Broadband Magnetic Response of Periodic Arrays of FeNi Dots

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We present a study of magnetization dynamics at room temperature in periodic arrays of 50 nm thick FeNi (Py) circular magnetic dots of 500 nm radius and different center to center distance (1200 and 2500 nm), by using a broadband magnetometer based on Vector Network Analyzer which works between 300 kHz and 8.5 GHz. We also present a comparison between the dynamic response, ferromagnetic resonance (FMR) and its linewidth, with static magnetic characteristics such as magnetization curves. The FMR peak appears just above the nucleation field and is perfectly described by Kittel formula taking into account the demagnetizing factor of an individual magnetic dot. In addition to FMR we observed a spin wave resonance below the uniform mode, which could be attributed to spin waves in confined systems. The FMR linewidth shows a significant broadening close to the field region corresponding to nucleation of magnetic vortex.

***Index Terms*—Magnetic devices, magnetic resonance, nanotechnology.**

I. INTRODUCTION

MAGNETIZATION dynamics in magnetic nanostructures such as thin films, magnetic multilayers, magnetic tunnel junctions and spin valves have attracted much attention due to their technological applications in magnetic random access memories (MRAM) [1] and patterned recording media [2]. During last decade spin dynamics in magnetic dots with different shapes and sizes have been intensively studied theoretically and experimentally. Spatial regularity of arrays of magnetic elements permits the investigation of interdot interactions [3] and collective excitations [4].

Depending on the aspect ratio $\beta = \mathrm{L}/\mathrm{R}$ where L is the thickness and R is the dot radius, the circular element could have in-plane or out-of-plane magnetization [5]. For $\mathrm{L} \ll \mathrm{R}$ all spins trend to align in-plane to minimize both exchange and total dipole energies. Reduction of the dot radius to micrometer or submicrometer length scales induces therefore appearance of a curling spin configuration in the dot and corresponding vortex state formation where spins are aligned out-of-plane close to the vortex core. This core has extension of the order of exchange length $(\mathrm{L}_{\mathrm{ex}})$ which depends on the exchange stiffness A and the saturation magnetization M_{S} as: $\mathrm{L}_{\mathrm{ex}} = (2\mathrm{A}/\mathrm{M}_{\mathrm{S}}^2)^{1/2}$. Presence of such unusual topologic anomaly, the magnetic vortex, is expected to give rise to a rich variety of interesting dynamic properties including excitation of translational, radial (RM) and azimuthal (AM) modes [6].

To study the dipolar interactions in the array of the magnetic dots in the saturated state, it is very important to examine the magnetization dynamics at high frequencies (GHz range) with the sample magnetized in plane. Different experimental techniques have been used to probe high frequency magnetization dynamics in Permalloy dots including Brillouin Light Scattering (BLS) [7] and conventional Ferromagnetic Resonance (FMR) [8]. Theoretical studies of saturated in-plane [9] and out-of-plane [10] dots predict multiresonance eigenmodes. In addition to the uniform Kittel resonance, the lateral confinement of spins within each dot may cause a marked discretization of the spin wave spectrum.

Here, we present broadband magnetization dynamics, both above and below the vortex nucleation field, measured in arrays of magnetic dots with 500 nm radius and 50 nm thickness. These parameters (thickness of about 3 L_{ex} and aspect ratio of about 0.1) ensure vortex configuration in the ground state and uniform magnetization along the dot thickness in the saturated state. In order to investigate possible influence of dipolar coupling we have measured response from the arrays with different center to center (CTC) dots distance: the high density (HD) sample had $\mathrm{CTC} = 1200\ \mathrm{nm}$ and the low density (LD) sample had $\mathrm{CTC} = 2500\ \mathrm{nm}$.

II. EXPERIMENTAL DETAILS

LD and HD arrays of polycrystalline Py dots were fabricated on silicon wafers by using electron beam (EB) lithography and lift-off techniques. A double layered resist spin coating and highly directional EB evaporation were used to obtain circular dots with sharp edges. This technique is very convenient to fabricate arrays of submicron dots with different diameters and periods, within area limited by substrate and with identical properties of magnetic material: grain size, distribution, orientation and film thickness over the whole sample (for more details in sample preparation see [12]). The patterned area has about $3 \times 3\ \mathrm{mm}^2$ with sufficient amount of magnetic material for a good detection of magnetization dynamics of the samples in our experimental set-up.

