**A comprehensive study of ferromagnetic resonance and structural properties
of iron-rich nickel ferrite ($\text{Ni}_x\text{Fe}_{3-x}\text{O}_4$, $x \leq 1$) films grown by chemical vapor
deposition**

Neha Pachauri,^{1,2} Behrouz Khodadadi,^{1,2} Amit V. Singh,² Jamileh Beik Mohammadi,^{1,2} Richard
L. Martens,³ Patrick R. LeClair,^{1,2} Claudia Mewes,^{1,2} Tim Mewes,^{1,2} and Arunava Gupta²

¹*Department of Physics and Astronomy, The University of Alabama, Tuscaloosa, Alabama 35487,
USA*

²*Center for Materials for Information Technology (MINT), The University of Alabama,
Tuscaloosa, Alabama 35487, USA*

³*Central Analytical Facility (CAF), University of Alabama, Tuscaloosa, Alabama 35487, USA*

Abstract:

We report a detailed study of the structural and ferromagnetic resonance properties of spinel nickel ferrite (NFO) films, grown on (100)-oriented cubic MgAl_2O_4 substrates by direct liquid injection chemical vapor deposition (DLI-CVD) technique. Three different compositions of NFO films ($\text{Ni}_x\text{Fe}_{3-x}\text{O}_4$ where $x=1, 0.8, 0.6$) deposited at optimized growth temperature of 600°C are characterized using X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Vibrating Sample Magnetometry (VSM), and broadband ferromagnetic resonance (FMR) techniques. XRD confirms the growth of epitaxial, single crystalline $\text{Ni}_x\text{Fe}_{3-x}\text{O}_4$ films. The out-of-plane lattice constant (c) obtained for $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ film is slightly higher than the bulk value (0.833 nm), indicating only partial strain relaxation whereas the other two compositions ($x=1$ and $x=0.6$) films exhibit complete relaxation. The in-plane and out-of-plane FMR linewidths measurements at 10 GHz give the lowest values of 458 Oe and 98 Oe, respectively, for $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ film as compared to the other two compositions. A comprehensive frequency (5-40 GHz) and temperature (10-300 K) dependent FMR study of $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ sample for both in-plane and out-of-plane configurations reveals two magnon scattering (TMS) as the dominant in-plane relaxation mechanism. It is observed that the TMS contribution to the FMR linewidth scales with saturation magnetization M_s . In-plane angle-dependent FMR measurements performed on the same sample show that the ferromagnetic resonance field (H_{res}) and the FMR linewidth (ΔH) have four-fold symmetry that is consistent with the crystal symmetry of the spinel. SEM measurements show formation of pyramid-like microstructures at the surface of the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ sample, which can explain the observed four-fold symmetry in the FMR linewidth.

Keywords: Chemical vapor deposition, Nickel ferrite, Ferromagnetic relaxation, Two magnon scattering

The magnetic response of epitaxial single crystalline thin films and bulk crystals of hexagonal and spinel ferrite at microwave frequencies has attracted a lot of research attention in recent years.¹⁻¹⁰ Nickel ferrite (NiFe_2O_4) is an important insulating magnetic spinel ferrite material for microwave device applications exhibiting a high Curie temperature of 585°C , a room temperature saturation magnetization of $\sim 270 \text{ emu/cm}^3$, with low microwave loss and magnetic anisotropy.¹¹⁻¹⁴ The observed properties are closely related to specific growth methods and process conditions, and can be tailored by factors such as surface morphology, microstructure, chemical composition, etc. Thin films of nickel ferrite (NFO) are being explored for potential applications in next generation tunable microwave devices (e.g., electric field tunable filters and phase shifters), monolithic microwave integrated circuits (MMIC) and also as possible candidates for use in spintronic devices. Nickel ferrite has an inverse spinel ($Fd\bar{3}m$) structure with half of the Fe^{3+} cations occupying the tetrahedral A sites, while the remaining Fe^{3+} and Ni^{2+} cations are distributed on the octahedral B sites. The magnetic structure of NFO is well-explained by the Néel model of ferrimagnetism, where a strong superexchange interaction between nearest neighbor A and B sites via oxygen results in anti-parallel alignment of the local magnetic moment of the cations at these sites.

