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Broad-band FMR study of ferromagnetic thin films patterned with antidot lattices

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ABSTRACT

Previous ferromagnetic resonance (FMR) studies of ferromagnetic (FM) thin films patterned with antidot (AD) arrays have generally avoided the low-field, hysteretic regime that is dominated by irreversible domain wall (DW) dynamics in unpatterned films. Moreover, FM vortices have not yet been identified and systematically studied in films patterned with AD lattices (ADLs). We have studied DC magnetization and broad-band FMR data for permalloy thin films of thickness $t \approx 25$ nm, patterned with square lattices of square-shaped AD of width D and separation $d = 1000$ nm. We observe highly reproducible magnetic hysteresis curves and FMR spectra in the low-field reversal regime (i.e., applied magnetic fields $H < H_C$, where H_C is the coercive field), which indicates the ADL enforces a reproducible evolution of spin textures compared to the more random behavior of DW evolution in unpatterned films. The width of the reversal regime ($2H_C$) and the field separation between observed FMR modes increases with D for a fixed separation d. Our micromagnetic simulations suggest these effects are consequences of both edge pinning of moments by individual AD, or DW pinning by the extended ADL, which involves two distinct length scales $L \approx d$ and $L \gg d$, respectively. FM vortices are observed in our simulations, and their stability sensitively depends upon the AD size and applied magnetic field history.

1. Introduction

Ferromagnetic (FM) thin films patterned on a sub-micron length scale have been intensively studied for applications in data storage schemes in which a local magnetization direction (e.g., up/down) corresponds to a binary logic state. A practical patterned film should exhibit both a low magnetic coercive field H_C for easy bit manipulation, and highly reproducible reversal dynamics with stable saturated states for reliable operation. However, FM thin films generally exhibit domain walls (DWs), whose existence and uncontrolled motion can adversely affect device performance [1–3]. In particular, DWs greatly complicate the low-field regime where magnetic reversal takes place, and their control is therefore highly important in IT applications.

Fortunately, FM thin films patterned into sub-micron dot or antidot lattices (ADLs) offer the possibility to control DW stability and pinning [2,3]. ADLs exhibit relatively stable FM order compared to nanoscale dots that are prone to superparamagnetism. On the other hand, FM dots of appropriate thickness and size adopt a remanent state composed of FM vortices (FVs) of positive or negative chirality that are promising candidates for data storage [4]. However, FVs have not yet been systematically studied in films patterned with ADL.

Strong modifications of spin waves and related collective excitations can be induced by sub-micron film patterning, which may facilitate low-power magnetic switching schemes for RAM and disk storage media [5,6]. Moreover, the fundamental interactions that give rise to magnetic excitations and their dispersion relations can be sensitively probed via ferromagnetic resonance (FMR) measurements [1]. Previous FMR studies of periodic lattices of submicron permalloy rings and dots have demonstrated the high sensitivity of their spectra (and potentially magnetic switching) to separation, edge imperfections and small asymmetries of the patterned features [7,8]. FMR data can be accurately modeled via recently developed analytical and numerical simulation methods [9–15]. Nevertheless, existing FMR studies and analyses of mode spectra have concentrated on the higher-field, saturated regime, which is simpler to understand than the device-relevant, low-field regime that is dominated by the hysteretic pinning of (presumably disordered) DWs.

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Here we report DC magnetization and broad-band (BB) FMR data for permalloy thin films of thickness $t \approx 25$ nm, patterned with square lattices of square-shaped antidots (ADs) of width D and separation d. We observe highly reproducible magnetic hysteresis curves and FMR spectra in the low-field reversal regime $H < H_C$ Our micromagnetic simulations show that edge pinning of moments or DWs by ADs strongly enhances the reproducible evolution of spin maps in ADLs compared to unpatterned films. FVs are observed in our simulations depending upon field history, but their stability sensitively depends upon the AD size and orientation with respect to applied magnetic field. This work represents a first step in developing methods to nucleate and systematically control FVs in patterned FM film media extending beyond FM dots.

2. Experimental details

We have used electron beam lithography to pattern square lattices of square ADs of thickness $t = 25$ nm, width $300\ \text{nm} \leqslant D \leqslant 700$ nm, but having the same lattice constant $d = 1000$ nm. ZEP positive resist was spin-coated on a Si wafer prior to electron beam exposure. After exposure and development, a permalloy film was then deposited using electron beam evaporation, with a base pressure of 10^{-7} torr. Final lift-off of resist was done using *N*-Methyl-2-pyrrolidone (NMP). All antidot lattices (ADLs) had a 2×2 mm overall dimension. A representative SEM image of a sample ADL is shown in Fig. 1.

