Vol. **118** (2010) *ACTA PHYSICA POLONICA A* No. 4

Interface Properties of Single and Bi-Layer Fe_3O_4 Films Grown on MgO(001) Studied by RBS and Channeling Experiments

N.-T.H. Kim-Ngan[a], A.G. Balogh[b], J. Brötz[b], M. Zając[c,d] and J. Korecki[c,e]
[a]Institute of Physics, Pedagogical University, Podchorążych 2, 30-084 Kraków, Poland
[b]Institute of Materials Science, Technische Universität Darmstadt, Petersenstr. 23, 64287 Darmstadt, Germany
[c]Faculty of Physics and Applied Computer Science, University of Science and Technology
al. Mickiewicza 30, 30-059 Kraków, Poland
[d]European Synchrotron Radiation Facility, 38043 Grenoble, France
[e]Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, 30-239 Kraków, Poland

(Received August 5, 2010)

Series of Fe_3O_4/MgO(001) and Fe_3O_4/Fe/MgO(001) films (single- and bi-layer films, respectively) with a total layer thickness in the range of $20 \div 150$ nm were investigated by the Rutherford backscattering spectrometry (2 MeV He^+ ion beam), by the Rutherford backscattering spectrometry channeling experiments (1.5 MeV He^+ ion beam). Depending on the layer thickness of each layer and the film geometry, a single Fe peak and/or a double-anomaly feature was revealed in the Rutherford backscattering spectra. For all films no magnesium presence in the surface layer was observed. For both single- and bi-layer films with a total layer thickness less than 60 nm only one minimum was observed in the channeling curves, while a double minimum was revealed for the bi-layer films with a larger thickness. X-ray reflectometry measurements have revealed that the film density is the same as that of the bulk one.

PACS numbers: 34.35.+a, 68.35.Ct, 68.35.Fx, 68.47.Gh

1. Introduction

Magnetite (Fe_3O_4) has attracted a large attention due to its interesting electronic and magnetic properties and its high potential for technological applications. In particular, it is viewed as a promising material for the spintronic application at room temperature. Fe_3O_4 crystallizes in the cubic inverse spinel structure with a lattice constant of $a = 8.396$ Å. Below the Néel temperature of 858 K, magnetite is ferrimagnetic with a net magnetic moment of 4.1 μ_B per formula unit. For a review of crystal structure and thermodynamic properties of magnetite see e.g. Refs. [1, 2]. An increasing interest is recently focused on the growth and characterization of magnetite thin films, since most spintronic devices are based on thin film technology. For molecular beam epitaxial (MBE) growth of magnetite films, the MgO(001) substrate has been frequently used due to the fact that the lattice mismatch is very small (0.31%). Despite of extensive investigations, many features of magnetite films are still not fully understood. For reviews see e.g. Refs. [3, 4]. The traditional method to prepare the Fe_3O_4(001) film is the reactive deposition of a magnetite layer directly on a MgO(001) substrate (denoted in this work as a single-layer magnetite film or Fe_3O_4/MgO(001) film). Another possibility is to deposit a magnetite layer on an epitaxial Fe(001) buffer layer grown epitaxially on the MgO substrate (i.e. bi-layer magnetite film or Fe_3O_4/Fe/MgO(001) film). The film characterizations by low energy electron diffraction (LEED) and conversion electron Mössbauer spectroscopy (CEMS) have revealed a surface oxidation and Mg outdiffusion from MgO substrate into the film for the single-layer Fe_3O_4 films, whereas no Mg diffusion was observed for the bi-layer ones, since it could be prevented by the Fe layer [4, 5].

We have recently investigated the surface and interface stoichiometry and crystalline quality of both single- and bi-layer MBE magnetite films using the Rutherford backscattering spectrometry (RBS) and RBS-channeling experiments (RBS-C) [6, 7]. The RBS data obtained for the as-grown films (with a thickness of 10–20 nm) confirmed the earlier observations by LEED and CEMS, e.g. the Mg interdiffusion in the single-layer film and the existence of a stoichiometric Fe_3O_4 layer on the surface of the bi-layer films [6]. Our RBS investigations on annealed and irradiated films have revealed that both annealing (in partial argon atmosphere up to 600 ℃) and ion irradiation (by 1 MeV Ar^+ ion beam with an ion fluence of

10^{15}–10^{16} ions/cm^2) induced a strong Fe–Mg–O mixing producing a large interface zone. However, the stoichiometric surface Fe_3O_4 layer of the bi-layer films is well preserved upon annealing and ion irradiation. Also, the Fe buffer layer has become oxidized completely upon annealing while it still existed upon ion irradiation although its thickness was decreased [7].