The measurements of high frequency magnetization dynamics were carried out by using Agilent E5071B Vector Network Analyzer (VNA) working at frequencies up to 8.5 GHz. A VNA-FMR inductive technique was used to determine the FMR frequency and the linewidth. Once the M-H loops were measured, both samples were covered with a thin layer of

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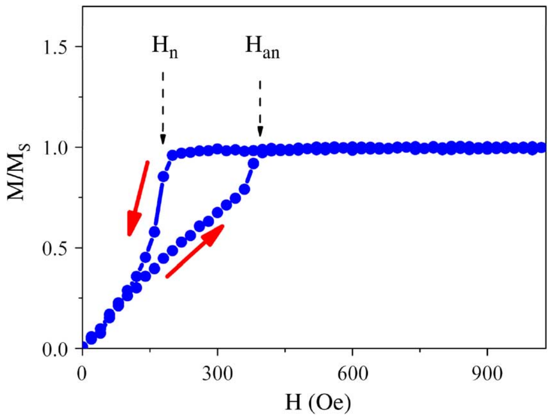

Fig. 1. Magnetization curve for HD sample measured at 300 K. Dashed arrows indicate nucleation and annihilation fields. The direction of the applied magnetic field H is marked by full arrows.

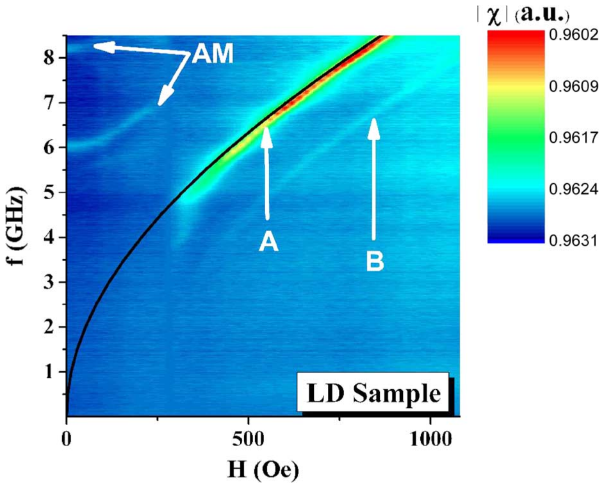

Fig. 2. Three-dimensional (3-D) image of the magnitude of dynamic susceptibility for the LD dot arrays when magnetic field is applied along the $\langle 10 \rangle$ direction. The black line represents theoretical calculations of the uniform mode. Arrows indicate different excited spin waves: (A) uniform mode, (B) magnetostatic backward volume spin wave and (AM) azimuthal modes. On the right hand we show the scale heights in arbitrary units.

photoresist to avoid direct electric contact with a coplanar wave guide (CPW) and were placed face-down on the top of CPW which is situated between the poles of an electromagnet.

The measurements were held by sweeping frequency of an excitation signal provided by the VNA port 1 that runs through a CPW creating RF field component (about 0.2 Oe) in the sample plane perpendicular to in-plane applied magnetic field $(\mathrm{H_{ap}})$. This geometry ensures small precession of the magnetization around the effective field, which is parallel to $\mathrm{H_{ap}}$. In order to evaluate the magnetic susceptibility we have measured transmission signal through the CPW to VNA port 2 and analyzed the data on the basis of transmission model developed by Barry [13] under the assumption that the dominant CPW mode is a transverse electromagnetic one and by neglecting the effect of reflection. We have normalized all the spectra by a reference spectrum taken at saturated state and measured spectra starting from 1100 Oe field where the FMR resonance frequency is located outside our frequency range. The obtained signals are proportional to the real and the imaginary parts of dynamic imaginary susceptibility $\chi = \chi' + i\chi''$. The resonance peak was fitted to a Lorentzian curve to obtain the resonance frequency and the linewidth.

III. RESULTS AND DISCUSSION

Fig. 1 shows the positive branch of the normalized room temperature magnetization curve for HD sample measured by vibrating sample magnetometer (VSM) technique. The magnetization data are in a good agreement with the previously reported results [14], and indicates a vortex formation below nucleation fields $(\mathrm{H_n})$ for both LD and HD samples. Above the annihilation field $(\mathrm{H_{an}})$ vortex is suppressed. The field region between these two fields $(\mathrm{H_n} < \mathrm{H} < \mathrm{H_{an}})$ could be considered as a metastable vortex state.

