Sub-micrometer yttrium iron garnet LPE films with low ferromagnetic resonance losses

Carsten Dubs1, Oleksii Surzhenko1, Ralf Linke1, Andreas Danilewsky2, Uwe Brückner3 and Jan Dellith3

1 INNOVENT e.V., Technologieentwicklung, Prüssingstr. 27B, 07745 Jena, Germany
2 Kristallographie, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 5, 79104 Freiburg, Germany
3 Leibniz-Institut für Photonische Technologien (IPHT), Albert-Einstein-Str. 9, 07745 Jena, Germany

E-mail: cd@innovent-jena.de

Received 10 January 2017, revised 31 March 2017
Accepted for publication 4 April 2017
Published 28 April 2017

Abstract
Using a liquid phase epitaxy (LPE) technique (1 1 1) yttrium iron garnet (YIG) films with thicknesses of ≈100 nm and surface roughnesses as low as 0.3 nm have been grown on (1 1 1) gadolinium gallium garnet (GGG) substrates as a basic material for spin-wave propagation experiments in microstructured waveguides. The continuously strained films exhibit nearly perfect crystallinity without significant mosaicity and with effective lattice misfits of ∆a/a ≈ 10−4 and below. The film/substrate interface is extremely sharp without broad interdiffusion layer formation. All LPE films exhibit a nearly bulk-like saturation magnetization of (1800 ± 20) Gs and an ‘easy cone’ anisotropy type with extremely small in-plane coercive fields <0.2 Oe. There is a rather weak in-plane magnetic anisotropy with a pronounced six-fold symmetry observed for the saturation field <1.5 Oe. No significant out-of-plane anisotropy is observed, but a weak dependence of the effective magnetization on the lattice misfit is detected. The narrowest ferromagnetic resonance linewidth is determined to be 1.4 Oe @ 6.5 GHz which is the lowest value reported so far for YIG films of 100 nm thicknesses and below. The Gilbert damping coefficient for investigated LPE films is estimated to be close to 1 × 10−4.

Keywords: material for magnon spintronics, thin-film insulator, spin-wave damping, yttrium iron garnet, liquid phase epitaxial films, submicrometer YIG films
(Some figures may appear in colour only in the online journal)

1. Introduction

Magnonics is an increasingly growing new branch of spin-wave physics, specifically addressing the use of magnons for information transport and processing [1–4]. Single crystalline yttrium iron garnet (YIG), which is a ferrimagnetic insulator with the smallest known magnetic relaxation parameter [5], appears to be a superior candidate for this purpose [6–8]. As bulk or as a thick film material, which is commonly grown by liquid phase epitaxy (LPE) [9], it has a very low damping coefficient and allows magnons to propagate over distances exceeding several centimeters [6]. However YIG functional layers for practical magnonics should be nanometer-thin with extremely smooth surfaces in order to achieve optimum efficiency in data processing and a dramatic reduction in energy consumption of sophisticated spin-wave devices. Therefore, high-quality thin and ultra-thin YIG films were grown using different growth techniques, such as LPE [10–13], pulsed
2. Samples and experimental details

2.1. Sample fabrication

YIG films were grown from PbO–B$_2$O$_3$ based high-temperature solutions resistively-heated in a platinum crucible at about 900 °C using a standard dipping LPE technique. During different growth runs, nominally pure YIG films were grown on one-inch (111) gadolinium gallium garnet (GGG) substrates to check the reproducibility of the sub-micrometer liquid phase epitaxial growth. For La substituted films La$_2$O$_3$ was added to the already used high-temperature solution. To remove the solution remnants from the sample surfaces, the holder had to be stored in a hot acidic solution after room temperature cooling. Afterwards the reverse side layer was removed by mechanical polishing from the double-side grown samples. Chips of different sizes were prepared by a diamond wire saw and sample surfaces were cleaned using ethanol, distilled water and acetone. The LPE film thickness was determined by x-ray reflectometry using a PANanalytical/X-Pert pro system.

2.2. Microstructural properties

The root-mean-square surface roughness was determined by AFM measurements for each sample at three different regions over 25 µm$^2$ ranges using a park scientific instrument, M5. HR-XRD studies were performed by a five-crystal diffraction spectrometer of Seifert (3003 PTS HR) equipped with a four-fold Ge 440 asymmetric monochromator using CuK$_\alpha$ radiation. The resolution limit was 1 × 10$^{-4}$ deg. GGG substrate lattice parameters were obtained by the Bond method. Depth profile analyses were carried out by an axis ultra DLD XPS system (Kratos Analytical Ltd.) using a mono-atomic argon-ion etching technique. Qualitative SIMS (hiden analytical) measurements were carried out. Here, a film area of 500 × 500 µm$^2$ is irradiated by 5 keV oxygen ions.