The bi-layer magnetite film seems to be a good solution to obtain a stoichiometric Fe_3O_4 layer on the film-surface. However, the extra Fe layer would introduce a large lattice mismatch (4%) at both Fe_3O_4/Fe and Fe/MgO interfaces, which can degrade the crystallinity of the film, as it was indicated by the RBS-C results [6]. We note here that it would be meaningful to use an ultrathin Fe layer, since it can be strained to MgO substrate and follow the lattice template of MgO substrate and the strained Fe layer will allow Fe_3O_4 epitaxy on it and thus the crystal quality of Fe_3O_4 layer will be improved. However, in our previous study [6], if the films are thin, it was impossible to separate the Fe signal of the Fe_3O_4 film from that of the Fe layer and thus we could not judge about the quality of each film itself for the bi-layer films. In the present work, we aim to investigate in more detail the interface properties of different interfaces in single- and bi-layer magnetite films with the total layer thickness in the range of 20–150 nm. The thickness of the Fe layer is in the range of 20–50 nm allowing to distinguish not only the Fe signal from two films but also the two different interfaces in the bi-layer films (the Fe_3O_4/Fe and Fe/MgO interface). Besides, since our main goal is to investigate the ion-beam-mixing effect in magnetite films, such the layer thickness of different films has been chosen accordingly to the layer thickness pre-estimated using SRIM code [8] for a possible ion penetration depth (at two interfaces separately) by using 1 MeV Ar^+ and Kr^+ ion beam. In this paper we present the different features of two different types of magnetite films in the as grown state.

2. Experiments

The films were prepared applying the growth procedure and the LEED and CEMS characterization in a multi-chamber UHV system reported previously [4, 5]. We have used 8 films: nd Fe_3O_4/MgO(001) and nd Fe_3O_4/md Fe/MgO(001) films, where $n = 1, 2, 4$, $m = 1, 2$ and the minimal value of the nominal thickness is $d = 25$ nm, allowing a comparison between single- and bi-layer films with a similar and/or with a double layer thickness. The film notations and parameters determined by RBS and X-ray reflectometry (XRR) are given in Table. The combination of ^{56}Fe and ^{57}Fe isotopes used during the sample preparation allowed selective CEMS measurements. Namely, ^{57}Fe isotope was used for preparation of all Fe_3O_4 layers, while it was used for deposition of the Fe buffer for a thickness of only about 10 nm and the rest (of the Fe buffer layer) was from the ^{56}Fe one. By doing this, we obtained adequate signals for the CEMS experiments without using too large amount of the expensive ^{57}Fe isotope. Six samples underwent a post-annealing treatment (ann.): the single-layer films (S1, S2, S3; Table) and the bi-layer films (S4, S6, S7) were annealed for 30 min, respectively, at 520 K and 800 K. For underlying the annealing effect, we study two bi-layer films with similar thickness, one under post-annealing (S6) and another one (S9) without annealing (non-ann.). Besides, in order to get clear features of the Fe layer beneath the Fe_3O_4 layer, we also study a bi-layer film with a thin Fe_3O_4 layer ($\approx$ 8 nm) deposited on a thick Fe buffer ($\approx$ 50 nm, S8 non-ann.)).

TABLE

RBS and XRR data analysis of single- and bi-layer magnetite films grown epitaxially on MgO substrates. The values given in the brackets are the layer-thickness values for the stoichiometric Fe_3O_4 and Fe layer determined from RBS (for more details see text). d is the layer thickness, r is the roughness determined from XRR.

