-rate dependent hysteresis loops for the single (a) and double (b) spin valves. The ''double-switching'' behavior which occurs at low sweep rates gradually becomes less clear as the sweep rate increases and then transforms to ''single switching'' at ~154 kOe/sec and ~192 kOe/sec, respectively, for the single and double spin valves.

Comparison with the available current theoretical models is difficult, since physical insight into the validity of the current theoretical models is still lacking, although previous experimental studies[9,10,13,17] demonstrated scale-invariant descriptions of the dynamic scaling behavior. In earlier theoretical models such as the 2D Ising spin model[2,4,5] and the continuous spin system[1,2,3] the magnetic anisotropy is not considered. However, the Ising model is expected to be of relevance to hysteresis in thin films with a strong uniaxial anisotropy, whereas the continuum model is expected to be relevant to single domain particles with very small magnetic anisotropy.[1] Very recently, a theoretical model[8] based on domain nucleation and wall dynamics has been used to show that the scaling behavior in the Ising model in the case of weak (domain wall width $w \gg$ lattice constant a) and strong ($w \approx a$) anisotropies, respectively, becomes equivalent after a simple rescaling. They consider a spin cluster of a size equal to the domain wall width as an elementary spin, but obtain the same scaling exponents in each case. Our results,

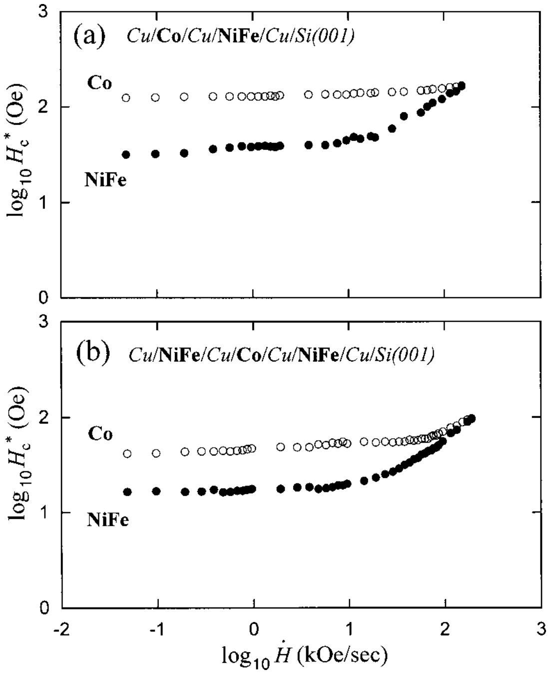

FIG. 4. Log-log plots of $H_c^{*,\mathrm{NiFe}}$ and $H_c^{*,\mathrm{Co}}$ against sweep rate for the single and double spin valves.

however, indicate that magnetic anisotropy strength influences the dynamic response to field sweep rate in the same dynamic region, which therefore differs from the prediction of the theoretical model in Ref. 8. Although the specific reversal mechanism may be associated with either domain wall motion or nucleation, it is likely that both the wall velocity and pinning energy are affected by the magnetic anisotropy strength. Therefore, since the structure and quality (i.e., number of defects) are comparable for the two films in our structures, we attribute the difference in scaling behavior to the differing magnetic anisotropy strengths.

IV. CONCLUSION

The magnetization reversal dynamics of epitaxial single ferromagnetic layers and spin-valve structures were investigated as a function of field sweep rate $\dot{H}(dH/dt)$ in the range 0.01–250 kOe/sec using the magneto-optic Kerr effect (MOKE). The hysteresis loop area A is found to follow the scaling relation $A \propto \dot{H}^{\alpha}$ with $\alpha \sim 0.13$ and ~ 0.02 at low sweep rates and ~ 0.70 and ~ 0.30 at high sweep rates, respectively, for the single NiFe and Co films. This result indicates that the NiFe and Co layers in the spin-valve structures can be expected to show distinct scaling behavior at high sweep rate. For the spin-valve structures, the ‘‘double-switching’’ behavior which occurs at low sweep rates transforms to ‘‘single switching’’ at ~154 kOe/sec and ~192 kOe/sec for the single and double spin valves, respectively, due to the different dynamic response of the NiFe and Co layers to a time-varying magnetic field. We conclude that the dynamic response is dependent upon the magnetic anisotropy strength.

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