2.3. Magnetic properties

The vibrating sample magnetometer (MicroSense LLC, EZ-9) was used to register the in-plane hysteresis loops of the YIG/GGG samples at room temperature. The external

| Growth method (reference) | Thickness (nm) | RMS-roughness (nm) | 4πM$^a$ (kGs) | $H_a$ (Oe) | $\Delta H^b$ FWHM (Oe) | $f_0$ (GHz) | $\Delta H^c$ FWHM (Oe) | $\alpha \times 10^{-4}$ |
|--------------------------|----------------|-------------------|---------------|------------|---------------------|------------|---------------------|----------------|
| LPE [12]                 | 100            | —                 | 1.81          | —          | 3.0                 | 7          | 1.6                 | 2.8           |
| LPE (this study)         | 83–113         | 0.3–0.8           | 1.78–1.82     | ≤0.2       | 1.4–1.6             | 6.5        | 0.5–0.7             | 1.2–1.7       |
| PLD$^a$ [14]             | 79             | 0.2               | 1.72          | <2         | 3.0                 | 10         | 1.4                 | 2.2           |
| PLD [15]                 | 23             | —                 | 1.60          | <1         | 3.5$^c$             | 9.6        | 3.5–7$^c$           | 2–4           |
| Sputtering [20]          | 22             | 0.13              | 1.78          | 0.4        | 12$^c$              | 16.5       | 6.4$^c$             | 0.9           |
| Sputtering [21]          | 20             | 0.2               | —             | 0.4        | 13$^c$              | 9.7        | 7$^c$               | 8             |
| PLD [16]                 | 20             | 0.2–0.3           | 2.10          | 0.2        | 3.3$^c$             | 6          | 2.4$^c$             | 2.3           |

$^a$ Measurements at room temperature with the in-plane external magnetic field H;

$^b$ YIG films grown on the (100) GGG substrates;

$^c$ Peak-to-peak value $\Delta H_{p-p}$ of the derivative of FMR absorption transformed into $\Delta H_{\text{FWHM}} = \Delta H_{p-p} \times \sqrt{3}$.
magnetic field $H$ was controlled with an error of $\leq 0.01$ Oe. To estimate the magnetization of the YIG films, we removed a contribution of the GGG substrates from the total VSM signal. To monitor the in-plane anisotropy as a function of the crystallographic orientation, the hysteresis loops at the azimuthal angles $\phi = 0^\circ$ to $360^\circ$ were measured with an angular step of $3^\circ$. The FMR absorption spectra were registered with a vector network analyzer (Rohde & Schwarz GmbH, ZV A 67) attached to a broadband stripline. The sample was disposed face-down over a stripline and the transmission signals ($S_{21}$ & $S_{12}$) were recorded. During the measurements, a frequency of microwave signals with the input power of $-10$ dBm (0.1 mW) was swept across the resonance frequency, while the in-plane magnetic field $H$ was constant and measured with an accuracy of 1 Oe. Each recorded spectrum was fitted by the Lorentz function and allowed us to define the resonance frequency and the FMR linewidth $\Delta H_{\text{FWHM}}$ corresponding to the applied field $H$.

### 3. Results

#### 3.1. Microstructural properties

Selected microstructural and magnetic properties of liquid phase epitaxial grown YIG (sample A–C) and La:YIG (sample D) films are given in table 2. The consistent magnetic, as well as microwave, properties obtained for films deposited during different growth runs demonstrate a high reproducibility of the LPE growth technique. XRR measurements of these films show thicknesses of about 100 nm, which are smaller than the previously reported thinnest LPE YIG films [10, 11, 13]. The smallest root-mean-square (RMS) surface roughness of about 0.25 nm obtained for the sample B is nearly comparable with the epi-polished GGG substrate quality of $\approx 0.15$ nm and with the best PLD and sputtered YIG films (see e.g. table 1).

Besides, films with slightly rougher surfaces (see table 2) were obtained as a result of additional dendritic aftergrowth and/or due to plateau formation, so called ‘mesas’, if any solution droplet adhered to the sample surface.

