J Supercond Nov Magn (2015) 28:3587–3591
DOI 10.1007/s10948-015-3178-3

ORIGINAL PAPER

FMR Investigations of Two-dimensional Periodic Arrays of Disc-shaped Co Particles at Different Temperatures

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Received: 14 July 2015 / Accepted: 21 July 2015 / Published online: 21 August 2015

Abstract Using ferromagnetic resonance method, we performed measurements of two-dimensional periodic arrays of disc-shaped cobalt particles with different diameters $a = 450$ and 900 nm and the distance between them $l = 2a$ and $3a$ with temperature variation in the range T = 140−300 K. The first derivative of the microwave absorption spectrum was registered. With the increase of T additional peaks on both sides from the main peak that move aside from it, all peaks show an increase of the intensity and a decrease of the width. Dependences of the resonance field on T shows saturation-like behavior with increasing temperature. They move to higher temperatures and show sharper behavior with a increase and l decrease, respectively. An increase of a leads to the intensity decrease and width increase of all three adsorption peaks.

Keywords Cobalt film · Dipole-dipole interaction · Ferromagnetic resonance (FMR)

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1 Introduction

Structured magnetic films are interesting for their use in magnetic storage, magnetic field sensors, and magnonics. Their magnetic properties can be substantially tailored by the lateral dimensions of the two-dimensional particles and by the distances between them. By varying these parameters, we obtain materials with modified magnetic characteristics. This research has an increasing scientific attention [1–3].

Ferromagnetic resonance (FMR) turns out to be very informative for the study of the mentioned systems. While homogeneous films show a single peak, i.e., a single resonance field, FMR measurements of structured films reveal two additional absorption peaks located on both sides from the main peak. They are referred to as low- and high-field satellites. The explanation of these peaks is based on the consideration of coupled exchange and dipole-dipole interactions [4]. The latter is characterized by anisotropy and long-range interaction. In this paper, we investigate the dispersion relation, the intensity, and the width of the resonance peaks as a function of temperature for different sizes and distances of Co particles.

2 Experimental

A (100)-oriented Si wafer covered with a natural oxide layer was used as a substrate. Thirty-nanometer-thick Co films were deposited on a Ta underlayer of 7 nm in thickness and coated with a Cu protection layer of 3 nm in thickness. Its structuring was performed by means of deep ultraviolet (DUV) photolithography and ion milling. The investigated structures comprise an array of two-dimensional round (disc-shaped) particles with diameters $a = 450$ and 900 nm

and a distance (l) between their centers. Two groups of samples had different ratios: $a{:}l = 1{:}2$ and 1:3. These samples were characterized by atomic force microscopy (AFM) and scanning electron microscopy (SEM). An atomic force microscope (NanoScope IIIa; Veeco, USA) and a scanning electron microscope (JSM 6300; JEOL, Japan) were used (see Fig. 1a, b).

FMR properties of structured ferromagnetic films have been investigated using an EMX 3-cm spectrometer (Bruker, Germany) [5, 6]. For the measurements, the samples were placed in the center of the rectangular TE_{102} cavity of the device. The external magnetic field was directed parallel to the sample plane. The magnetic component of the microwave field was perpendicular to the applied external magnetic field and was directed parallel to the sample plane.

The first derivative of the absorption spectrum was registered using a lock-in technique employing field modulation with a frequency of 100 kHz. A conventional variable nitrogen temperature control Bruker system (ER 4131VT) was used to provide the measurements within the temperature range 100−500 K. The sample temperature was varied in the range T = 140−300 K.