Sample	RBS analysis	XRR analysis			
		Fe_3O_4		Fe	
		d [nm]	r [nm]	d [nm]	r [nm]
S1 (ann.)	(105.5 nm)Fe_3O_4/MgO				
S2 (ann.)	(21.9 nm)Fe_3O_4/MgO	19.79	1.10	0	0
S3 (ann.)	(52.7 nm)Fe_3O_4/MgO	49.98	0.55	0	0
S4 (ann.)	(29.5 nm)Fe_3O_4/(24.2 nm) Fe/MgO	29.00	1.00	28.10	1.00
S6 (ann.)	(59.6 nm)Fe_3O_4/(29.0 nm) Fe/MgO	54.7	0.90	28.24	0.90
S7 (ann.)	(105.4 nm)Fe_3O_4/(28.5 nm) Fe/MgO				
S9 (non-ann.)	(58.5 nm)Fe_3O_4/(29.1 nm) Fe/MgO				
S8 (non-ann.)	(8.4 nm)Fe_3O_4/(41.3 nm) Fe/MgO	8.1	0.65	40.92	0.27

The RBS and RBS-C experiments were performed at the Institute of Nuclear Physics of the University Frankfurt/Main. Details of the experiment conditions for RBS and RBS-C experiments have been already reported earlier [6, 7]. For the data evaluation the computer code SIMNRA [9] was used taking into account the electronic stopping power data by Ziegler and Biersack, Chu + Yang's theory for electronic energy-loss straggling and Andersen's screening function to the Rutherford cross--section. The contribution from a double and/or multiple scattering into the RBS spectra were taken into account using the calculating facilities of SIMNRA. XRR has been also employed to determine the layer density and thickness of these films by using a Seifert two-circle diffractometer with the Seifert Reflectivity software for the data analysis.

3. Results and discussion

In Fig. 1, the random RBS spectra (at a tilted angle $\varphi = 40°$) of different films revealing different features are shown: (1) the spectrum with only a single Fe peak and no (separated) O signal for a single Fe_3O_4 layer, (2) the spectrum with an overlapped Fe signal from Fe in the Fe buffer and Fe_3O_4 layer and a distinguished O-peak from the Fe_3O_4 film and (3) the spectrum with well-separated Fe and O peaks from the 2 layers. The simulated spectra by SIMNRA are shown as solid lines in the same figure and the estimated layer thickness is given in Table. The RBS spectrum of single-layer magnetite film (e.g. the sample S3) is always characterized by a sharp Fe peak (around the energy of 1.5 MeV), a steep Mg edge (Mg (sub.)) and O edge (O(sub.)) from the MgO substrate (around 0.95 MeV and 0.7 MeV, respectively). Increase of the film thickness leads to an increase of the width and intensity of the Fe peak and a shift to a lower energy of both the Mg- and O-edge, but the oxygen signal from the Fe_3O_4 film and MgO substrate is always overlapped and thus no separated O-peak can be observed in the random RBS spectrum for the single-layer films. (We note here that a separated O-peak can appear in the RBS-C spectrum [6].) For the bi-layer films (e.g. sample S4), the presence of the Fe buffer between the Fe_3O_4 film and the MgO substrate implies an appearance of a distinguishable O-peak (O(film)). Such the oxygen signal of the Fe_3O_4 film becomes more pronounced with increasing the layer-thickness of either Fe film or Fe_3O_4 film. With the increase of the thickness of both layers, a large Fe peak with a double feature related to the backscattered signal from the Fe atoms in the Fe buffer layer (the maximum, Fe(f-2)) and in the Fe_3O_4 layer (the shoulder on the right-hand side of the maximum, Fe(f-1)) was observed (sample S6). The shoulder feature becomes more pronounced with increasing further the layer thickness of the Fe_3O_4 layer (sample S7). The overlap of the Fe signals in the sample S4 is a quite surprising fact, since the layer-thickness value in this case is much higher than the RBS depth resolution. To check this point we conducted the SIMNRA simulation for the peak-feature dependence on the layer thickness. With the presence of the Fe layer between the Fe_3O_4 film and MgO substrate in bi-layer films, the oxygen signal from Fe_3O_4 film and the MgO substrate could be already separated if the magnetite layer is thicker than 8 nm (indicated by an appearance of a kink in the step-rise of the oxygen edge). However, the separation of the Fe signal would appear (indicated by a shoulder in the right hand side of the peak) only if either the magnetite layer or the Fe layer is larger than 30 nm, i.e. only when the difference of the areal density of the two layers can be large enough and thus detectable.