HR-XRD studies of our thin epitaxial LPE films have been found to be difficult because of the nearly super-imposed diffraction pattern of the YIG film and GGG substrate. Although the angle distances between the film and substrate Bragg reflections were above the resolution limit of our HR-XRD equipment, the diffraction intensity of the film reflection was very low and results only in a broadening of the GGG Bragg reflection. Figure 1(a) shows a $\omega$-scan (rocking curve) with a Gaussian-like fitted GGG substrate 4 4 4 reflection and a second fitted peak at the right shoulder, which corresponds to the YIG 4 4 4 film reflection. This indicates a tensile stressed YIG film because of the smaller film lattice parameter.
compared to the commercially available Czochralski-grown GGG substrate ($a_s = 1.2382$ nm). For La:YIG films, we observed a perfect pseudo-Voigt fitted substrate peak without any additional shoulder (not shown) which indicates a perfect lattice match between the substrate and LPE film. This is in remarkable contrast to the YIG films deposited by various gas phase techniques, such as PLD and rf-sputtering [15, 16, 20, 21, 24, 25] on GGG substrates. For those films, the YIG reflection has always been detected at considerably lower Bragg angles compared to the GGG substrate, indicating a significant distortion of the cubic YIG garnet cell with remarkably enlarged lattice parameters (compressive stress) [24, 26].

The relative effective misfit $\Delta a/a = (a_s - a_YIG)/a_s$ obtained from the strained film lattice parameter in the growth direction $a_YIG$ and the substrate lattice parameter $a_s$ can be used as a measure for epitaxial induced in-plane tension or strain. Due to YIG Poisson’s ratio of $\nu = 0.29$ pseudomorphically grown, fully strained YIG films with an ideal YIG$_{bulk}$ lattice parameter $a_{YIG} = 1.2375$ nm [27] should have a relative effective misfit of $\Delta a/a_s = +1 \times 10^{-4}$ (tensile stress). In the case of our sub-micrometer YIG films, $\Delta a/a_s$ has been determined to be in the range between zero and $+5 \times 10^{-4}$ (see table 2) compared to PLD-grown YIG films with up to $\Delta a/a_s = -100 \times 10^{-4}$ (see e.g. [15]). Hence, our LPE films are under tension, but not to the extent which we expected for nominally pure YIG material without additional lattice expansion by lattice defects or impurities. To find the reason for this, a high-resolution reciprocal space map (HR-RSM) and XPS investigations were performed. Figure 1(b) shows a HR-RSM plot around the symmetrical 444 Bragg reflection with symmetrical diffracted intensity for the GGG substrate and asymmetric diffracted intensity toward higher scattering angles along $Q_z$ (2$\theta$-$\omega$-Scan), which we attribute to the YIG 444 film reflection. Broadening of the film reflection along $Q_z$ is due to the finite coherence length of the sub-micrometer thin film in the growth direction and other broadening mechanisms as for example heterogeneous strain. The extension of the film reflection up to the substrate peak position suggests that the film is continuously strained, due to an existing compositional and/or strain gradient. No peak broadening along the $Q_y$ direction ($\omega$-scan) indicates single crystalline perfection parallel to the film plane without significant mosaicity, due to tilts of epitaxial regions with respect to one another.

To evaluate the compositional homogeneity along the growth direction of the films and to detect expected impurities (e.g. Pb from solvent) depth profile analyses were carried out by XPS. Figure 2(a) shows a homogeneous distribution of the YIG matrix elements along the film growth direction and a sharp transition at the film/substrate interface. The obtained width of the transition layer for sample B is below 5 nm. But the obtained depth profile consists of a convolution of the true concentration profile with the depth resolution of the XPS system under the concrete measuring conditions and should be narrower. Therefore, these profiles demonstrate that no broad interdiffusion layer is formed by element intermixing at the interface at an early state of epitaxial growth or by diffusion of substrate ions into the epitaxial layer and vice versa during the subsequent growth process.

Whereas XPS surface analysis of the very first atomic layers (not shown) gives a Pb content of about 0.2 at-%, no Pb signal could be observed during the depth profile analyses within the detection limit of 0.1 at-% 4. Therefore, it is assumed that the Pb signal corresponds to a surface contamination of condensed PbO vapor from the high-temperature solution and this contamination is completely removed by the first argon-ion etching step. For YIG films grown in La$_2$O$_3$ containing solution, no La signal could be detected by XPS that gives an indication that the La content must be below 0.5 at-% 5. In order to improve the detection capability, additional qualitative SIMS measurements were carried out. Due to the resulting sputtering effect and by time-dependent detection of the sputtered sample ions, one obtains the depth profiles of the film elements, as shown for $^{139}$La in figure 2(b). Here, the counts of two separate measurements taken under identical

4 0.1 at-% Pb corresponds to $x_{Pb} \approx 0.02$ formular units in stoichiometric $Y_{3-0.02Pb}Fe_5O_{12}$.

