Substrate influence on the structure and properties of YbFeO₃ films

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Keywords: YbFeO₃, magneto-optical properties, substrate-induced effect, degree of lattice mismatch, magnetism, magnetic circular dichroism

Abstract
Herein, YbFeO₃ films are synthesized by using radio frequency magnetron sputtering and influence of substrate on film quality and magneto-optical properties is systematically investigated by depositing YbFeO₃ films on different substrates, such as quartz glass, sapphire(0001), MgO(111), YSZ(111), SrTiO₃(STO)(100) and SiO₂(0001). The crystal structure, surface morphology, magnetic behavior and magnetic circular dichroism are characterized by using x-ray diffraction, scanning electron microscopy, vibrating sample magnetometer and magnetic circular dichroism spectrometer. The crystallinity of films has been enhanced by thermal annealing at elevated temperatures. The results reveal that highly crystalline YbFeO₃ films can be obtained after annealing at 800 °C. Moreover, the influence of lattice mismatch between substrate and film on film quality, growth orientation and surface morphology has been discussed in detail. The results reveal that large degree of lattice mismatch led to the formation of surface cracks and hindered the preferred growth orientation of film. Furthermore, it has been demonstrated that the choice of substrate significantly affected the optical, magnetic and magneto-optical properties of the YbFeO₃ films, which exhibited obvious magnetic anisotropy, excellent coercivity of ∼882 Oe and significant magneto-optical anisotropy.

1. Introduction
RFeO₃, where R refers to the rare earth elements, is a derivative of the ideal cubic perovskite structure and possesses a twisted perovskite structure [1, 2]. According to the properties of the material, RFeO₃ can be divided into different categories, such as dielectric materials, gas-sensitive materials, photocatalytic materials, ferromagnetic materials and magneto-optical materials [3–7]. Especially in the field of magneto-optical materials, since these materials possess some advantages such as fast response, high sensitivity, high magneto-optical figure of merit and high Curie temperature (643 K) [8], and they can grow on series of substrates such as SrTiO₃(STO), quartz glass, Al₂O₃, MgO, they have a good application prospect in the field of the integrated optoelectronic devices. The magneto-optical properties of YFeO₃, SmFeO₃, EuFeO₃, GdFeO₃, DyFeO₃, ErFeO₃ and LuFeO₃ materials have aroused extensive researches [9, 10]. YbFeO₃ is an important member of RFeO₃-type perovskite family, which is expected to render excellent magnetic and magneto-optical properties like other RFeO₃ phases [11, 12]. However, theoretical and experimental studies on the magneto-optical performance of YbFeO₃ are rare due to it is difficult to obtain the large and high-quality YbFeO₃ crystal at present.

Furthermore, thin film materials are more conducive to device miniaturization than bulk crystals. However, apart from the intrinsic properties of a particular material, the quality of thin films is strongly influenced by the choice of substrate. One should note that the lattice mismatch and difference in thermal expansion coefficient (TECs) between the substrate and film directly affect the epitaxial growth of the thin film [13, 14]. As a result, a defective single crystal film is obtained, which renders inferior device performance. Hence, systematic studies have been carried out to investigate the influence of substrate on film quality for various materials.

Therefore, the present study aimed to synthesize films of YbFeO₃ and systematically investigate the influence of substrate selection on film quality and optical, magnetic and magneto-optical properties of the as-prepared
YbFeO$_3$ films. Herein, a series of YbFeO$_3$ films are prepared by RF magnetron sputtering on different substrates, such as quartz glass, sapphire (0001), MgO (111), YSZ (111), SrTiO$_3$ (STO) (100) and SiO$_2$ (0001). The crystal structure, surface morphology, magnetism and magnetic circular dichroism properties of the as-prepared YbFeO$_3$ thin films are characterized by using x-ray diffraction (XRD), scanning electron microscopy (SEM), vibrating sample magnetometer (VSM) and magnetic circular dichroism spectrometer (MCDS), respectively.

2. Experimental

YbFeO$_3$ targets were prepared by conventional ceramic processing route. Briefly, stoichiometric amounts of Yb$_2$O$_3$ and Fe$_2$O$_3$ powders were uniformly mixed in a corundum mortar and pre-sintered at 1000 °C for 10 h in air. Then, the pre-sintered powder was pressed under the uniaxial pressure of 30 MPa for 15 min and sintered at 1200 °C for 10 h to obtain the target material.