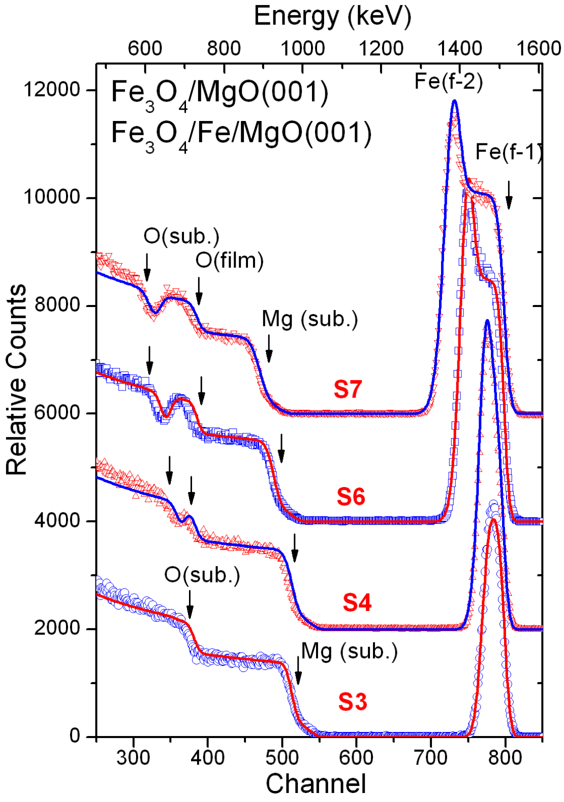

Fig. 1. Random RBS spectra (at tilted angle $\varphi = 40°$) for selected Fe_3O_4/MgO(001) film (sample S3) and Fe_3O_4/Fe/MgO(001) films (S4, S6, S7) with different layer thicknesses (see Table). The simulated spectra are shown by solid lines.

For all investigated films, a strong channeling effect was observed even if using the standard RBS aparatus. Namely, a large decrease of the backscattered signal for untilted samples (i.e. measured at an angle $\varphi = 0°$ with respect to the main crystallographic direction (001) of the films) was obtained in a comparison with that measured at e.g. tilted angle $\varphi \geq 10°$ (the random RBS signal). Such a channeling effect was most visible for sample S8, a bi-layer film with a very thin Fe_3O_4 film on a thick Fe buffer (8.4 nm Fe_3O_4/41.3 nm Fe/MgO(001)). In Fig. 2, the comparison of the RBS spectra at $\varphi = 40°$ and $\varphi = 0°$ for the sample S8 is shown. An enormous reduction of the intensity of the Fe peak and Mg edge was observed at $\varphi = 0°$. Moreover, an additional O-peak was appeared, as a consequence of a separation of the O-signal from the Fe_3O_4 film from that of MgO substrate. The random RBS spectrum at the tilted angle $\varphi = 40°$ revealed only one single Fe peak, while that obtained at $\varphi = 0°$ revealed a double peak indicating a splitting of the Fe-peak from the 2 layers. The Fe peak at a high-channel and the O-peak disappear simultaneously with increasing the tilted angles. It is thus considered to originate from the Fe_3O_4 layer. The Fe peak at the low channel is attributed to the Fe layer. The RBS analysis by SIMNRA revealed that the peak intensity and width of the high-channel Fe-peak was in a good agreement with the random RBS backscattered signal from the 8.4 nm thick Fe_3O_4 layer. Thus the observed channeling effect for untilted sample at $\varphi = 0°$ is attributed to the channeling through the Fe buffer layer (and not through the Fe_3O_4 layer). It suggested that there is a small difference in the orientation between the atomic rows in the Fe film and the Fe_3O_4 one.

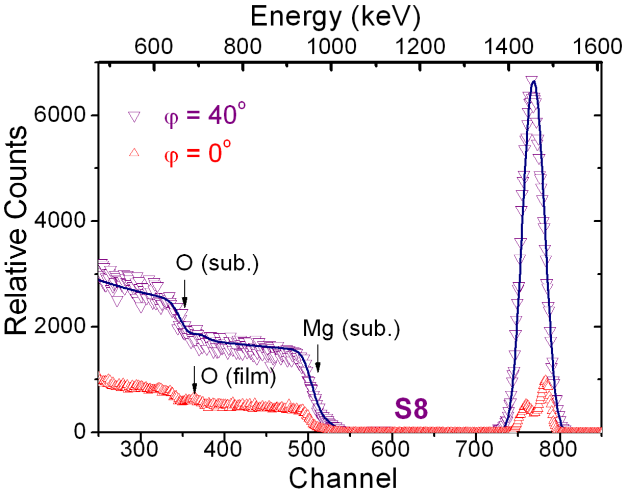

Fig. 2. Comparison between the random RBS spectra at a tilted angle $\varphi = 40°$ and that at $\varphi = 0°$ (untilted sample) for the bi-layer Fe_3O_4/Fe/MgO(001) film-sample S8, revealing a strong channelling effect in this sample.