5 0.5 at-% La corresponds to $x_{La} \approx 0.9$ formular units in stoichiometric $Y_{3-0.09}La_3Fe_5O_{12}$.  

Figure 2. (a) XPS depth profile of sample B reveals a very narrow interface between film and substrate. The Pb 4f signal could not be detected within the detection limit of about 0.1 at-%. (b) SIMS depth profile analysis detects the $^{139}$La signal of the film (green squares) as well as the $^{69}$Ga signal of the substrate (blue triangles) and their changes at the film/substrate interface (sample D).
measuring conditions at neighboring sample positions were added up in order to enhance the statistical significance. It is clearly visible that the lanthanum signal decreases at the film/substrate interface, whereas substrate signals like $^{69,7}$Ga simultaneously increase.

3.2. Static magnetic measurements

The vibrating sample magnetometry was used to measure the net magnetic moment $m$ of the YIG/GGG samples at room temperature. As the thickness of GGG substrates $\approx 5000$ times exceeded those of the studied YIG films, a proper calculation of the YIG parameters required us (i) to extract the GGG contribution that linearly increased with the external field $H$ and (ii) to prefer the in-plane sample orientation that ensured considerably lower fields $H_s$ for the YIG films to attain the saturation.

Figure 3(a) presents a typical dependence of the total magnetic moment $m$ versus the in-plane magnetic field $H$ and illustrates the method allowing us to separate the $m^t$ components produced by the YIG film and the GGG substrate. Being subsequently normalized to the film volume, the YIG components produced by the YIG film and the GGG substrate.

Unfortunately, the GGG component of the total VSM signal is qualitatively confirmed by our out-of-plane measurements. The obtained coercivity ($\gamma M_s$) is much larger than magnetic moments in figure 3(b) seems independent of $\varphi$. A saturation magnetization $M_s$ in figure 3(b) demonstrates such results as polar semi-log plots versus the azimuthal angle $\varphi$. A saturation magnetization $M_s$ in figure 3(b) seems independent of $\varphi$. The obtained $4\pi M_s$ values cluster around the 1800 Gs usually reported [28] for bulk YIG single crystals. Within an experimental error (mostly defined by the YIG volume uncertainty of $\pm 2\%$), the same is valid for the $4\pi M_s$ values in other LPE films listed in table 2. The obtained coercivity ($H_c \leq 0.2$ Oe) in studied LPE films is among the best values reported for gas phase epitaxial films (see table 2). No distinct influence of the crystallographic orientation on the $H_c$ values is also registered. In contrast, the azimuthal dependence of the saturation field $H_s$ reveals the six-fold symmetry which matches the crystallographic symmetry of YIGs. The $H_s$ maxima coincide with the in-plane $\{110\}$ projections of the hard magnetization axes, whereas the $H_s$ minima correspond to the $\{112\}$ crystallographic directions. The $\{112\}$ ‘easy axes’ orientation suggests an ‘easy cone’ anisotropy after Ubizskii [29]. He has also demonstrated [30] that relatively small in-plane magnetic fields lead to single-domain YIG films, although a deviation of magnetization vector from the film plane still remains due to finite values of the cubic anisotropy constants.

In conclusion, as the demagnetizing factor at the out-of-plane YIG film orientation is 1, the out-of-plane saturation field has to be close to the in-plane $4\pi M_s$ values. This fact is qualitatively confirmed by our out-of-plane measurements. Unfortunately, the GGG component of the total VSM signal at fields $H_s \approx 1.8$ kOe is much larger than magnetic moments of YIG films with a thickness of $\approx 100$ nm (see, for instance, figure 3(a)) and, hence, a reasonable accuracy of $\pm 0.5\%$ at the GGG signal elimination inevitably results in too large errors for the YIG parameters. One may conclude that the out-of-plane configuration may provide reliable results when the ratio of YIG to GGG thickness exceeds, at least, $10^{-3}$.

