Nanosecond magnetization reversal in nanocrystalline magnetic films

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Abstract. This paper reports on the investigation of dynamic magnetization reversal process in electrodeposited nanocrystalline Ni and Ni80Fe20 films by employing nanosecond magnetic pulse technique. The surface morphology has been investigated using SEM, EDAX, XRD and AFM analyses and static magnetic properties of the films are characterized by vibrating sample magnetometer (VSM). Two different techniques are designed and employed to study the nanosecond magnetization reversal process in nanocrystalline thin films: Magneto-Optical Kerr Effect (MOKE) and nanosecond pulsed field magnetometer. Results of dynamical behavior as a function of several variables such as magnitude of applied bias magnetic field, amplitude and width of the pulsed magnetic field are analyzed in detail using both techniques. A computer simulation package called Object Oriented Micro-Magnetic Framework (OOMMF) has been used to simulate the magnetic domain patterns of the samples.

1. Introduction
An important current issue for magnetic material to be used as recording heads and sensors are placed on achieving faster read or write times, as the disk data storage density increases. Therefore, dynamic characterization of the magnetic materials to elucidate the magnetization reversal behavior, together with the need to understand the mechanisms involved in the dynamical processes of these materials is crucial for the development and design of read/write heads and sensors used in future data storage applications. For this intention, we have designed and developed two different techniques to determine the magnetization reversal in the magnetic thin films. These two techniques are: Magneto-Optical Kerr Effect (MOKE) that has been described by Rizzo et al. [1] and Nanosecond Pulsed Field Magnetometer reported by Hancock [2]. The second technique has been modified for convenience to achieve accuracy in the measurement. A computer simulation package called Object Oriented Micro-Magnetic Framework (OOMMF) has been used to simulate the magnetic domain patterns of the samples as a function of applied magnetic field for comparison with the experimentally observed data.

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2. Samples preparation

The deposition of Ni and Ni$_{80}$Fe$_{20}$ films on aluminum substrates were performed using the conventional electrodeposition technique [3]. A Solartron potentiostat 1285 was employed to control the deposition parameters. To produce regular thin film an analogue sweep type in galvanostatic mode of operation with 1 mA cm$^{-2}$ current was set throughout the deposition period. After depositions the samples were thoroughly washed with deionized water and dried with nitrogen gun.

| Sample | Component Salts | Concentration (g l$^{-1}$) | pH | Temp (°C) | Time (Min) | Film Thickness (µm) | Coercivity (kA m$^{-1}$) | Grain Size (nm) |
|--------|----------------|--------------------------|----|-----------|-----------|--------------------|----------------------|----------------|
| Ni     | NiSO$_4.6$H$_2$O | 330                      | 3  | 40        | 180       | 5.61               | 20                   | 102.4          |
| NiCl$_2.6$H$_2$O | 45 | H$_3$BO$_3$ | 38 |          |           |                    |                      |                |
| Ni$_{80}$Fe$_{20}$ | NiSO$_4.6$H$_2$O | 273.34                | 3  | 40        | 180       | 3.36               | 14                   | 102.4          |
|       | Fe$_2$SO$_4.7$H$_2$O | 7.78                |    |           |           |                    |                      |                |
|       | H$_3$BO$_3$          | 50.08                 |    |           |           |                    |                      |                |

3. Experimental techniques

3.1. Magneto-Optical Kerr Effect (MOKE)

The experimental setup is shown in figure 1. The high magnetic field pulses were generated using a coplanar waveguide (CPW), which was designed and fabricated by PCB technique. The CPW was fed with commercially available high voltage Avtech AVIR-4-B pulse generator. The magnetization reversal caused by a given pulsed magnetic field (Max 400 kA m$^{-1}$) and bias dc magnetic field (110 kA m$^{-1}$) was quantified using a modified magneto-optical microscope.

![Figure 1. MOKE setup.](image1)

![Figure 2. Nanosecond pulsed field magnetometer setup.](image2)

For each data point, the samples were saturated in the positive x-direction using dc bias magnetic field provided by a modified electromagnet. Then, a digital image of the remanent state of the samples was acquired using a 16-bit CCD camera and calibrated. After that a nanosecond high magnetic pulse field ($H_p$) plus external dc bias magnetic field ($H_0$) was applied in the negative x-direction. Then, a second image was acquired and digitally subtracted from the first image to obtain the relative change in the magneto-optic contrast measured after application of a pulse magnetic field of duration $t_p$. This image was then compared with the reference image of the samples and the percentage remanent
magnetization was calculated. This process was carried out for different pulsed magnetic field, bias dc magnetic field and pulse duration. All data were then plotted on a graph to extract the minimum pulse width (relaxation time) required to switch magnetization reversal to zero for a particular sample.

3.2. Nanosecond pulsed field magnetometer
The modified Vibrating Sampling Magnetometer (VSM) was employed for nanosecond pulsed field magnetometer technique. The CPW was placed in the VSM system on a specially constructed stand to push the waveguide up or down depending on the need to apply pulsed magnetic field on the samples. The experimental setup is shown in figure 2. Initially, applying dc bias field using VSM electromagnet system in one direction the samples were saturated. Samples were then subjected to the dc bias field plus nanosecond pulsed magnetic field by means of pushing up the CPW stand under the samples. Both the dc bias field and the pulsed field were applied in the opposite direction to the saturation field. After the application of both fields remanent magnetization was measured. The sample was then saturated both in the positive and negative direction with the intention that the percentage changes in magnetization could be calculated.