We start with discussion of the dynamics measurements with magnetic field applied along the $\langle 10 \rangle$ direction (i.e., along dot array axis) for LD and HD samples when the magnetic field ranges from 1100 Oe down to 0 Oe, by using field steps of 20 Oe. Fig. 2 shows the spectra obtained for the LD sample. In both types of dot arrays a well defined uniform mode, Kittel resonance mode, has been observed. In addition to the experimental data, the solid black curve shows theoretical calculations of the uniform mode that takes into account both the demagnetizing factor of an individual dot and the CTC distance (for more details see [11]). In theoretical calculations we used $\mathrm{dot\ radius} = 500\ \mathrm{nm}$, $\mathrm{dot\ thickness} = 50\ \mathrm{nm}$, $\mathrm{M_S} = 830\ \mathrm{Oe}$ and $(\gamma/2\pi) = 2.96\ \mathrm{MHz/Oe}$ (these data were experimentally obtained in [10]). For the magnetic fields below vortex nucleation field $\mathrm{H_n}$ (which is about 300 Oe for LD and of 180 Oe for HD sample) the uniform mode is not observable anymore.

Careful analysis of the 3-D images where we plot magnitude of the susceptibility (see Fig. 2) shows that for the LD sample, in addition to the main FMR uniform mode (A), one can distinguish clearly much weaker resonance (B). This resonance with characteristic frequencies situated below Kittel mode has been observed previously by using BLS technique [15]. The resonance B-mode observed in the present experiments could be interpreted as a magnetostatic backward volume spin wave mode appearing due to quantization of the wave vector q along two directions: direction of the applied field and direction perpendicular to the surface.

Both LD and HD samples show a similar dependence of resonant frequency on magnetic field, but with a shift of both A and B-modes to higher frequencies and a reduced B-mode intensity for the HD sample (not shown). As example we indicate that in the case of A-mode, for a frequency of 6 GHz we observe a shift to the lower magnetic field of about ~30 Oe which corresponds to the one reported previously [11]. In the case of the B-mode the corresponding shift to lower magnetic fields is stronger (~60 Oe), probably due to enhanced influence of the dipolar coupling between the dots on the B-mode, in agreement with similar observation reported before by using BLS technique [16].

Interestingly, previous studies [11] revealed small (<6%) angular dependence of the resonance fields due to a fourfold anisotropy of the in-plane FMR when CTC distance becomes comparable to the dot diameter. In order to investigate this

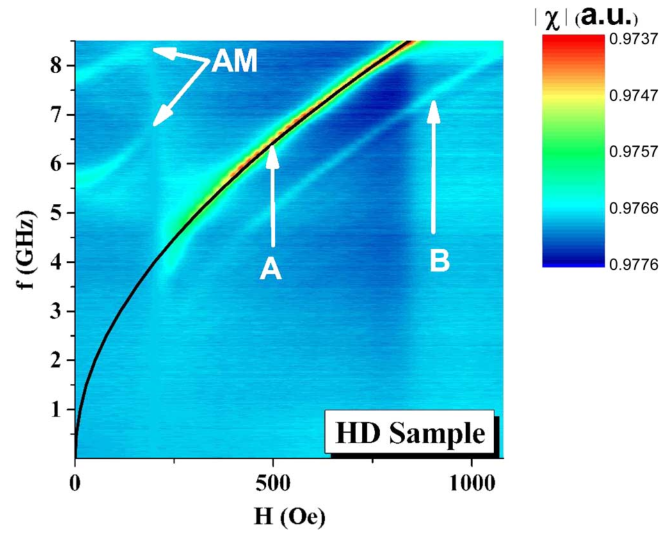

Fig. 3. 3-D plot for the magnitude of the susceptibility for HD sample when magnetic field is applied along $\langle 11\rangle$ direction, with the corresponding theoretical calculation of the uniform mode (black line). The different modes are marked as in Fig. 2.

effect further, dynamics measurements have been carried out for both LD and HD samples when the magnetic field was applied along the $\langle 11\rangle$ (i.e. diagonal) direction. Experimental results along $\langle 11\rangle$ direction show that while for the LD sample the spectra is practically independent of the field direction, the HD sample shows a significant increase of the intensity for the B-mode in the $\langle 11\rangle$ direction compared with $\langle 10\rangle$ direction and the resonance fields shift to lower values, providing further support for previously reported small fourfold magnetic anisotropy in the HD sample [11]. Fig. 3 shows the spectra obtained by HD sample when magnetic field was applied along $\langle 11\rangle$ direction.

