Permeability spectra of hole arrays defined on single layer Permalloy thin films

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Although considerable work has been done investigating the properties of arrays of magnetic elements, there have been few investigations on the reverse geometry, i.e., an array of nonmagnetic regions defined within a magnetic thin film. The 10 Hz \(BH\) loops, 10–500 MHz permeability spectra, and domain patterns of homogeneous, single layer 100 nm radio frequency (rf) sputtered Ni\textsubscript{81}Fe\textsubscript{19} films with arrays of 23-, 50-, and 100-\(\mu\text{m}\)-diam holes defined by laser ablation were measured. The holes were defined in a grid along the hard and easy axes of the sample. Letting \((x,y)\) represent, respectively, the hole spacing parallel to the easy and hard axes, the point to point spacing of the ablated circular regions was varied from \((5, 2)\) mm to \((0.1, 0.1)\) mm. © 1997 American Institute of Physics. [S0021-8979(97)58808-6]

I. INTRODUCTION

The motivation of this work comes from a desire to control the rf permeability of magnetic thin films. With control potential applications would include identification markers, films for the absorption of stray electromagnetic fields, etc. Earlier work investigated the magnetic properties of Permalloy thin films with laser defined stripes.\(^1\) This work reports on the magnetic properties of Permalloy thin films with arrays of holes defined on the films by laser ablation.

The holes were defined in a grid along the hard and easy axes of the sample using an excimer laser. Letting \((x,y)\) represent, respectively, the hole spacing parallel to the easy and hard axes, the point to point spacing of the ablated circular regions was varied from \((5, 2)\) mm to \((0.1, 0.1)\) mm; holes sizes of 23, 50, and 100 \(\mu\text{m}\) sizes were used.

II. EXPERIMENT

A MPB PSX-100 KrF excimer laser, with a 248 nm wavelength, was used to define arrays of circular holes on 100-nm-thick magnetically soft Ni\textsubscript{81}Fe\textsubscript{19} films. Three different hole diameters were used: 23, 50, or 100 \(\mu\text{m}\). The Ni\textsubscript{81}Fe\textsubscript{19} films were fabricated by rf magnetron sputtering using a Perkin-Elmer 4410; the base pressure was \(6\times10^{-3}\) Torr, the sputtering pressure 4 mTorr, and argon sputtering gas was used.

Excimer lasers do not operate continuously, but deliver pulses of high optical power. An incident energy density of 18 J/cm\(^2\) was used; the laser pulse was 2.5 ns for a power density of 7.4 GW/cm\(^2\). The sample was mounted on a motorized translation stage, the laser beam was incident normal to the plane of the sample, and the samples were processed in air.

The coercive force \(H_c\) and anisotropy field \(H_k\) of the samples were measured using a \(BH\) looper, the 10–500 MHz complex permeability spectra of the samples measured using a thin film permeameter,\(^2\) and Kerr images were obtained of the magnetic domains.\(^3\)

III. RESULTS

The coercive force and anisotropy field of the patterned films change in response to the density of the hole array and the size of the laser defined hole. For relatively open array spacings the coercive force remains approximately equal to the as-deposited value, increasing rapidly after reaching a threshold array density. For example, with 100 \(\mu\text{m}\) holes the coercive force stays roughly equal to the as-deposited film value until a center to center array spacing of approximately 0.3 mm\(\times0.3\) mm is reached whereupon it rapidly increases. Conversely, the anisotropy field, measured by extrapolation of the hard axis initial linear magnetization curve to the easy-axis saturation value, stays approximately equal to the as-deposited value until the hole density reaches the same threshold in array density where it begins to rapidly decrease with increasing hole array density. At the highest array densities, where the amount of material ablated is approximately equal to or greater than the material left, the films tended to become isotropic. Table I lists illustrative \(H_c\) and \(H_k\) data.