Ferromagnetic resonance (FMR) study on nickel ferrite in either bulk or thin film is an essential aspect to understand the magnetic relaxation mechanism in this material. Since the early 1950's there have been several reports on ferromagnetic resonance properties of bulk single crystal of nickel ferrite.^{13, 15-19} Yager *et al.* reported a temperature-dependent FMR study on spherically shaped single crystals of two different nickel ferrite compositions to explain the relaxation effect using a thermodynamic model.¹⁹ These bulk samples showed an increase in

linewidth for larger iron content NFO samples. Another FMR study on polycrystalline NFO by Torres *et al.* reported very broad FMR linewidths (500-1100 Oe) with no clear frequency or temperature dependence. By varying the Fe composition they observed the lowest linewidth for NiFe_2O_4 sample.²⁰ So far there have been limited reports on the FMR characterization of single crystalline NFO thin films. Li *et al.*⁸ reported a microstructural and ferromagnetic resonance study of NiFe_2O_4 films grown by chemical vapor deposition (CVD), observing FMR linewidths approximately an order of magnitude lower than the pulsed laser deposited films at comparable frequencies.^{8, 17}

We focused on a detailed temperature, frequency and angle dependent ferromagnetic resonance study of different compositions of single crystalline nickel ferrite films deposited by direct liquid injection chemical vapor deposition (DLI-CVD), to understand the dynamic magnetic properties. High quality epitaxial NFO films on MgAl_2O_4 substrates were deposited at three different growth temperatures (500°C, 600°C and 700°C), and were characterized for crystal structure, surface morphology, chemical composition, and static magnetic properties before the detailed FMR measurements.⁸ A deposition temperature of 600°C was found to be optimal to obtain symmetric, single resonance FMR signal, with films grown at other deposition temperatures showing higher FMR linewidths. The vaporizer parameters as well as the flow of precursors were further optimized in the CVD reactor to fabricate and study the properties of NFO films with different compositions ($\text{Ni}_x\text{Fe}_{3-x}\text{O}_4$, where $x = 0.6, 0.8$ and 1). A frequency (5 - 40 GHz) and temperature (10 - 300 K) dependent FMR study was performed for all three compositions in both in-plane and out-of-plane orientations. We obtained the lowest in-plane FMR linewidth values for $x=0.8$ ($\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$) composition at all frequencies. In this paper, we report on comprehensive structural and FMR study of a 700 nm thick $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ film deposited

at 600°C, to identify and quantify the physical relaxation mechanism in the as-grown film on MgAl₂O₄ substrate.

DLI-CVD technique was used to grow epitaxial nickel ferrite films on MgAl₂O₄ (100) substrates at an optimized growth temperature.²¹ Anhydrous metal acetylacetonates (Ni(acac)₂ and Fe(acac)₃) precursors were dissolved in the solvent, N,N-dimethylformamide (DMF). Ultrahigh purity Helium was used to pressurize liquid flow from the solution container to the vaporization system (DLI-200/Brooks instruments) where the vapor was generated at a temperature of 155°C. The flow rate of the liquid was set at 6 g/h and was accurately controlled by a liquid mass flow controller. Argon was used as the carrier gas, which served both as the vaporization medium, as well as the delivery gas. The vaporized mixture was combined with a flow of preheated oxygen gas prior to introduction into the CVD reactor. The deposition was carried out in a low-pressure quartz tube reactor placed in a three-zone furnace. Polished (100)-oriented MgAl₂O₄ substrates (5 mm x 5 mm) with a thickness of 0.5 mm were ultrasonically cleaned sequentially in acetone and isopropanol before being loaded into the deposition chamber and were pumped down to the deposition pressure of 1.7 Torr.

The crystalline structure of the as-deposited films was analyzed using an X-ray diffractometer (Philips X'pert Pro, Cu K α source). Large-angle θ -2 θ scans showed diffraction peaks corresponding to (h00) planes of the substrate and the NFO films (figure not shown). Figure 1(a) shows a partial θ -2 θ plot in the region of (400) peaks of the NFO films (x=0.6, 0.8, 1) and the substrate. The splitting in (400) MAO peak seen is due to Cu K α_1 and K α_2 radiations. NiFe₂O₄ and MgAl₂O₄ have bulk lattice constant values of 0.834 nm and 0.809 nm, respectively, with a lattice mismatch of ~3%.^{22, 23} Using the substrate (400) peak position as the calibration

standard for NFO (400) peak we obtain an out-of-plane lattice constant (c) as 0.836 nm for $x=0.8$ film, slightly higher than the bulk value (0.833 nm), indicating only partial strain relaxation.²³

Figure 1: (a) Partial 2θ - ω scan around (400) peaks of $x=0.6$, 0.8 and 1.0 $\text{Ni}_x\text{Fe}_{3-x}\text{O}_4$ films grown on (100)-oriented MgAl_2O_4 substrate at 600°C . (b) Rocking curve of $x=0.8$ NFO (400) reflection with narrow FWHM= 0.43° , indicating high structural quality of the film, and (c) Φ scan of $x=0.8$ NFO (220) reflection confirming the epitaxial growth and the fourfold symmetry of spinel structure.