4. Results and discussion

4.1. Surface analysis and static magnetic properties of Ni and Ni$_{80}$Fe$_{20}$ thin films
The deposited Ni and Ni$_{80}$Fe$_{20}$ films are investigated using JEOL JSM-840 scanning electron microscopy (SEM) and TOPOMETRIC atomic force microscope (AFM) that have revealed the nanostructure and crystallographic textures of the surface. The AFM image and SEM image of the Ni and NiFe surface are shown in figure 3 and figure 4 respectively. SEM images are shown in figure 4(a) and (b) for Ni and Ni$_{80}$Fe$_{20}$ films respectively. The surface texture of the samples show that the deposits are consisted of columnar grains that have increased in size with thickness in the absence of continuous nucleation of new grains. This is in agreement with the finding in a report by Ebrahimi et al. [4]. This type of growth can induce some magnetic anisotropy and hence increase in coercivity.

![Figure 3. AFM results for (a) Ni films and (b) Ni$_{80}$Fe$_{20}$ films on aluminum substrate.](image)

![Figure 4. SEM results for (a) Ni films and (b) Ni$_{80}$Fe$_{20}$ films on Aluminum substrate.](image)
The Energy Dispersive X-ray Analyses (EDAX) for Ni and Fe samples of sample are carried out to examine the percentage concentration of the constituent elements and are found to be in agreement. X-ray diffraction (XRD) analyses using Philips X’pert X-ray diffraction machine has revealed the polycrystalline nature of the films, average crystallite size and the crystal orientation. Intentionally, same deposition condition has been used for both samples to achieve constant percentage lattice strain and grain size. XRD analyses have shown that the lattice strain percentage and the grain size for the both samples are 0.089 and 102.3 nm respectively. This is an important step to compare the dynamic magnetization for two different samples. The static magnetic properties of the samples are extracted from the hysteresis loop traced by a VSM system. The sample coercivities are found to be ~20 k Am\(^{-1}\) and ~14 k Am\(^{-1}\) for the Ni and Ni\(_{80}\)Fe\(_{20}\) thin films respectively.

4.2. Magnetization reversal analysis thin films

4.2.1. Change of percentage magnetization with DC bias field: We have measured the magnetization response of the sample as a function of dc bias field \(H_B\). Figure 5 shows comparison of simulation and experimental data on percentage remanent magnetization as a function of dc bias magnetic field for Ni\(_{80}\)Fe\(_{20}\) sample applied for about 5 seconds and has demonstrated near agreement. In this case simulation is performed with high damping factor, \(\alpha\). When very low value of damping factor, \(\alpha\) is chosen simulation results depicted the ringing effect as shown in figure 6.

![Figure 5](image)

**Figure 5.** (a) Change of percentage magnetization with DC bias field (b) MOKE images for different remanent states and (c) Simulation images of different remanent states with \(\alpha = 0.5\) using OOMMF package [5].

4.2.2. Change of percentage magnetization with nanosecond pulsed field: The magnetic switching or relaxation time can be defined, as the pulse duration required bringing the magnetization to zero. For this reason, time extracted for fields insufficient to demagnetize the sample is not the true switching or relaxation time [1]. The total magnetic fields used in these measurements are in the range of 10 to 50 kA m\(^{-1}\). Figure 7(a) demonstrates the magnetization response as a function of pulse durations, \(t_p\) for fixed pulsed magnetic field amplitudes. Simulated images of Ni\(_{80}\)Fe\(_{20}\) for total magnetic field (dc bias plus pulsed field) of 30 kA m\(^{-1}\) field are shown in figure 7(b). Relaxation time is extracted from the
data in figure 7(a) for those fields only, which are sufficient to demagnetize the sample to zero. Plot of the inverse of relaxation time as a function of total magnetic field, \( H \) is shown in figure 7(c). For Ni\(_{80}\)Fe\(_{20}\), the maximum relaxation time is extracted from figure 7(c) and is found to be \( \sim 1 \) ns and agreed with the finding in a report by Atkinson et al. [7]. The data with open circles are taken at 30 kA m\(^{-1}\) for Ni sample and extracted value of the relaxation time is found to be \( \sim 1.5 \) ns.

**Figure 7.** Simulation results: (a) Normalized remanent magnetization of Ni\(_{80}\)Fe\(_{20}\) sample versus pulse durations (logarithmic scale) for total field values \( H=10, 20, 25, 30, 50 \) kAm\(^{-1}\). The data with open circle (30 kAm\(^{-1}\)) were taken for Ni sample. (b) Ni\(_{80}\)Fe\(_{20}\) domain pattern for field of 30 kAm\(^{-1}\) with different pulse duration. (c) Inverse relaxation time versus applied field.

5. Conclusion

We have developed two techniques to study magnetic relaxation process in electrodeposited Ni and Ni\(_{80}\)Fe\(_{20}\) samples. The surface texture of the samples has shown deposits consisted of columnar grains that contributed to magnetic anisotropy and higher coercivity. The simulation results on Ni\(_{80}\)Fe\(_{20}\) sample show dynamic relaxation time is in the order of \( \sim 1 \) ns in the fields sufficient to cause saturation. Although for higher applied magnetic field, the response time is reduced in inverse proportion to the applied field above some critical value, as would be expected from simple model of domain wall propagation. For Ni sample, the relaxation time is found to be more then one nanosecond (\( \sim 1.5 \) ns). The relatively low relaxation time of Ni\(_{80}\)Fe\(_{20}\), compared with that of Ni sample, is a result of low coercivity of the sample. This analysis implies that thin films with lower coercivity will reverse faster than the thin film with higher coercivity (maintaining all other parameters at the same level such as, deposition parameters, grain size and the percentage lattice constant of the deposited film). Simulation and experimental data on percentage remanent magnetization as a function of dc bias field have demonstrated near agreement.

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