Narrow-band (NB) FMR measurements were carried out at $f = 9.7$ GHz using a Bruker ESP 300E EPR Spectrometer in applied magnetic fields $H \leqslant 10$ kOe. BB FMR measurements were done using a meander line method, a description of which can be found elsewhere [16]. The main advantage of using BB FMR is that the frequency f can be varied continuously up to 20 GHz in our setup. The DC applied magnetic field could be swept continuously through zero in the range +2.5 kOe to −2.5 kOe, and the field direction could be rotated within the film plane, which permits a thorough characterization of many FMR modes in the low-field hysteresis regime. All FMR measurements were done at room temperature. The NB FMR and BB FMR experiments on a given sample were in excellent agreement where they overlap at $f = 9.7$ GHz; and the NB FMR results will therefore not be discussed further. Complementary room-temperature DC magnetization measurements were performed using a Quantum Design MPMS5 SQUID Magnetometer to determine the effects of antidot shape and size on the magnetic coercivity and FM saturation behavior.

Simulations of both the DC magnetization and FMR response were performed using the RKMAG [17] and OOMMF [15] micromagnetic codes. The RKMAG simulations assumed periodic boundary conditions and used a three-dimensional grid size of 20 nm × 20 nm × 25 nm (thickness). The RKMAG simulations were initialized with all dipoles randomly oriented; the field was then swept from +2.5 kOe to −2.5 kOe with a 25-Oe step size. OOMMF simulations employed an 8 × 8 unit cell area of the ADL with Neumann boundary conditions and a three-dimensional grid size of 10 nm × 10 nm × 10 nm, with field steps of 10 Oe between +2.5 kOe and −2.5 kOe.

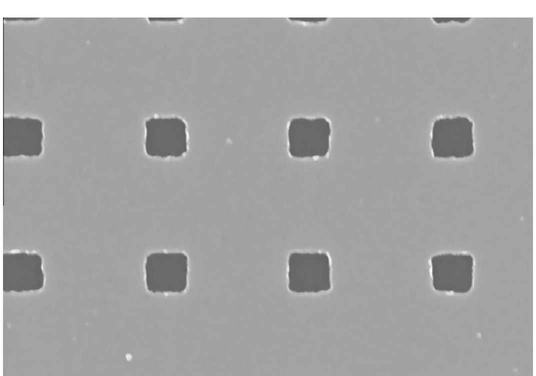

Fig. 1. SEM micrograph of a square array of square antidots with antidot size $D = 300$ nm, separation $d = 1000$ nm, and total dimension 2 mm × 2 mm. The film material is permalloy of $t = 25$ nm thickness.

3. Experimental and simulation results

Fig. 2 shows DC magnetization data for several ADL of different AD widths D, but the same AD spacing $d = 1000$ nm and film thickness $t = 25$ nm. It is apparent that H_C increases monotonically with D, which is in marked contrast to the monotonic ***decrease*** of H_C with D observed by Torres et al. [2] for permalloy ADLs of thickness $t = 40$ nm. Our observed strong increase of H_C with D indicates that longer AD edges and/or higher AD density are more effective in pinning DW in the low-field reversal regime. This tentative conclusion is consistent with the results of both RKMAG and OOMMF simulations of the DC magnetization, as shown in Fig. 3. RKMAG is less successful than the OOMMF code for predicting H_C; this is because periodic boundary conditions (applied by RKMAG) are not consistent with the existence of DW structures with characteristic length scales L that markedly exceed the ADL spacing d.

Figs. 4 and 5 show BB FMR results for a square antidot array with $D = 300$ nm, and $d = 1000$ nm, for microwave frequencies $f = 9$ GHz and 5.25 GHz, respectively. The 9 GHz data represent a largely saturated regime in which we observed three strong modes on both sides of zero applied field, and minimal hysteresis. The highest-field mode has not been previously reported for permalloy ADLs. The field separation between the lower and higher field modes increased from 290 Oe to 1050 Oe (at 9 GHz) in the saturated regime as we increased D from 300 to 700 nm. For $f = 5.25$ GHz, the lowest-field mode moved toward even lower fields and into the magnetic reversal regime where remarkable hysteretic behavior was evident: When the field was swept from positive saturation to negative fields, the lowest-field mode appears at a positive field, but is absent for negative fields; conversely, when field was swept from negative saturation to positive fields, the same mode appears at a symmetric negative field and is

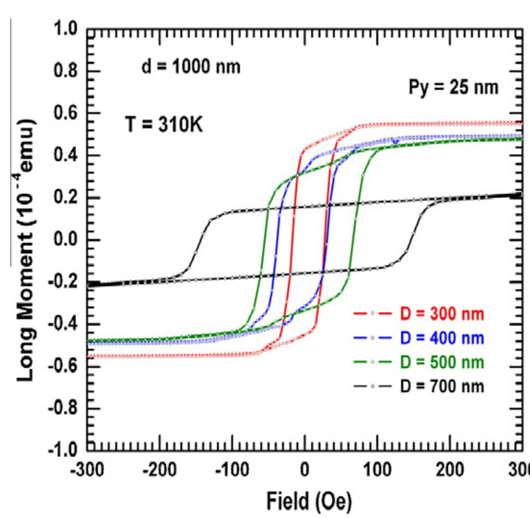

Fig. 2. DC magnetic moment for antidot arrays having separation $d = 1000$ nm and sizes D shown in different colored curves. Note the increasing values of the coercive field for larger values of D. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)