In addition to the VNA-FMR data, we have also measured FMR by using the conventional cavity method. Fig. 4 compares derivative of microwave absorption at 10 GHz for HD and LD samples with field along $\langle 10\rangle$ direction. The high amplitude peak corresponds to Kittel resonance (A-mode) and the second smaller peak with much smaller amplitude and marked with arrow, is the spin wave resonance (B-mode) detected at higher fields. Additionally, a third peak at low fields in the spectra could be related to a vortex resonance excitations. The separation between A and B modes is $\sim$270 Oe for HD and $\sim$330 Oe for LD sample. Extrapolation of the VNA-FMR data above 8.5 GHz for both samples at 10 GHz shows separation between A-mode and B-mode of $\sim$280 Oe for HD, and $\sim$315 Oe for LD sample, demonstrating reasonably good agreement between both techniques.

In the magnetic vortex state a few modes have been also detected at high frequency with VNA-FMR. In contrast to the conventional FMR where magnetic field is swept, our technique sweeps frequency at constant magnetic field, so that magnetic field configuration in the dots during the measurements remains constant. This ability makes the VNA-FMR a very convenient technique for the observation of both FMR and magnetic vortex dynamics. It has been previously reported [6] that two kinds of spin wave resonances associated with vortex may appear. The low frequency one, called gyroscopic mode, is typically situated in the range of hundreds of MHz and a high frequency (radial and azimuthal) modes—in the GHz range. We believe that low field modes reflect two split azimuthal modes (AM), reported before for zero field by using pulse technique [17], [18]. Detailed investigation of this splitting including its dependence on the aspect ratio, dipolar interaction and magnetic field will be subject of forthcoming publications.

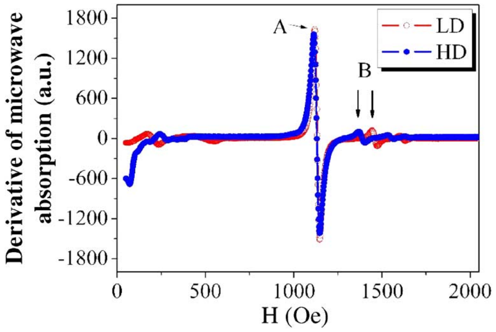

Fig. 4. Conventional FMR measured with magnetic field applied along $\langle 10\rangle$ direction at 10 GHz. The microwave absorption shows two peaks. The main peak correspond to Kittel resonance mode (A) which shows the same values for both samples while low amplitude signals, marked with arrows (B), are different for HD and LD samples. Additionally, a third small peak is detected at low magnetic fields, indicating a vortex resonance excitation.

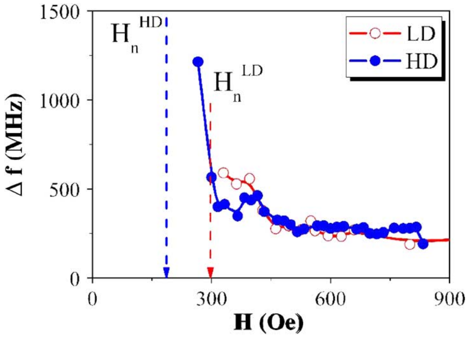

Fig. 5. VNA-FMR linewidth versus magnetic field applied along $\langle 10\rangle$ direction determined for HD and LD samples with magnetic field decreased from the saturated state. Arrows indicate nucleation fields for both samples.

Finally we discuss the VNA-FMR linewidth. Fig. 5 demonstrates the relation between linewidth and applied magnetic field in the $\langle 10\rangle$ direction for the uniform FMR mode with decreasing magnetic field. It is clearly seen that close to the vortex nucleation field $(\mathrm{H_n})$, where the magnetization inhomogeneties in the dots start to grow up, the VNA-FMR linewidths strongly increase. This increase could be explained by proximity to the vortex metastable state with magnetic inhomogeneities appearing in the dot. At the same time, at high in-plane magnetic fields the FMR for both HD and LD samples has nearly constant linewidth with values close to 280 MHz.

In conclusion, by using vector network analyzer based broadband magnetometer we have observed simultaneously qualitatively different types of spin excitations in the arrays of Py dots including uniform Kittel mode, spin waves in confined geometries and vortex state related spin waves. These measurements have been supported by conventional FMR experiments. The ferromagnetic resonance linewidth in the saturated state has been found to increase notably when approaching the vortex nucleation regime. We have observed qualitative difference in the dynamic response between high density and low density Py dot arrays in the saturated state, indicating that magnetization dynamics of individual dots is affected by dipolar coupling between dots when interdot distance is reduced. Finally the angular dependence of the in-plane resonance fields for the LD and the HD samples confirm the presence of a weak ($<6\%$) magnetic anisotropy in the samples [11] when the interdot distance becomes less or comparable to the dot diameter.

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