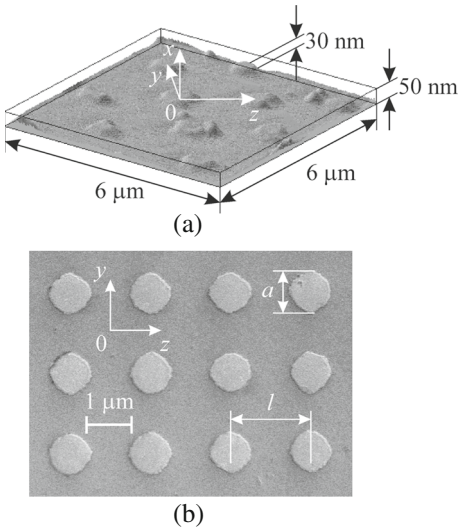

Fig. 1 AFM (**a**) and SEM (**b**) image of a two-dimensional periodic array of disc-shaped Co particles with the height (d) of 30 nm and the size (diameter; a) located in a square lattice with period l. Here, the y-axis and z-axis of the Cartesian coordinate system lay in the sample plane and the x-axis is normal to it. The external magnetic field ($\boldsymbol{H}$) is directed along the z-axis which goes through nearest points of square lattice. The magnetic component of the microwave field is directed along the y-axis

3 Results and Discussion

Series of FMR spectra obtained at different temperatures for continuous and structured Co films are shown in Figs. 2 and 3, respectively. Parameters of the structured film are a = 450 nm (Fig. 3a, b) and a = 900 nm (Fig. 3c, d) and also $a{:}l = 1{:}2$ (Fig. 3a, c) and $a{:}l = 1{:}3$ (Fig. 3b, d). FMR spectra of structured (see Fig. 3a–c) as well as continuous films (see Fig. 2) have a main absorption peak which corresponds to the uniform resonance mode. The resonance field of the main peak is different for continuous and structured films. This fact is associated with the interparticle interactions that results in the changes of the local magnetic field for the disc-shaped cobalt particles as compared to the non-interacting particles or unstructured continuous film [5, 7]. The FMR spectra of two-dimensional particle arrays show additional weak resonance peaks in the low-field area (LFA) and high-field area (HFA) in addition to the main resonance (MA). Measurements performed on structured Co films (Fig. 3a–c) correlate well qualitatively with the experimental results reported previously for permalloy particles located at square lattice points [4, 7]. Micromagnetic simulations show that the satellite peaks in the FMR spectra are associated with coupled exchange and dipole spin-wave modes and one makes a conclusion that the LFA resonance is dominated by exchange interaction, whereas the HFA mode is prevailed by dipole interaction [7]. A change of the distance between the Co particles provokes changes of the resonance field (H_{res}) for all absorption peaks (Fig. 3a–c), indicating a contributing dipole interaction in the LFA and MA modes, too [4, 7].

The resonance condition (resonance frequency) for all detected peaks can be written as $\omega_{\mathrm{res}} = \gamma H_{\mathrm{eff}} = \frac{\gamma}{M \sin\theta}\sqrt{F_{\varphi\varphi}F_{\theta\theta} - F_{\varphi\theta}^2}$ [8], where γ is the gyromagnetic ratio, H_{eff} is the effective magnetic field, $M = |\boldsymbol{M}|$ is the

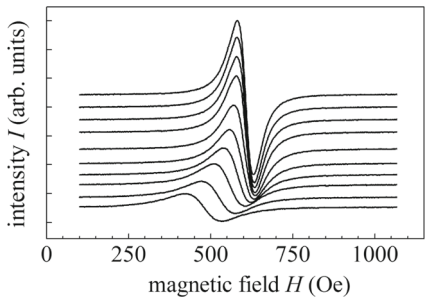

Fig. 2 Temperature series of FMR spectra from the continuous Co film with a thickness of 30 nm. Measurements were performed with decreasing temperature starting from room temperature (293 K) for the *upper curve* and then in steps of 10 K