For all investigated films, the simulated RBS areal density values (10^{15} at./cm^2) were converted into the layer thickness value (nm) by using the mass density of the bulk, since the film density was found to be equal to that of the bulk from XRR measurements (see next section). The estimated values for layer thickness of the investigated films from RBS data were given in Table, in a good agreement with the nominal thicknesses (±5–10%). We note that the RBS experiments were performed about one week after the samples were exposed to air. Unlike the thin magnetite films ($d = 10$ nm) [6, 7], no presence of magnesium was found in the surface layer of the Fe_3O_4 films deposited directly on MgO substrates indicating no segregation of Mg atoms to the surface for the thick films exposed to air in a short time. However, a small amount of Mg outdiffusion was found at the interface leading to a spinel-type composition ($(Fe_{1-x}Mg_x)_3O_4$) of the interface zone (with a thickness $d < 5$ nm and the x content is $x = 5$–10%). For the bi-layer films, as expected, the surface layer is a stoichiometric Fe_3O_4 layer. However, for the samples under a post-annealing (S4, S6, S7) the RBS analysis indicated a thicker Fe_3O_4 layer and a much thinner Fe layer in a comparison with the nominal thickness. Besides, a wustite layer was found to locate between the Fe layer and MgO substrate ($d < 5$ nm). Even for the sample S9 without a post-annealing, a similar estimated thickness value (as that for S6) was found, e.g. the thickness of the Fe buffer layer is only 29 nm, much smaller than the nominal thickness of 50 nm ($m = 2$). The thickness of the Fe buffer layer is estimated to be 41.3 nm for the sample S8 without a post-annealing, i.e. it is quite close to the nominal one. Moreover, no wustite layer was detected in this case. The larger thickness value of the Fe_3O_4 layer and the existence of the wustite layer in samples S4–S9 suggested that the top and bottom part of the Fe layer was oxidized and thus the thickness of the pure Fe was decreased. The lack of a wustite layer in sample S8 indicated that such an oxidation rather occurred during the growth of the Fe_3O_4 film than during the post-annealing. Despite of that fact that the existence of spinel and wustite layers was evidenced from our RBS data, it is not really practical to discuss in detail about several nm thick layers while using a standard RBS.

It is essential to investigate the film crytallinity by RBS-C experiments. The normalized angular yield curves (with respect to the maximal backscattered yield of the random spectra) for Fe in the film for selected magnetite films are shown in Fig. 3. The minimum yield for the MgO substrate was determined to be $\chi_{\min}(\mathrm{Mg}) < 5\%$ indicating a perfect crystal quality of the MgO substrate. For the sample S2 (21.9 nm thick Fe_3O_4/MgO film), the minimum yield value and the full width at half maximum (FWHM) for Fe in the film are: $\chi_{\min}(\mathrm{Fe}) = 18\%$, $\psi_{1/2}(\mathrm{Fe}) = 1.86°$ (Fig. 3a). Increasing the film thickness (up to 100 nm) introduced only a small increase of the $\chi_{\min}(\mathrm{Fe})$-value and a small decrease of the $\psi_{1/2}(\mathrm{Fe})$-value. The results indicate that a good crystallinity of the Fe_3O_4 film is always obtained for the single-layer magnetite films. For the bi-layer film S4, the angular yield curve (Fig. 3a) revealed only one minimum with a larger value of $\chi_{\min}(\mathrm{Fe})$ and a lower value of $\psi_{1/2}(\mathrm{Fe})$ ($\chi_{\min}(\mathrm{Fe}) = 60\%$, $\psi_{1/2}(\mathrm{Fe}) = 1.52°$) indicating that the crystal quality is lower. For this film, the Fe_3O_4 layer is still thin and an overlapped Fe signal from 2 layers was observed from the RBS spectra. Thus we cannot judge the quality of neither Fe_3O_4 film nor Fe film separately. The larger value for $\chi_{\min}(\mathrm{Fe})$ was attributed to a large atomic disorder due to a large lattice mismatch (4%) at both Fe_3O_4–Fe and Fe–MgO interface. For sample S6 (and S7), the Fe_3O_4 layer is thick enough implying a sep-