This threshold also corresponds to changes in the measured permeability spectra. Figure 1 shows the complex permeability spectra of a film measured along the hard axis after an easy axis saturation with 100-\(\mu\text{m}\)-diam spots spaced 2.0 mm\(\times2.0\) mm apart with trace \(a=\mu'\) and trace \(c=\mu''\), and 0.35 mm\(\times0.35\) mm apart with trace \(b=\mu'\) and trace \(d=\mu''\); the permeability values are normalized, taking into account the ablated material. The 2.0\(\times2.0\) array spectrum is essentially that of the as-deposited film, while the 0.35\(\times0.35\) array shows a spectrum in which the loss peaks at a much lower frequency. The increased loss at lower frequency (=80 MHz) in the higher density hole array films is thought to be
associated with the increased number of domain walls between the array holes.\textsuperscript{4,5} Figures 2(a) and 2(b) are Kerr images of the domain structure associated with two different hole array densities.

Figure 2(a) is for a spacing of 0.4 mm×0.4 mm; Fig. 2(b) is for a spacing of 0.2 mm×0.25 mm. In both images the easy axis is vertical, the contrast displays the easy axis component of magnetization for the samples in a remanent state after a hard axis saturation. The increased number of domains with the greater hole density is readily apparent.

For samples below, yet near, the array density threshold, for which the permeability spectra are still similar to the as-deposited sheet, the $\mu''$ peak can also be shifted to lower frequencies by first saturating the film in the hard axis direction which results in a greater number of domain walls. To demonstrate this, the hard axis permeability of the films was measured after saturating the film in both easy and hard axis directions; for a given hole size and array spacing the number of domains is increased by saturating the film along the hard axis. Figure 3 shows the hard axis complex permeability spectra for a 23-μm-diam spot 0.25 mm×0.25 mm array measured after saturation along the easy axis, trace $a=\mu'$, trace $c=\mu''$, and after saturation along the hard axis, trace $b=\mu'$, trace $d=\mu''$. As can be seen in Fig. 3, the hard axis saturation has shifted the resonant frequency from approximately 500 to 90 MHz.

Table I. Coercive force and anisotropy field dependence on spot diameter and spot array spacing defined on 100 nm Ni$_8$Fe$_{19}$ Permalloy film, with values given in Oe.

<table>
<thead>
<tr>
<th>Array spacing (mm)</th>
<th>100 μm spots</th>
<th>50 μm spots</th>
<th>25 μm spots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_c$</td>
<td>$H_k$</td>
<td>$H_c$</td>
</tr>
<tr>
<td>0.1×0.1</td>
<td>...</td>
<td>...</td>
<td>1.35</td>
</tr>
<tr>
<td>0.2×0.2</td>
<td>1.06</td>
<td>1.92</td>
<td>1.10</td>
</tr>
<tr>
<td>0.25×0.25</td>
<td>0.92</td>
<td>2.70</td>
<td>1.04</td>
</tr>
<tr>
<td>0.35×0.35</td>
<td>0.86</td>
<td>3.16</td>
<td>...</td>
</tr>
<tr>
<td>1.0×1.0</td>
<td>0.84</td>
<td>3.05</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Figure 4 shows the Kerr response of a 0.2 mm×0.25 mm array of 100 μm holes. The contrast displays changes in the hard axis component of magnetization in response to small changes in a hard axis applied field (±0.4 Oe). Figure 4(a) shows the response of the sample in a remanent state after a easy axis saturation, and Fig. 4(b) the response of the sample in a remanent state after a hard axis saturation. The hard axis saturation has resulted in a larger number of domains between the holes along the easy axis, which can explain the lower frequency $\mu''$ peak seen in Fig. 3. The overall Kerr
response of the sample is weaker after hard axis saturation of the sample [Fig. 4(b)] than after easy axis saturation [Fig. 4(a)]. This may be due to the effect of stray fields associated with the wall network changing the orientation of the remanent magnetization.

IV. CONCLUSIONS

The magnetic properties of 100 nm thin films of 81:19 Permalloy with laser defined hole arrays were investigated. High hole array densities greatly increase the number of domains between holes, which after a threshold density that is dependent upon the hole size is reached, correlate to an increase in the coercive force, decrease in the anisotropy field, and lowering of the permeability spectra resonance frequency. The array of holes is thought to change the magnetic properties of the sample through increased nucleation of domain walls. The $\mu^\alpha$ peak can be shifted to lower frequencies by either increasing the array density above a certain threshold value or, for films near threshold spacing, by saturating the film in the hard axis direction.

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