For the other two compositions, viz., $x=1$ and $x=0.6$, the value of c is 0.833 nm. Using several off-axis scans we obtain the in-plane lattice constants (a) as 0.833, 0.831 and 0.833 nm for compositions $x=1.0$, 0.8 and 0.6 , respectively. These values suggest that $x=0.8$ NFO film is partially strained whereas the other two compositions are completely relaxed. Rocking curve (ω -

scan) analysis of $x=0.8$ NFO (400) diffraction peak is used to characterize the degree of film texture, as shown in Fig. 1(b). The measured full width at half maximum (FWHM) is 0.43° (FWHM value of the MgAl_2O_4 substrate is $\sim 0.03^\circ$). We examined the in-plane texture from ϕ scan of the NFO (220) reflection. Figure 1(c) shows the ϕ scan results of both the NFO film ($x=0.8$) and MgAl_2O_4 substrate. The four 90° spaced diffraction peaks clearly illustrate the four-fold symmetry of the spinel structure. The coincidence of these four peaks with the (220) peaks from the MgAl_2O_4 substrate confirm cube-on-cube epitaxial growth.

Fig.2: (a) Plan view SEM image of a 700 nm NFO thin film deposited at 600°C on MgAl_2O_4 substrate by DLI-CVD technique, the inset is a magnified view. (b) The same image with higher resolution.

The composition of the NFO thin films was determined by energy dispersive spectrometry (EDS). The film surface roughness was characterized by scanning electron microscopy (SEM). Figures 2(a) and 2(b) show the plan view SEM images for the 700 nm thin NFO film grown on MgAl_2O_4 , which indicate formation of pyramid-like microstructures on the surface of the film, exhibiting four-fold symmetry.

Fig.3: (a) In-plane raw FMR spectra at 10 GHz for the NiFe_2O_4 (x=1) thin film deposited at 500°C (solid red), 600°C (solid black) and 700°C (solid blue), the fitted values of linewidth are 767 Oe, 568 Oe and 899 Oe, respectively. The fits to the experimental data are shown as dotted lines. (b) In-plane raw FMR spectra at 10 GHz for the NiFe_2O_4 (solid red), $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ (solid black) and $\text{Ni}_{0.6}\text{Fe}_{2.4}\text{O}_4$ (solid blue) thin films deposited at 600°C, the fitted values of linewidth are 568 Oe, 458 Oe and 554 Oe, respectively. The fits to the experimental data are shown as dotted lines.

Broadband ferromagnetic resonance (FMR) was used to investigate the magnetization dynamics.²⁴ The derivative of a Lorentzian lineshape having both absorption and dispersion contributions was used to fit the raw FMR spectra to determine the resonance field H_{res} and the peak-to-peak FMR linewidth ΔH .²⁵ The room temperature in-plane FMR spectra at 10 GHz for NiFe_2O_4 ($x=1$) films deposited on MgAl_2O_4 at 500°C, 600°C and 700°C are shown in Fig. 3(a) with FMR linewidth values of 767 Oe, 568 Oe and 899 Oe, respectively. Figure 3(b) shows the room temperature in-plane FMR spectra at 10 GHz for the $\text{Ni}_x\text{Fe}_{3-x}\text{O}_4$ ($x=0.6, 0.8$ and 1.0) films deposited at this optimized growth temperature of 600°C. It is observed that the ferromagnetic resonance plot of $x=0.8$ film is shifted towards left with respect to the $x=1$ film, indicating a possible presence of out-of-plane uniaxial anisotropy, with the film surface being as easy plane, due to compressive strain in the film.^{26,27} This is confirmed by a comparative increase in the out-of-plane lattice constant ($c=0.836$ nm) from its bulk value (0.833 nm). The other two compositions show complete relaxation ($c=0.833$ nm). It is noteworthy that the substrate imparts an in-plane compressive stress on the films. We find that $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ ($x=0.8$) film deposited at 600°C has the lowest FMR linewidth at 10 GHz (458 Oe) as compared to the other two compositions (568 Oe for $x=1$ and 554 Oe for $x=0.6$). This is true for other frequencies, as well (data not shown). The lowest reported value in literature is ~750 Oe for NiFe_2O_4 films in the in-plane geometry at the same frequency.⁸ It is important to mention that in all of these films the FMR linewidths are largely influenced by extrinsic contributions such as inhomogeneities and various defects present in the film, therefore it is difficult to draw any systematic correlation between the composition (e.g., $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio) and intrinsic linewidth or damping in the NFO films.