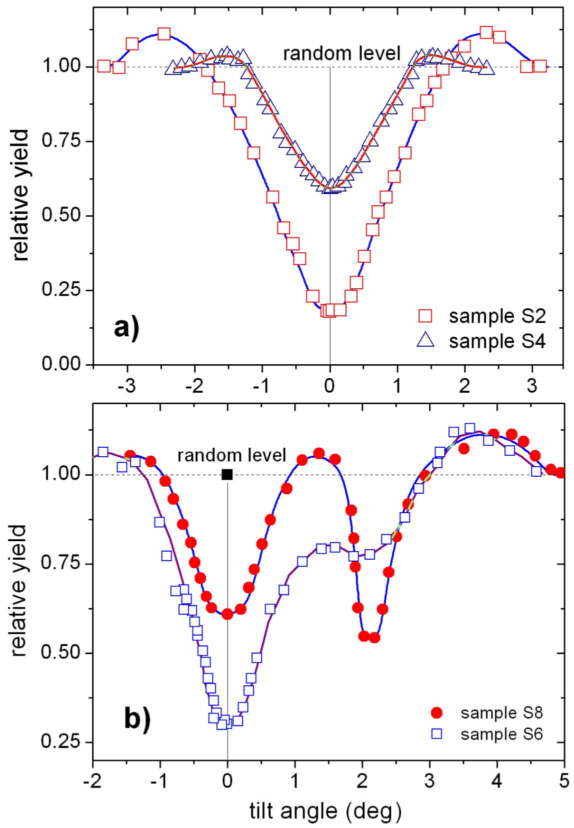

Fig. 3. The channelling curves of Fe with respect to the [001] direction showing (a) only a single minimum for sample S2 (21.9 nm Fe_3O_4/MgO(001) and S4 (29.5 nm Fe_3O_4/24.2 nm Fe/MgO(001)) and (b) a double minimum for S6 (59.6 nm Fe_3O_4/29.0 nm Fe/MgO) and S8 (8.4 nm Fe_3O_4/41.3 nm Fe/MgO(001)).

aration of the Fe signal and a visible O-peak in the RBS spectra, one would expect to observe channeling effects separately from the 2 layers. Indeed, a double minimum was observed in the channeling curve (Fig. 3b). The deep minimum ($\chi_{\min}(\mathrm{Fe}) = 31\%$, $\psi_{1/2}(\mathrm{Fe}) = 1.40°$) at a normalized tilted angle $\varphi = 0°$ was considered to be as a result of channeling through the Fe_3O_4 layer (i.e. the surface layer), while the minimum-shoulder feature located at the right hand side ($\chi_{\min}(\mathrm{Fe}) = 75\%$) was attributed to the channeling effect of the Fe film. The angle difference between the two minima is 2 degrees indicating an orientation difference of the atomic rows between the Fe layer and the Fe_3O_4 layer. In order to clarify this point we have performed the RBS-C experiments on the sample S8, i.e. the sample with a very thin Fe_3O_4 layer on a thick Fe layer. Indeed, two deep minima were revealed in the channeling yield curve, shown in Fig. 3b. The wider minimum ($\chi_{\min}(\mathrm{Fe}) = 60\%$, $\psi_{1/2}(\mathrm{Fe}) = 1.11°$) and the narrow minimum ($\chi_{\min}(\mathrm{Fe}) = 55\%$, $\psi_{1/2}(\mathrm{Fe}) = 0.64°$) was attributed to the channeling respectively of the Fe_3O_4 and the Fe layer. In such a case, the angle-difference between the two minima is equal to 2 degrees, confirming that the difference of the orientation of the atomic rows in the Fe layer and Fe_3O_4 layer is 2°. The results are summarized as following:

1) A good crystallinity is found always obtained for the single-layer films of magnetite.

2) For the bi-layer films, if a layer thickness of each layer is not large enough ($d < 30$ nm), the lattice mismatch at both two interfaces largely influence the channeling (leading to a much higher value of $\chi_{\min}(\mathrm{Fe})$ and a lower value of $\psi_{1/2}(\mathrm{Fe})$). Besides, it is difficult to judge the crystallinity of each layer, due to an overlap of the Fe signals.

