Control of the permeability loss-peak frequency of Ni$_{81}$Fe$_{19}$ thin films through laser ablation of triangular and square cluster geometries

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Laser ablation arrays of triangular and square shaped clusters, comprised of 23 $\mu$m diam circular holes, are defined upon 100 nm thick Ni$_{81}$Fe$_{19}$ films used to control the rf permeability spectra. Cluster-to-cluster spacing is varied from 200 to 600 $\mu$m. For each geometry it is found that the loss peak frequency and permeability magnitude shift lower, in a step-wise fashion, at a cluster-to-cluster spacing between 275 and 300 $\mu$m. The nonlinear shift in the behavior of the permeability spectra correlates with a dramatic increase in domain wall density. © 2000 American Institute of Physics.

INTRODUCTION

We are motivated to control the rf permeability of magnetic thin films. Potential applications include fabrication of ferromagnetic conductive waveguides that can be switched between a lossy off state to a nonlossy on state by the temporary application of a saturating magnetic field. It is a further objective of our work to control the permeability loss-peak frequency $\mu''$ for the absorption of frequency-specific magnetic fields. To control the rf permeability spectra of the film, using laser ablation arrays of triangular and square shaped clusters comprised of 23 $\mu$m diam holes are defined upon 100 nm thick Ni$_{81}$Fe$_{19}$ films; the triangular cluster pattern is shown schematically in Fig. 1. The laser beamwidth is held constant at 23 $\mu$m, cluster to cluster spacing is varied from 200 to 600 $\mu$m, and intracluster nearest-neighbor spacing is fixed at 37.5 $\mu$m. The laser ablated holes act as domain wall nucleating sites that can pin the magnetization vector in a particular direction. Earlier work showed how the anisotropy field and complex permeability frequency spectra of ferromagnetic thin films could be controlled through definition of stripe geometries upon the film$^{1-3}$ by counterbalancing the anisotropy field associated with the as-deposited easy axis against the demagnetizing field of the stripe.

EXPERIMENTAL RESULTS

The Ni$_{81}$Fe$_{19}$ films used in this work were fabricated by rf sputtering using a Perkin–Elmer 4410; the base pressure was $6 \times 10^{-7}$ Torr, the sputtering pressure 4 mTorr, and argon sputtering gas used. A MPB PSX-100 KrF excimer laser, with a 248 nm wavelength, was used to define the clusters by laser ablation. 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$^2$. High power densities are crucial for definition of a well-defined laser ablated spot. As dependent upon the material and thickness, a low power density results in only partially defined holes having a greater amount of edge roughness. As is well known, rough edges lend themselves to domain wall pinning, resulting in decreased permeability.$^{4,5}$ The laser beam power density of 7.4 GW/cm$^2$ resulted in a clean-edged, well defined laser ablated hole as seen in Fig. 2, a SEM image of three 23 $\mu$m diam ablated holes. Note that the individual holes are not perfectly symmetrical, presumably due to slight aberrations in the focusing lenses. The laser beam was incident normal to the plane of the sample, with the sample mounted on a motorized translation stage. The samples were processed in air. The coercive force $H_c$ and anisotropy field $H_k$ of the samples were measured using a SHB Model 109 hysteresis loop tracer,$^6$ the 10–500 MHz complex permeability spectra was measured using a thin film permeameter,$^7$ and domain images were obtained using ferrofluid imaging.

Figure 3 shows the complex permeability spectra of an as-deposited film, measured along the hard axis after an easy-axis saturation, and the same film with a triangular cluster array, 275 $\mu$m cluster-to-cluster spacing, defined upon the film using laser ablation. As seen in Fig. 3 with definition of the triangular cluster pattern, corresponding to ablation of $\approx$1.8% of the film, the loss peak has shifted from about 400 to 80 MHz with the magnitude of the loss peak reduced by 50%. As will be shown, at a cluster-to-cluster spacing between 275 and 300 $\mu$m there is a dramatic, nonlinear increase in the number of domain walls propagating between clusters switching the permeability mechanism of the film from rotation to domain wall motion. The domain walls result in a lower loss-peak frequency and a reduced permeabil-

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FIG. 1. Schematic drawing of triangular cluster-array geometry. Cluster-to-cluster spacing is varied from 200 to 600 $\mu$m, intracluster spacing is 37.5 $\mu$m.
ity magnitude. Furthermore, below this threshold upon application of a saturating field along the hard axis the magnetization vector of the film does not return to the easy axis, but rather is pinned by the domain walls in the direction which the field was last applied.\textsuperscript{8–11} No longer do the films demonstrate a clearly defined easy and hard axis, but rather a rotatable anisotropy.