Figure 4: Out-of-plane raw FMR spectrum at 10 GHz for the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ thin film deposited at 600°C. Three resonance peaks are observed, the two additional signals are most likely standing spin wave modes. While the middle signal is assumed to be the FMR mode ($\Delta H=98$ Oe), the temperature and frequency dependence of the FMR linewidth is similar for all the three signals.

The out-of-plane FMR spectra for all the samples show a multiple-line resonance pattern. Figure 4 shows a three resonance peak out-of-plane spectrum observed for the 600°C deposited $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ sample at 10 GHz with linewidth values varying between 98 Oe to 140 Oe, which are less than the reported lowest value of 160 Oe.⁸ The separation between the three modes along the field axis decreases with decreasing frequency, therefore the formation of the multiple peaks in the out-of-plane geometry can likely be attributed to sample inhomogeneities that result in local variations of the internal field. The experimental data that corresponds to the signal with the largest absorption amplitude (in Fig. 4) and of linewidth 98 Oe, is considered as the out-of-plane FMR mode.

Figure 5: In-plane Kittel plots (resonance frequency as a function of resonance field) at different temperatures. It is difficult to distinguish the experimental data at different temperatures as the changes in the resonance field with temperature are very small. The red and blue dashed-lines are the exemplary Kittel fits to the experimental data at 300K and 10K.

Broadband FMR measurements were carried out as a function of temperature down to 10K for both in-plane and out-of-plane geometries for all three NFO films grown at optimized growth temperature of 600°C. However, in the following discussion, we only report the temperature- and angle-dependent FMR results of the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ sample as this composition has the lowest linewidth values. The in-plane H_{res} data were fitted using the well-known Kittel formula to determine the effective magnetization M_{eff} at each temperature²⁸

$$f = \gamma' \sqrt{(H_{\text{res}} - H_{\text{ip},4})(H_{\text{res}} - H_{\text{ip},4} + 4\pi M_{\text{eff}})} \quad (1)$$

where gyromagnetic ratio γ' and effective magnetization M_{eff} are the fit parameters. $H_{ip,4}$ indicates the magnitude of the in-plane four-fold anisotropy. The in-plane broadband measurements were carried out along the magnetic hard axes. The effective magnetization (M_{eff}) is defined²⁸ as the sum of the demagnetization field ($4\pi M_s$) and the uniaxial magnetic anisotropy field ($\frac{2K_u}{M_s}$)

$$4\pi M_{\text{eff}} = 4\pi M_s + \frac{2K_u}{M_s} \quad (2)$$

Figure 5 shows the in-plane frequency dependent H_{res} data at different temperatures and also the exemplary in-plane Kittel fits (equation 1) to the experimental data at 300K and 10K. A comparison of the temperature dependence (300-10K) of the effective magnetization (M_{eff}) and the saturation magnetization M_s obtained from FMR and VSM measurements, respectively, is shown in Fig. 6.

Figure 6: Temperature dependence of M_{eff} (blue squares) and M_s (red squares) obtained from broadband FMR and VSM measurements, respectively. Typical error bars are shown for the determined values at 50K.

The difference observed between the experimental values of M_{eff} and M_s imply that the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ film most likely has a small negative perpendicular magnetic anisotropy (K_u). This means that the magnetization tends to stay in the plane of the film due to a possible compressive strain, which is consistent with the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ film having larger out-of-plane lattice constant compared to the other two compositions ($x=1$ and $x=0.6$). However, making a quantitative comparison is difficult because of the error margins in the experimental determination of M_s and M_{eff} due to uncertainties in determining (i) the effective volume of the NFO thin film (M_s) and (ii) the in-plane magnetic anisotropy (M_{eff}).