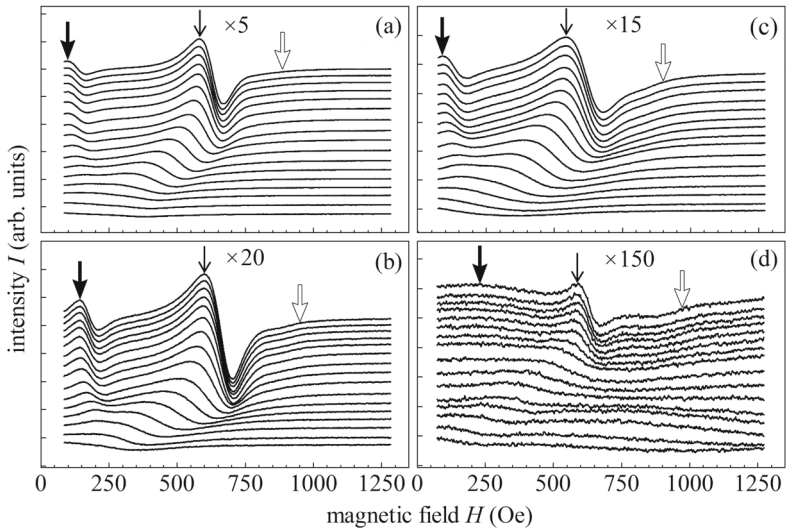

Fig. 3 Temperature series of FMR spectra from structured Co films: $d = 30$ nm, $a = 450$ nm (a, b), and $a = 900$ nm (c, d) and also $a : l = 1 : 2$ (a, c) and $a : l = 1 : 3$ (b, d). The scale of FMR signal intensity in a–c is the same as for Fig. 2. Since the intensity from the FMR spectra is very low, the corresponding spectra were scaled by the indicated factors. The *upper curve* was obtained at room temperature (293 K), and the following measurements were carried out with decreasing temperature in steps of 5 K

magnetization, and $F_{\varphi\varphi}$ and $F_{\theta\theta}$ are the second derivatives of the magnetic free energy density (F) after the spherical coordinates φ and θ (angles of the magnetization ($\boldsymbol{M}$)). The latter can be expressed as a sum of $F = F_{\mathrm{ex}} + F_{\mathrm{an}} + F_{\mathrm{me}} + F_{\mathrm{d}} + F_{\mathrm{Z}}$, where F_{ex} is the energy of exchange interaction, F_{an} is the energy of crystallographic magnetic anisotropy, F_{me} is the energy of magneto-elastic interaction, F_{d} is the energy of the demagnetizing field, and F_{Z} is the energy of interaction between the magnetized sample and the external magnetic field (Zeeman energy). In our measurements, azimuthal (φ) and polar (θ) angles of the magnetization ($\boldsymbol{M}$) are almost equal to 0° and 90°, respectively; as the external magnetic field ($\boldsymbol{H}$) is directed along the z-axis (see Fig. 1), the magnetic component of the microwave field shows along the y-axis within the sample plane. The anisotropy term (F_{an}) that favors the out-of-plane anisotropy due to the (0001) texture of the film (which is the same in our case) decreases with increasing temperature (see Ref. [9]). The same effect is shown also by magnetic anisotropy constants which decrease with increasing temperature [10, 11]. As a result, the resonance field is expected to increase with increasing temperature. This is indeed observed experimentally for mode MA. Figure 3a–c shows changes of the resonance field, the intensity, and the full width at half maximum (FWHM) with temperature for all three modes.

The MA peak can be well described using a Lorentzian line. The comparison of the experimental spectra and the spectra describing the MA peak clearly indicates the presence of additional resonance absorption in lower and higher magnetic fields. The HFA peak is superimposed on the MA peak due to the large width and is registered as a deviation from the baseline.

All three peaks (MA, LFA, and HFA) can be seen in Fig. 3b. With the change of the diameter of disc-shaped Co particles, the distance between the spectra can deform but, qualitatively, should stay the same, i.e., still contain all the three peaks.