3.3. FMR absorption

FMR absorption spectra for each of the studied YIG films were recorded at several values ($H \leq 5$ kOe) of the in-plane magnetic field along the $\{112\}$ orientation. The inset in figure 4 shows such a spectrum at $H = 1.6$ kOe that looks like the Lorentz function with a linewidth $\Delta \nu_{FWHM} \approx 4$ MHz centered near the FMR frequency $f = 6.5$ GHz. Since the FMR linewidth is mostly expressed in units of magnetic field, we, at first, used the centers $f$ of the measured spectra and the corresponding in-plane fields $H$ to estimate the gyromagnetic ratio $\gamma$ and the effective magnetization $M_{eff}$ in the Kittel formula [31].
Figure 4. Frequency dependence of FMR absorption linewidth $\Delta H_{\text{FWHM}}$ for YIG LPE films A (green circles), B (downward black triangles), C (blue squares) and D (upward red triangles) at various values of the in-plane magnetic field ($H \leq 5$ kOe) parallel to the [1 1 2] direction. Straight lines are linear fits that the Gilbert damping factors $\alpha$ are obtained from. Inset shows an example of FMR absorption spectrum measured for the sample A at $H = 1.6$ kOe.

$\Delta H_{\text{FWHM}} = \Delta H_0 + \frac{2\alpha f}{\gamma}$. \hspace{1cm} (2)

As the FMR performance of thin YIG films strongly depends on the working frequency of future magnonic applications, we have included various quality parameters in table 2, viz. (i) the Gilbert damping coefficient $\alpha$ which is mostly responsible for the FMR losses at high magnetic fields ($H \gg 4\pi M_{\text{eff}}$), (ii) the inhomogeneous contribution $\Delta H_0$ that dominates at small fields ($H \ll 4\pi M_{\text{eff}}$), as well as (iii) the FMR linewidth at the reference frequency $f = 6.5$ GHz which approximately corresponds to the case $H \approx 4\pi M_{\text{eff}}$. The latter is estimated down to $\Delta H_{\text{FWHM}} = 1.4$ Oe, which is, to our knowledge, the narrowest value reported so far for YIG films with a thickness of about 100 nm and smaller. The Gilbert damping coefficients are estimated to be close to $\alpha \approx 1 \times 10^{-4}$, which is comparable to the best values reported so far (compare with table 1). The zero frequency term $\Delta H_0$ is found to be almost the same for all YIG films, including the La substituted one. The obtained value $\Delta H_0 \approx 0.5 - 0.7$ Oe also appears to be appreciably lower than that for gas phase epitaxial films (see table 1).

In summary, optimized LPE growth and post-processing conditions improve FMR linewidths and Gilbert damping coefficients (compare this study and [32] with [12]). However, the improved values are still far from those in bulk YIGs and relatively thick YIG films (see figure 5) due to the decreasing volume to interface ratio in sub-micrometer films. For example, imperfections at the film interface of thin films should have a stronger influence on the magnetic losses in contrast to the dominating volume properties of perfect thick films. It requires us to undertake further attempts to minimize the FMR performance deterioration with a decrease of the YIG film thickness. These attempts will be focused on avoiding the most probable sources of FMR losses, such as contributions due to homogeneous broadening (interface roughness, homogeneously distributed defects and impurities) and inhomogeneous broadening (geometric and magnetic mosaicity, single surface defects) and, thus, on approaching the ‘target’ parameters of $\Delta H_{\text{FWHM}} = 0.3$ Oe at 6.5 GHz and $\alpha = 0.4 \times 10^{-4}$ reported for bulk discs made of single YIG crystals [33].

4. Outlook and conclusions

Besides the efforts to avoid growth defects as well as interface roughness and to reduce impurity incorporation during the LPE deposition process, further high-resolution investigations are necessary to gain more insight into the YIG microstructure and to identify the properties which play an essential role in its FMR performance. Therefore, in future studies we will carry out HR-RSM scans with asymmetrical
reflections to determine in-plane and axial strain, respectively, and the time-of-flight (ToF) SIMS analysis technique using respective standards to precisely quantify the La substitution concentration, as well as to detect impurity elements from the high-temperature solutions in our sub-micrometer LPE films. Furthermore, angular dependent measurements of the resonance field and of the FMR linewidth will be intended to determine the influence of uniaxial magnetic anisotropies on the ferromagnetic resonance losses.

In conclusion, liquid phase epitaxy has the potential to provide sub-micrometer YIG films with outstanding crystalline and magnetic properties to meet the requirements for future magnon spintronics with ultra-low effective losses if a drastic miniaturization down to the nanometer scale is possible. First sub-100 nm lateral sized structures have presently been prepared [34] which could be the next step to LPE-based micro- and nanoscale spintronic circuits. The development of YIG LPE films with thicknesses below 100 nm is now in progress and remains a big challenge for the classical thick-film LPE technique.