Figure 7: (a) Broadband temperature-dependent in-plane FMR linewidth measured along in-plane hard axis ([010] crystallographic direction) for the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ thin film deposited at 600°C . (b) Broadband temperature-dependent out-of-plane FMR linewidth for the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ thin film deposited at 600°C .

The frequency-dependent FMR linewidths in the out-of-plane orientation are significantly narrower as compared to the in-plane values at all temperatures, as shown in Figs. 7(a,b). This is expected for thin films as two magnon scattering contributes significantly only to the linewidth

in the in-plane configuration and not to the out-of-plane linewidth.²⁹⁻³⁴ Detailed in-plane angle-dependent FMR measurements have been carried out to further investigate the symmetry of the magnetic anisotropy and ferromagnetic relaxation. As shown in Fig. 8(a), the ferromagnetic resonance field (H_{res}) exhibits four-fold in-plane symmetry. More interestingly the FMR linewidth also shows a four-fold in-plane symmetry as shown in Fig. 8(b). A similar four-fold symmetry in the in-plane FMR linewidth has also been reported recently for epitaxial nickel zinc ferrite thin film.³⁵

Figure 8: (a) In-plane four-fold magnetic anisotropy shown by the in-plane angular dependency of H_{res} at 40 GHz. (b) Four-fold symmetry in FMR linewidth at 40 GHz, in-plane angle of 45° is equivalent to the [011] crystallographic direction. Data corresponds to the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ thin film deposited at 600°C.

The behavior of the FMR linewidth in the detailed temperature, frequency and angle dependent observations can be explained by the characteristics of the extrinsic two magnon scattering (TMS) relaxation mechanism.^{29,30} According to this theory, inhomogeneities in the magnetic properties can couple the uniform precession mode magnon (with $k = 0$) to another magnon with $k \neq 0$. The dispersion relation for magnons in thin films causes the TMS relaxation mechanism to be absent in the out-of-plane FMR geometry. This is consistent with our results, as the out-of-plane linewidth has a lower value compared to its in-plane counterpart at all frequencies in the temperature-dependent data shown in Figs. 7(a,b). The inhomogeneities or scattering centers causing the TMS relaxation can result from different sources, such as pores, voids, surface roughness, misfit dislocations or a combination of some of these defect microstructures.³¹⁻³⁴

The theory developed by Slater, Loudon and Kittel (SLK)^{32, 36, 37} predicts that the TMS contribution to the FMR linewidth scales with M_s . This is consistent with the observed in-plane FMR linewidth increase with decreasing temperature as shown in Fig. 7(a) and the increase of M_s and M_{eff} in the VSM and FMR measurements (Fig. 6). In contrast to this, the linewidth data for out-of-plane measurements shows significantly less variation with temperature than the in-plane data, as seen in Fig. 7(b). Furthermore, the linewidth in this case tends to decrease with decreasing temperature. The frequency dependence of the TMS contribution to the in-plane FMR linewidth based on random distribution of surface roughness defects have been studied earlier by Lenz *et al.*³⁸ and Arias *et al.*³⁹ However, prior work on periodically perturbed films, both experimentally⁴⁰ and theoretically,⁴¹ indicate the presence of peaks in the frequency dependence of the linewidth. While no clear periodicity of the pyramid shaped features was found in our samples, these features are of similar size, which could cause the observed broad shoulder in the

frequency dependence of linewidth.

The four-fold symmetry of the pyramid-like microstructures observed on the surface of the $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ sample deposited by DLI-CVD should, however, lead to an anisotropic TMS contribution to the linewidth. This explains the observed four-fold symmetry of FMR linewidth seen in Fig. 8(b). A similar reasoning has also been used to relate the anisotropic extrinsic ferromagnetic relaxation to the symmetry breaking on the TMS potential caused by the network of misfit dislocations³⁴ or exchange bias coupling.⁴² It is noteworthy to mention that there is also a linewidth broadening due to field dragging effect caused by the small misalignment between the external magnetic field and the magnetization vectors.^{38, 43, 44} However, our numerical simulations based on the experimentally determined FMR properties show that the misalignment angle in our case is very small and its influence on the in-plane dependence of the linewidth is negligible. Furthermore, the symmetry of the field drag contribution to the linewidth is eight-fold for a film with an in-plane four-fold magnetocrystalline anisotropy.