3) For the bi-layer films with a total thickness larger than 60 nm, it is possible to observe the channeling effect is found separately for each layer. The results indicate that the orientation difference between the atomic rows of the Fe layer and the Fe_3O_4 layer is 2°.

4) A good channeling effect was found for the Fe buffer indicating that this layer possesses a good atomic arrangement in the layer. However, increasing the thickness of Fe_3O_4 layer grown on Fe buffer, the channeling effect on Fe layer becomes less visible (the Fe minimum in the films S6 is higher and less deep than that in S8).

5) A good channeling is always observed for the Fe_3O_4 layer in the bi-layer films. For a thin Fe_3O_4 layer, the large lattice mismatch at the Fe_3O_4/Fe interface would largely influence the channeling (a higher value of $\chi_{\min}(\mathrm{Fe})$ in S8). With increasing the Fe_3O_4 layer thickness, a better match of atomic arrangement and a less visible mismatch at the interface would imply a better channeling (a lower value of $\chi_{\min}(\mathrm{Fe})$ in S6).

6) The post annealing does not influence the channeling, since there is no visible difference in the channeling between sample S6 (annealed) and S9 (non-annealed). However, the presence of wustite layer at the Fe/MgO surface may influence the channeling of the Fe layer.

We note here also that the minimum yield value for the thin bi-layer films is $\chi_{\min}(\mathrm{Fe}) > 50\%$ [6]. Thus increasing the thickness of Fe layer does not imply a further increase in $\chi_{\min}(\mathrm{Fe})$. The results indicate that such a high value is mainly due to the lattice mismatch at the Fe/MgO interface. The observation of two minima and the "orientation" effect in particular in sample S8 indicate that each layer possesses good atomic arrangements and that the lattice mismatch at the Fe_3O_4/Fe interface did not imply a chaotic atomic disorder, but rather made a change in the orientation of 2° between the Fe atomic rows in the Fe layer and Fe_3O_4 layer.

XRR measurements have been performed on selected single- and bi-layer magnetite films to determine the absolute values of the film thickness and film density independently of the RBS measurements. As examples, the XRR curves for the samples S3 and S8 are shown in Fig. 4. We notice here that from the XRR measurements, the thickness, the molar density and the roughness of the top layer (d_1, ρ_1, r_1) can be estimated very accurately, while all other values might have larger errors. The error bar is, respectively, ±0.2 nm for d_1 and

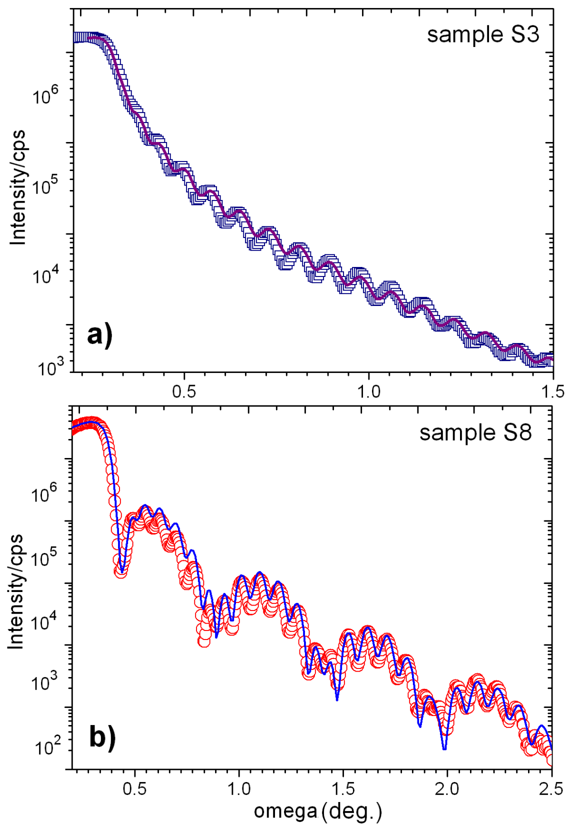

Fig. 4. X-ray reflectivity results for selected single- and bi-layer magnetite films: for sample S3 (52.7 nm Fe_3O_4/MgO(001)) and S8 (8.4 nm Fe_3O_4/41.3 nm Fe/MgO(001)). The XRR fits are shown by solid lines.