YbFeO$_3$ films were deposited on quartz glass, sapphire (0001), MgO (111), YSZ (111), SrTiO$_3$ (STO) (100) and SiO$_2$ (0001) substrates by using radio frequency (RF) magnetron sputtering technology. The details of sputtering parameters are as follow: background pressure $< 3.8 \times 10^{-4}$ Pa, sputtering gas: Ar, sputtering gas flow: 20 sccm, sputtering pressure: 1.9 Pa, substrate-target distance: 50 mm, substrate temperature: 550 °C, RF power: 80 W, and deposition time: 8 h. The as-deposited thin films were annealed at different temperatures to enhance the crystallinity. First, YbFeO$_3$/Quartz-glass films were annealed at different temperatures in air and the optimal annealing temperature was found to be 800 °C. Then, YbFeO$_3$ films at other substrates were annealed at 800 °C in the air.

The crystal structure, thickness and surface morphology of YbFeO$_3$ films were analyzed by using x-ray diffractometer, equipped with Cu K$_\alpha$, radiations (Rigaku D/max-3c, $\lambda = 1.5406$ Å, 30 kV, 20 mA), Tencor Alpha-step 500 profilometer and scanning electron microscope (Hitachi S4800, Japan), respectively. The transmission spectra were measured by using a UV/VIS/IR spectrometer (Perkin-Elmer Lambda 900) in the range of 300 to 3000 nm. The magnetic behavior has been analyzed by using with a vibrating sample magnetometer (LakeShore-7407). Magnetic circular dichroism (MCD) spectra were measured by using a circular dichroism tester (Bio-Logic, MOS-450) with strong magnetic field equipment, which is parallel to the direction of light propagation, 7000 Oe.

3. Results and discussion

3.1. Crystallization temperature

The crystal structure and properties of thin films are significantly influenced by the composition. The composition of the as-deposited YbFeO$_3$/quartz-glass films was measured by using inductively coupled plasma emission spectrometer. The composition of YbFeO$_3$ film was found to be Yb:Fe = 1.0:1.00, which implies that Yb to Fe ratio is consistent with the corresponding target. Hence, pure-phase YbFeO$_3$ films can be obtained from the used target. The thickness of YbFeO$_3$ films were measured by Tencor Alpha-step 500 profilometer. The results show the thickness of films is uniform and the thickness of YbFeO$_3$/quartz-glass, YbFeO$_3$/sapphire(0001), YbFeO$_3$/MgO(111), YbFeO$_3$/YSZ(111), YbFeO$_3$/STO(100) and YbFeO$_3$/SiO$_2$(0001) films are 690.3, 671.4, 596.1, 703.3, 700.8 and 668.5 nm, respectively.

XRD patterns of the annealed YbFeO$_3$/quartz-glass films and the standard PDF card (No.74-1482) of YbFeO$_3$ are presented in figure 1. By comparison with standard card of YbFeO$_3$, one should note that the as-deposited film even after annealing at 650 °C, the YbFeO$_3$/quartz-glass film retained its amorphous nature and did not show any diffraction peak, corresponding to YbFeO$_3$ phase. This indicates that the atomic energy of as-deposited YbFeO$_3$/Quartz-glass film, annealed at 650 °C, is not enough for atomic migration and diffusion on the substrate surface. On the other hand, the diffraction peaks of YbFeO$_3$ and YbFe$_2$O$_4$ phases have been observed after annealing at 700 °C, which implies that the as-deposited film started to crystallize at 700 °C. Furthermore, when the annealing temperature was increased to 800 °C, YbFe$_2$O$_4$ diffraction peak disappeared and pure-phase YbFeO$_3$ is obtained. However, the diffraction peaks, corresponding to SiO$_2$ phase, started to emerge with further increase in annealing temperature to 900 °C, which can be ascribed to the crystallization of amorphous quartz glass substrate at 900 °C. Therefore, the optimal annealing temperature for YbFeO$_3$ film was found to be 800 °C. In addition, the diffraction peaks from (002), (200) and (004) planes of YbFeO$_3$ have been observed in as-deposited YbFeO$_3$/quartz-glass films after annealing at 800 °C. However, (002) and (004) peaks of YbFeO$_3$ have exhibited a slight shift towards higher 2θ values, which indicates the presence of compressive stress in YbFeO$_3$/quartz-glass films. One should note that a large mismatch of lattice parameters exists between the quartz-glass substrate and YbFeO$_3$ film due to the quartz-glass is amorphous material while YbFeO$_3$ film is a crystal film with high crystallinity. In addition, a large mismatch of the thermal expansion coefficients exists between the quartz-glass substrate and YbFeO$_3$ film. For instance, the thermal expansion coefficient of...
quartz-glass and YbFeO₃ is $5.4 \times 10^{-7}$ K$^{-1}$ [15] and $1.1 \times 10^{-5}$ K$^{-1}$ [16], respectively, in the temperature range of 0 to 1000 °C. Hence, the selection of a suitable substrate plays a critical role in film quality.