In summary, epitaxial growth of nickel ferrite films on MgAl_2O_4 (100) substrates with lowest FMR linewidth has been achieved by optimizing the DLI-CVD deposition parameters for a $\text{Ni}_{0.8}\text{Fe}_{2.2}\text{O}_4$ film. Frequency and temperature-dependent FMR measurements indicate two-magnon scattering as the prominent relaxation mechanism in these films. In-plane angle-dependent FMR measurements also exhibit a four-fold symmetry for both the magnetic anisotropy and ferromagnetic relaxation. The anisotropic ferromagnetic relaxation measured by FMR linewidth can be explained based on the anisotropic interface roughness and two magnon scattering relaxation.

ACKNOWLEDGMENTS

This work has been supported by NSF Grant No. ECCS-1509875. Tim Mewes and Behrouz Khodadadi would like to acknowledge support by NSF-CAREER Award No. 0952929.

REFERENCES

1. Y.-Y. Song, S. Kalarickal and C. E. Patton, Journal of Applied Physics **94**, 5103 (2003).
2. Z. Wang, Y.-Y. Song, Y. Sun, J. Bevivino, M. Wu, V. Veerakumar, T. J. Fal and R. E. Camley, Applied Physics Letters **97**, 072509 (2010).
3. J. Jalli, Y.-K. Hong, S. Bae, J.-J. Lee, G. S. Abo, J.-H. Park, B.-C. Choi, T. Mewes, S.-G. Kim, S.-H. Gee, I.-T. Nam and T. Tanaka, Journal of Applied Physics **109**, 07A509 (2011).
4. Y. Nie, I. Harward, K. Balin, A. Beaubien and Z. Celinski, Journal of Applied Physics **107**, 073903 (2010).
5. Y.-Y. Song, J. Das, P. Krivosik, N. Mo and C. E. Patton, Applied Physics Letters **94**, 182505 (2009).
6. T. Kato, H. Mikami and S. Noguchi, Journal of Applied Physics **110**, 123901 (2011).
7. J. Jalli, Y.-K. Hong, S.-H. Gee, S. Bae, J. Lee, J. C. Sur, G. S. Abo, A. Lyle, S.-I. Lee, H. Lee and T. Mewes, IEEE Transactions on Magnetics **44**, 2978 (2008).
8. N. Li, S. Schaefer, R. Datta, T. Mewes, T. M. Klein and A. Gupta, Applied Physics Letters **101**, 132409 (2012).
9. N. Li, M. Liu, Z. Zhou, N. X. Sun, D. V. B. Murthy, G. Srinivasan, T. M. Klein, V. M. Petrov and A. Gupta, Applied Physics Letters **99**, 192502 (2011).

10. N. Pachauri, B. Khodadadi, M. Althammer, A. V. Singh, B. Loukya, R. Datta, M. Iliev, L. Bezmaternykh, I. Gudim, T. Mewes and A. Gupta, Journal of Applied Physics **117**, 233907 (2015).
11. V. G. Harris, A. Geiler, Y. Chen, S. D. Yoon, M. Wu, A. Yang, Z. Chen, P. He, P. V. Parimi, X. Zuo, C. E. Patton, M. Abe, O. Acher and C. Vittoria, Journal of Magnetism and Magnetic Materials **321**, 2035 (2009).
12. C. N. Chinnasamy, A. Narayanasamy, N. Ponpandian, K. Chattopadhyay, K. Shinoda, B. Jeyadevan, K. Tohji, K. Nakatsuka, T. Furubayashi and I. Nakatani, Physical Review B **63**, 184108 (2001).
13. W. A. Yager, J. K. Galt, F. R. Merritt and E. A. Wood, Physical Review **80**, 744 (1950).
14. G. Nabiyouni, M. J. Fesharaki, M. Mozafari and J. Amighian, Chinese Physics Letters **27**, 4 (2010).
15. H. Schröder and E. Glauche, Journal of Applied Physics **39**, 1155 (1968).
16. L. Torres, M. Zazo, J. Iniguez, C. de Francisco and J. M. Munoz, Magnetics, IEEE Transactions on Magnetics **29**, 3434 (1993).
17. C. N. Chinnasamy, S. D. Yoon, A. Yang, A. Baraskar, C. Vittoria and V. G. Harris, Journal of Applied Physics **101**, 09M517 (2007).
18. D. W. Healy, Physical Review **86**, 1009 (1952).
19. W. A. Yager, J. K. Galt and F. R. Merritt, Physical Review **99**, 1203 (1955).
20. L. Torres, M. Zazo, A. G. Flores, V. Raposo and J. Iñiguez, Journal of Applied Physics **79**, 5422 (1996).
21. N. Li, Y. H. A. Wang, M. N. Iliev, T. M. Klein and A. Gupta, Chemical Vapor Deposition **17**, 261 (2011).