Figure 4 shows, for the triangular cluster array as a function of cluster-to-cluster spacing, the loss-peak frequency, percentage of material removed, and the 10 MHz permeability magnitude $|\mu|$ normalized to the as-deposited value (multiplied by three so as to be included clearly on the same graph). There is a distinct cluster spacing threshold between 275 and 300 $\mu$m, at which the frequency of the $\mu''$ loss peak shifts nonlinearly lower. This occurs although less than 1.5\% of the material has been ablated. Figure 5 presents the same data for the square cluster arrays.

Independently of the cluster arrays, the 10 Hz values of both $H_c$ and $H_k$ of the magnetic thin films remain essentially constant, approximately 1.1 and 3.2 Oe, respectively. We believe that the qualitative difference in behavior between how the permeability spectra changes with pattern density while the quasistatic $BH$ loop properties remain essentially

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**FIG. 2.** SEM image of 23 $\mu$m diam laser ablated hole in 100 nm thick layer of permalloy using power density of 7.4 GW/cm$^2$.

**FIG. 3.** Hard-axis complex permeability spectra of as-deposited NiFe film, measured after an easy-axis saturation, and the same film with a triangular cluster array, 275 $\mu$m cluster-to-cluster spacing, defined upon the film.

**FIG. 4.** Loss-peak frequency, percentage of material removed through ablation, and the 10 MHz permeability magnitude $|\mu|$ normalized to the as-deposited value (multiplied by three so as to be included clearly on the same graph), for the triangular cluster array as a function of cluster-to-cluster spacing.

**FIG. 5.** Loss-peak frequency, percentage of material removed through ablation, and the 10 MHz permeability magnitude $|\mu|$ normalized to the as-deposited value (multiplied by three so as to be included clearly on the same graph), for the square cluster array as a function of cluster-to-cluster spacing.

**FIG. 6.** Number of domain walls surrounding each square or triangular cluster, after an easy-axis saturation, as a function of cluster-to-cluster spacing.
easy or hard axis. In contrast, at cluster-to-cluster spacing \( \approx 275 \) \( \mu m \) the films demonstrate significantly different permeability spectra depending upon whether a saturating magnetic field is first applied to the easy or hard axis. Films first saturated along the easy axis demonstrate a greater number of domain walls and a lower loss peak frequency, as shown, while those first saturated along the hard axis demonstrate fewer domain walls and a loss peak frequency approximately equal to that of the as-deposited film. This film characteristic would enable fabrication of materials with switchable on/off high frequency properties. Figure 7(a) is a schematic drawing of the domain wall structure surrounding a triangular cluster, 275 \( \mu m \) cluster-to-cluster spacing, after a hard axis saturation, while Fig. 7(b) is the domain structure of the same cluster after a easy-axis saturation.

**CONCLUSIONS**

Using laser ablation arrays of triangular and square shaped clusters, comprised of 23 \( \mu m \) diam circular holes, are defined upon 100 nm thick Ni_{81}Fe_{19} films. Cluster-to-cluster spacing is varied from 200 to 600 \( \mu m \), with intracluster nearest-neighbor spacing fixed at 37.5 \( \mu m \). A nonlinear increase in the number of cluster-to-cluster domain walls occurs at cluster-to-cluster spacing between 275 and 300 \( \mu m \). The increased number of domain walls leads to domain wall motion losses, and causes the loss peak frequency to shift in a step-wise fashion from approximately 400 to 80 MHz, with a reduction in the peak magnitude of approximately 50%. Below the switching threshold, the loss peak frequency can be controlled through momentary application of a saturating dc magnetic field along the easy- or hard-axis direction, enabling fabrication of switchable, on/off high frequency waveguides.

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