r_1 and ± 0.2 g/cm^3 for ρ_1. The XRR parameters are given in Table. In all cases, the film densities of the magnetite layers and Fe layers are found to be $\rho(Fe_3O_4) =$ 5.2–5.4 g/cm^3, $\rho(Fe) = 7.8$–7.9 g/cm^3, respectively. They are similar to the bulk density of magnetite (5.21 g/cm^3) and iron (7.87 g/cm^3), confirming the good film stoichiometry. The XRR results confirmed the presence of only one single layer on the MgO substrate for the directly deposited Fe_3O_4/MgO films and of two-layers for the bi-layer magnetite films. The wustite layers would not be revealed from the XRR measurements, since the density of such layers is very close to that of the MgO substrate. In general, a good agreement for the layer thickness was obtained between RBS and XRR.

4. Summary

Interface stoichiometry and crystalline quality of epitaxial single- and bi-layer magnetite films (Fe_3O_4/MgO(001) and Fe_3O_4/Fe/MgO(001) films) with a layer thickness in the range of 20–150 nm were investigated using RBS, RBS-C. In addition the XRR was employed to determine the layer thickness and density. The film densities were found to be very similar to that of the bulk, indicating a good stoichiometry of the films. No magnesium was found on the topmost (magnetite) layer. For the bi-layer films, some Fe oxidization was found during the film growth leading to an increase of the thickness of the magnetite layer. The channeling experiment indicated a good crystallinity of the single-layer magnetite films. A larger value of the minimum yield of Fe (> 50%) for the bi-layer films indicated a large influence of the lattice mismatch at the Fe/MgO interface on the channeling. A good atomic arrangement was found for both Fe and Fe_3O_4 layer. The lattice mismatch at the Fe_3O_4/Fe interface would not influence the crystal quality, it is rather related to a change in the atomic orientation of 2° between the Fe atomic rows in the Fe layer and in the Fe_3O_4 layer.

Acknowledgments

The financial support from German Academic Exchange Service (DAAD)-project D/08/07729 (between Germany and Poland) is highly acknowledged. N.-T.H.K.-N. acknowledges the financial support by the Ministry of Science and Higher Education (MNiSW project No. 651N-DAAD/2010/0). A.G.B. acknowledges the financial support by German Research Foundation (DFG; SFB-595 project). This work was supported in part by the Team Program of the Foundation for Polish Science co-financed by the EU European Regional Development Fund.

References

[1] N. Tsuda, K. Nasu, Y. Yanase, K. Siratori, in: *Electronic Conductions in Oxides*, Eds: M. Cardona, P. Fulde, K. von Klitzing, H.-J. Queisser, Vol. 94, Springer-Verlag Series in Solid-State Sciences, Springer, Berlin 1990.

[2] G. Subías, J. García, J. Blasco, *Phys. Rev. B* **71**, 155103 (2005) and references therein.

[3] S.F. Ceballos, G. Mariotto, K. Jordan, S. Murphy, C. Seoighe, I.V. Shvets, *Surf. Sci.* **548**, 106 (2004).

[4] N. Spiridis, J. Barbasz, Z. Łodziana, J. Korecki, *Phys. Rev. B* **74**, 155423 (2006) and references therein.

[5] M. Zajac, D. Aernout, K. Freindl, K. Matlak, N. Spiridis, M. Slezak, T. Slezak, J. Korecki, *Acta Phys. Pol. A* **112**, 1319 (2007).

[6] N.-T.H. Kim-Ngan, A.G. Balogh, J.D. Meyer, J. Brötz, S. Hummelt, M. Zając, T. Ślęzak, J. Korecki, *Surf. Sci.* **602**, 2358 (2008).

[7] N.-T.H. Kim-Ngan, A.G. Balogh, J.D. Meyer, J. Brötz, M. Zając, T. Ślęzak, J. Korecki, *Surf. Sci.* **603**, 1175 (2009).

[8] SRIM2008 developed by J.F. Ziegler, M.D. Ziegler, J.P. Biersack, `http://www.srim.org` .

[9] M. Mayer, *AIP Conf. Proc.* **475**, 541 (1999); SIMNRA (Simulation program for the analysis of NRA, RBS and ERDA), `http://www.rzg.mpg.de/~mam/` .