The peak-to-peak intensity decreases with decreasing temperature, whereas the width increases for all resonance signals. The resonance field (H_{res}) for the LFA (MA) mode moves to higher (lower) fields at low temperature. The LFA and MA mode frequencies approach towards each other and converge at $T \approx 150$ K. The temperature dependences of the resonance LFA and MA modes show saturation-like behavior for all investigated films (Fig. 4) near room temperature. A decreasing distance (l) between particles leads to a sharper transition from a pronounced increase with temperature (T) to a saturation-like behavior.

The MA mode surpasses by intensity the LFA and HFA modes for all temperatures. The widths of the absorption peaks are equal for structured and continuous films at the same temperature.

The FMR spectra obtained for the sample with $a = 900$ nm and $a{:}l = 1{:}3$ (Fig. 3d) differ from the spectra for the other samples. In this case, the LFA peak is very broad and difficult to identify. The MA peak shows a very low intensity and becomes narrower. On the other hand, the HFA peak is more pronounced. Only this sample gives FMR spectra where a temperature dependence of the resonance field of HFA peak can be seen.

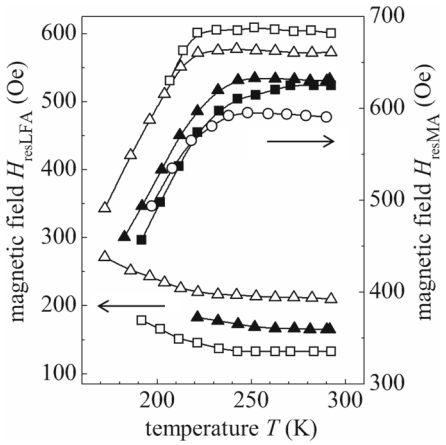

Fig. 4 Temperature dependences of the resonance field of the MA and LFA modes for the continuous film (*empty circle*) and for structured films with $a = 450$ nm (*empty triangle*, *filled triangle*) and $a = 900$ nm (*empty square*, *filled square*) for which the ratios are $a{:}l = 1{:}2$ (*filled triangle*, *filled square*) and $a{:}l = 1{:}3$ (*empty triangle*, *empty square*)

Let us consider in more detail how the shape of a FMR spectrum changes with the variation of one of the structured film parameters. The variation of parameter l with $a = \text{const}$ is equivalent to the change of the particle concentration. A FMR spectrum obtained for α-Fe/C particles in a polymer matrix has shown changes of intensity and width of absorption lines with increasing particle concentration similar to our case. This has been associated with an increase of the magnetic exchange interaction [12]. FMR spectra for Fe-SiO_2 nanoparticle films also have shown an additional resonance signal in low fields, where saturation magnetization is not reached. This field depends on the concentration of magnetic nanoparticles. The latter increases with decreasing temperature due to decreasing concentration of nanoparticles in superparamagnetic state [13]. The same concentration effect has being confirmed in FMR investigations of Co/CoO nanoparticles [14].

Our FMR spectra show that with the increasing distance (l) between the particles from 900 nm (Fig. 3a) to 1350 nm (Fig. 3b) and fixed $a = 450$ nm, a shift to higher fields occurs for all the three absorption peaks. In addition, the position of the main peak for the structured film is shifted closer to the resonance peak position for the continuous film. At the same time, the intensity of the FMR signal decreases for all the three peaks with increasing l. Comparing the intensity of the main peak of the structured Co film with $l = 900$ nm (1350 nm) and the continuous film, one sees it weakening by five (20) times, respectively. The width of all absorption peaks for particles with $a = 450$ nm decreases with decreasing l. Thus, the width of the MA peak approaches the width of the absorption peak of the continuous film. FMR studies of the structured Co film with $a = 900$ nm showed qualitatively similar results, but when $a{:}l$ changes from 1:2 to 1:3, peaks shift to higher field stronger than those for the sample with $a = 450$ nm. Comparing intensities of MA peaks of structured Co films with $a = 900$ nm and $a{:}l = 1{:}2$ (1:3) with the continuous film, one can see the intensity decrease by 20 (250) times, whereas for the samples with $a = 450$ nm, this decrease is an order of magnitude smaller. The width of absorption peaks increases for LFA and HFA and decreases for MA peak with increasing distance l. So, for the structured film with $a = 900$ nm and a large parameter l, the width of the MA peak is close to the width of the absorption peak of the continuous film.