22. T. Ito, A. Yoshiasa, T. Yamanaka, A. Nakatsuka and H. Maekawa, *Zeitschrift Fur Anorganische Und Allgemeine Chemie* **626**, 42 (2000).
23. J. M. Hastings and L. M. Corliss, *Reviews of Modern Physics* **25**, 114 (1953).
24. S. Keshavarz, Y. L. Xu, S. Hrady, C. Lemley, T. Mewes and Y. P. Bao, *Ieee Transactions on Magnetism* **46**, 1541 (2010).
25. C. J. Oates, F. Y. Ogrin, S. L. Lee, P. C. Riedi, G. M. Smith and T. Thomson, *Journal of Applied Physics* **91**, 1417 (2002).
26. J. Macháčková, *Physica Status Solidi (b)* **26** (2), 435 (1968).
27. A. B. Smith and R. V. Jones, *Journal of Applied Physics* **37**, 1001 (1966).
28. A. Natarajarathinam, Z. R. Tadisina, T. Mewes, S. Watts, E. Chen and S. Gupta, *Journal of Applied Physics* **112**, 053909 (2012).
29. C. E. Patton, C. H. Wilts and F. B. Humphrey, *Journal of Applied Physics* **38**, 1358 (1967).
30. P. Landeros, R. E. Arias and D. L. Mills, *Physical Review B* **77**, 214405 (2008).
31. H. Lee, Y.-H. A. Wang, C. K. A. Mewes, W. H. Butler, T. Mewes, S. Maat, B. York, M. J. Carey and J. R. Childress, *Applied Physics Letters* **95**, 082502 (2009).
32. R. D. McMichael, M. D. Stiles, P. J. Chen and W. F. Egelhoff, *Journal of Applied Physics* **83**, 7037 (1998).
33. M. J. Hurben and C. E. Patton, *Journal of Applied Physics* **83**, 4344 (1998).
34. G. Woltersdorf and B. Heinrich, *Physical Review B* **69**, 184417 (2004).
35. Debansu Roy, S. Sakshath, Geetanjali Singh, Rajeev Joshi, S. V. B. and P. S. A. Kumar, *Journal of Physics D: Applied Physics* **48**, 125004 (2015).
36. M. Sparks, R. Loudon and C. Kittel, *Physical Review* **122**, 791 (1961).

37. A. K. Srivastava, M. J. Hurben, M. A. Wittenauer, P. Kabos, C. E. Patton, R. Ramesh, P. C. Dorsey and D. B. Chrisey, *Journal of Applied Physics* **85**, 7838 (1999).
38. K. Lenz, H. Wende, W. Kuch, K. Baberschke, K. Nagy and A. Jánossy, *Physical Review B* **73**, 144424 (2006).
39. R. Arias and D. L. Mills, *Physical Review B* **60**, 7395 (1999).
40. M. Körner, K. Lenz, R. A. Gallardo, M. Fritzsche, A. Mücklich, S. Facsko, J. Lindner, P. Landeros and J. Fassbender, *Physical Review B* **88**, 054405 (2013).
41. P. Landeros and D. L. Mills, *Physical Review B* **85**, 054424 (2012).
42. T. Mewes, R. L. Stamps, H. Lee, E. Edwards, M. Bradford, C. K. A. Mewes, Z. Tadisina and S. Gupta, *Magnetics Letters, IEEE* **1**, 3500204 (2010).
43. J. Dubowik, K. Załęski, H. Głowiński and I. Gościańska, *Physical Review B* **84**, 184438 (2011).
44. K. Zakeri, J. Lindner, I. Barsukov, R. Meckenstock, M. Farle, U. von Hörsten, H. Wende, W. Keune, J. Rocker, S. S. Kalarickal, K. Lenz, W. Kuch, K. Baberschke and Z. Frait, *Physical Review B* **76**, 104416 (2007).