Acknowledgments

The authors thank B Hillebrands and A Chumak for valuable discussions, as well as M Frigge for EPMA analysis, Ch Schmidt for XRR measurements and R Meyer and B Wenzel for technical support. Partial financial support by the Deutsche Forschungsgemeinschaft (DU 1427/2-1) is gratefully acknowledged.

References

[1] Kruglyak V V and Hicken R J 2006 J. Magn. Magn. Mater. 306 191–4
[2] Neusser S, Botters B and Grundler D 2008 Phys. Rev. B 78 054406
[3] Kruglyak V V, Demokritov S O and Grundler D 2010 J. Phys. D: Appl. Phys. 43 264001
[4] Stamps R L et al 2014 J. Phys. D: Appl. Phys. 47 333001
[5] LeCraw R C, Spencer E G and Porter C S 1958 Phys. Rev. 110 1311–3
[6] Serga A A, Chumak A V and Hillebrands B 2010 J. Phys. D: Appl. Phys. 43 264002
[7] Chumak A V, Serga A A and Hillebrands B 2014 Nat. Commun. 5 4700
[8] Chumak A V, Vasyuchka V I, Serga A A and Hillebrands B 2015 Nat. Phys. 11 453–61
[9] Giess E A, Kuptsis J D and White E A D 1972 J. Cryst. Growth 16 36–42
[10] Castel V, Vlietstra N, van Wees B J and Youssef J B 2012 Phys. Rev. B 86 134419
[11] Hahn C, de Loubens G, Klein O, Viret M, Naletov V V and Ben Youssef J 2013 Phys. Rev. B 87 174417
[12] Pirro P, Bräcker T, Chumak A V, Ligel B, Dubs C, Surzhenko O, Görtner P, Leven B and Hillebrands B 2014 Appl. Phys. Lett. 104 012402
[13] Cornelissen L J, Liu J, Dune R A, Leven B and van Wees B J 2015 Nat. Phys. 11 1022–6
[14] Onbasli M C, Kehlberger A, Kim D H, Jakob G, Kläui M, Chumak A V, Hillebrands B and Ross C A 2014 APL Mater. 2 106102
[15] Howe B M, Emori S, Jeon H M, Oxhol T, Jones J G, Mahalingam K, Zhuang Y, Sun N X and Brown G J 2015 IEEE Magn. Lett. 6 3500504
[16] d’Allivy Kelly O et al 2013 Appl. Phys. Lett. 103 082408
[17] Hahn C et al 2014 Appl. Phys. Lett. 104 152410
[18] Yu H et al 2014 Sci. Rep. 4 6848
[19] Hamadeh A et al 2014 Phys. Rev. Lett. 113 197203
[20] Chang H, Li P, Zhang W, Liu T, Hoffmann A, Deng L and Wu M 2014 IEEE Magn. Lett. 5 6700104
[21] Wang H 2015 PhD Thesis The Ohio State University
[22] Lustikova J, Shiomi Y, Qiu Z, Kikawa T, Iguchi R, Uchida K and Sañé E 2014 J. Appl. Phys. 116 153902
[23] Jungfleisch M B et al 2015 J. Appl. Phys. 117 17D128
[24] Manuilov S A, Fors R, Khartsev S I and Grishin A M 2009 J. Appl. Phys. 105 033917
[25] Sun Y, Song Y Y, Chang H, Kabatek M, Jantz M, Schneider W, Wu M, Schultheiss H and Hoffmann A 2012 Appl. Phys. Lett. 101 152405
[26] Manuilov S A, Khartsev S I and Grishin A M 2009 J. Appl. Phys. 106 123917
[27] Hergl R, Pfeiffer H, Görnert P, Wendt M, Keszei B and Vandrlik J 1987 Phys. Stat. Sol. (a) 104 769–76
[28] Winkler G 1981 Vieweg Tracts in Pure and Applied Physics vol 5 (Braunschweig: Vieweg) ch 2, pp 75–9
[29] Ubezii S B 1999 J. Magn. Magn. Mater. 195 155–82
[30] Ubezii S B 2000 J. Magn. Magn. Mater. 219 127–41
[31] Kittel C 1948 Phys. Rev. 73 155–61
[32] Lauer V et al 2016 Appl. Phys. Lett. 108 012402
[33] Möschmann P and Tolksdorf W 1983 Mater. Res. Bull. 18 449–59
[34] Lober T, Chumak A V and Hillebrands B unpublished results