Now, let us consider in more detail a change of the FMR spectra with changing a. The increase of the parameter a from 450 to 900 nm in the case of $a{:}l = 1{:}2$ leads to weakening of the MA peak intensity by a factor of 4, and for the ratio $a{:}l = 1{:}3$, the intensity decreases by a factor of 150. So, after analyzing the size dependences of FMR spectrum, we can identify two structures, for which all the three absorption peaks are most pronounced. Their parameters are $a = 450$ nm and $a{:}l = 1{:}3$ (Fig. 3b) and also $a = 900$ nm and $a{:}l = 1{:}2$ (Fig. 3c).

From the analysis of the spectrum in Fig. 3a–d, one may conclude that for a fixed particle size ($a = \text{const}$) and increasing $a{:}l$, the resonance field (H_{res}) of the MA mode decreases. The position of this peak mainly depends on the local field of the particles which consists of the external magnetic field, the demagnetization field of the particle itself, and the sample stray field. The latter is significantly influenced by the sample structuring, as it changes the magnetic structure. The increase of the dipole-dipole interaction between the particles leads to a gradual decrease of the resonance field (H_{res}) of the MA mode, leading to the inverse proportionality of the H_{res} to the interparticle dipole-dipole interaction (Fig. 5).

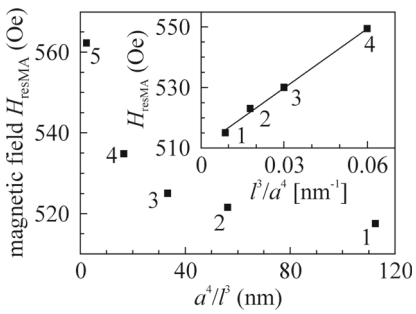

Fig. 5 Resonance field for the MA mode (H_{resMA}) as a function of the $a^4{:}l^3$ ratio that, in fact, characterizes the energy of the dipole-dipole interaction between particles at their constant thickness. The *inset* demonstrates the proportionality of the resonance field (H_{resMA}) to the parameter $l^3{:}a^4$. Here, a and l are equal to *1* 900 and 1800 nm, *2* 450 and 900 nm, *3* 900 and 2700 nm, *4* 450 and 1350 nm, and *5* which corresponds to the continuous Co film

After structuring of the Co film, we obtain new FMR modes. The position and shape of the absorption peaks varies depending on the structuring parameters. The absorption peaks show a strong and different temperature dependence. The absolute value of the resonance field may be subject to external influence such as a modified interface anisotropy due to the lithography process.

4 Conclusions

We investigated FMR spectra of structured Co films with a thickness of 30 nm, varying the size (diameter) of two-dimensional disc-shaped particles ($a = 450$ and 900 nm) and the distance between them ($l = 2a$ and $3a$) within the temperature range $T = 140-300$ K. It was shown that

1. The shape of an FMR spectrum can be effectively controlled. An increase of temperature leads to distancing of LFA and HFA modes from the main MA mode and to an intensity increase and width decrease for all absorption peaks. An increase of a, on contrary, leads to the intensity decrease and the width increase of all the three absorption peaks.
2. The resonance field depends on the temperature because of the temperature-dependent crystallographic magnetic anisotropy.
3. The resonance field of the absorption peaks reaches an apparent saturation with increasing T. The resonance field at which the saturation takes place strongly depends on the parameters of structuring, a and l (increasing a leads to a shift in higher temperature dependence $H_{\mathrm{res}}(T)$, and decreasing l causes a sharper temperature dependence).

Acknowledgments The authors gratefully acknowledge the financial support by the Center of Material and Technology (COMATT).

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