3.2. Crystal structure and lattice orientation

XRD patterns of YbFeO₃ films deposited on different substrates, are presented in figures 2–6. The diffraction peaks from (020), (112) and (200) planes of YbFeO₃ can be readily observed in XRD patterns of YbFeO₃/sapphire(0001), YbFeO₃/MgO(111), YbFeO₃/YSZ(111) and YbFeO₃/SiO₂(0001) films after annealing at 800 °C. However, the diffraction peak corresponding to (001) plane of YbFeO₃, has only been observed in YbFeO₃ film deposited on STO (100) substrate, which indicates the preferred orientation of YbFeO₃ on STO(100) substrate. This can be related to the lattice mismatch between the film and substrate, and the induction of the substrate on film growth. The crystal quality and orientation of the films are directly affected by degree of lattice mismatch, which follows the given relationship [17]:

$$t = \frac{a_s - a_f}{a_s}$$ (1)

where $a_s$ refers to the lattice constant of the substrate without any stress, $a_f$ corresponds to the lattice constant of the film and $t$ represents the lattice mismatch degree. The lattice mismatch degree between orthorhombic YbFeO₃ film and substrate is calculated by using equation (1) and shown in table 1.

Table 1 shows that the lattice mismatch degree between YbFeO₃ film and substrate followed the given order: YbFeO₃/sapphire(0001) > YbFeO₃/MgO(111) > YbFeO₃/YSZ(111) > YbFeO₃/STO(100) > YbFeO₃/SiO₂(0001). The YbFeO₃ film and sapphire(0001), MgO(111) and YSZ(111) substrates have shown a large degree of lattice mismatch, which led to the weak induction effect of substrate and lack of preferred orientation. The degree of lattice mismatch between YbFeO₃ film and STO(100) substrate is low led to the induction effect of the substrate is strong. Hence, YbFeO₃/STO(100) films have shown preferred orientation in (001) plane. It is worth mentioning that the degree of lattice mismatch between YbFeO₃ film and SiO₂(0001) substrate is minimum among tested substrates, theoretically, YbFeO₃/SiO₂(0001) films should exhibit the optimal orientation. However, YbFeO₃/SiO₂(0001) films did not exhibit any preferred orientation due to the large mismatch of the thermal expansion coefficients exists between the SiO₂ substrate and YbFeO₃ film. For instance, the thermal expansion coefficient of SiO₂ and YbFeO₃ is
2.3 \times 10^{-6} \text{ K}^{-1} [18] \text{ and } 1.1 \times 10^{-5} \text{ K}^{-1} [16], \text{ respectively. While the thermal expansion coefficient of STO is } 3.2 \times 10^{-5} \text{ K}^{-1} [19].

3.3. Surface morphology

Figures 7(A)–(E) present the high-magnification (10000X) SEM images of crystallized YbFeO$_3$ films, deposited on different substrates. It can be readily observed that the crystallized films exhibit uniform particles and compact surface. Figures 7(a)–(e) show relatively low-magnification (2000X) SEM images of crystallized YbFeO$_3$ films, deposited on different substrates. It can be seen that the surfaces of YbFeO$_3$/YSZ(111), YbFeO$_3$/MgO(111) and YbFeO$_3$/Sapphire(0001) films contain multiple cracks, which increased with increasing degree of lattice mismatch between YbFeO$_3$ film and substrate. On the other hand, YbFeO$_3$/STO(100) and YbFeO$_3$/SiO$_2$(0001) films exhibit a smooth surface without any obvious cracks. The SEM observations are consistent with the degree of lattice mismatch, as shown in table 1. Large compressive stress exists between the film and substrate due to a large degree of lattice mismatch between YbFeO$_3$ film and sapphire(0001), MgO(111) and YSZ(111) substrates, which led to the formation of cracks during crystallization.
On the other hand, the degree of lattice mismatch between YbFeO₃ film and STO (100) and SiO₂ (0001) substrate is relatively small. Hence, a crack-free and smooth surface has been observed after crystallization.

3.4. Transmission spectra

Due to the transmitted light is used in magneto-optical effect, small interference effect will little effect on transmitted light, then small interference effect between substrate and film is very important for the magneto-optical material. Figure 8 presents the transmission spectra of YbFeO₃ films deposited on different substrates, after annealing at 800 °C in the air. The transmission spectra of YbFeO₃/ quartz-glass, YbFeO₃/sapphire(0001), YbFeO₃/MgO(111) and YbFeO₃/SiO₂(0001) films have shown obvious interference patterns, which can be ascribed to the interference effect of the light that reflected from the film surface and film/substrate interface. The interference of the reflected light is influenced by the thickness (d), refractive-index (n) and absorption coefficient (α) of the film [20, 21]. The interference effect follows the given relationship [21]:

\[ 2nd = m\lambda \]  

(2)
where \( m \) refers to the order number and \( \lambda \) corresponds to the wavelength. For a film, the larger thickness (\( d \)) and higher refractive index (\( n \)) result in a larger order number (\( m \)), which leads to more interference fringes in transmission spectra.

On the other hand, the transmission spectra of \( \text{YbFeO}_3/\text{YSZ}(111) \) and \( \text{YbFeO}_3/\text{STO}(100) \) films exhibit the weak interference behavior. One should note that the refractive index of \( \text{YbFeO}_3 \) and \( \text{STO}(100) \) substrate is relatively close \([22, 23]\), which weakened the interference effect.

**Figure 6** XRD patterns of \( \text{YbFeO}_3/\text{SiO}_2(0001) \) films annealed at 800 °C.

**Figure 7.** SEM images of \( \text{YbFeO}_3 \) films on different substrates after annealing at 800 °C: (A, a) \( \text{YbFeO}_3/\text{sapphire}(0001) \), (B, b) \( \text{YbFeO}_3/\text{MgO}(111) \), (C, c) \( \text{YbFeO}_3/\text{YSZ}(111) \), (D, d) \( \text{YbFeO}_3/\text{STO}(100) \) and (E, e) \( \text{YbFeO}_3/\text{SiO}_2(0001) \).

### Table 1. Lattice mismatch degree between \( \text{YbFeO}_3 \) film and substrate.

| Film/substrate   | Matching crystal plane | Arrangement period of atoms (unit: Å) | Degree of lattice mismatch (\( t \)) |
|------------------|------------------------|---------------------------------------|-------------------------------------|
| \( \text{YbFeO}_3/\text{sapphire} \) | \( (010)_{\text{YbFeO}_3}/(0001)_{\text{sapphire}} \) | 11.114/12.970 | 14.31% |
| \( \text{YbFeO}_3/\text{MgO} \) | \( (010)_{\text{YbFeO}_3}/(111)_{\text{MgO}} \) | 5.557/5.936 | 6.38% |
| \( \text{YbFeO}_3/\text{YSZ} \) | \( (001)_{\text{YbFeO}_3}/(111)_{\text{YSZ}} \) | 7.570/7.253 | 4.37% |
| \( \text{YbFeO}_3/\text{STO} \) | \( (001)_{\text{YbFeO}_3}/(100)_{\text{STO}} \) | 7.570/7.810 | 3.07% |
| \( \text{YbFeO}_3/\text{SiO}_2 \) | \( (010)_{\text{YbFeO}_3}/(0001)_{\text{SiO}_2} \) | 5.557/5.405 | 2.81% |
3.5. Magnetic properties

Figure 9 presents the out-of-plane magnetization curves of as-deposited YbFeO$_3$ films deposited on different substrates. The YbFeO$_3$ films exhibited a large coercivity of $\sim 882$ Oe, which may be due to a stress existed in the film material, which makes the film structure changed, and then affects the magnetism of the film. Since the film thicknesses are in the range of 600 nm to 700 nm, the structure of the film is mainly influenced by substrate induction and stress. Under the double action of substrate induction and stress, the structure of the film was distorted to different degrees, which results in a certain difference in the magnetic properties of the films [3, 24]. Moreover, the saturation magnetization of YbFeO$_3$/STO(100) films is larger than other films, which can be ascribed to the preferred orientation and magnetic anisotropy of the YbFeO$_3$/STO(100) film. One should note that perovskite-type RFeO$_3$ phases exhibit obvious magnetic anisotropy [25]. According to the XRD analysis, presented in sections 3.1 and 3.2, the (001)-oriented YbFeO$_3$/STO(100) film has the maximum saturation magnetization, whereas YbFeO$_3$/quartz-glass, YbFeO$_3$/sapphire(0001), YbFeO$_3$/MgO(111), YbFeO$_3$/YSZ(111) and YbFeO$_3$/SiO$_2$(0001) films lack the preferred orientation and do not exhibit desirable magnetic behavior. In RFeO$_3$-type phases, the (001) direction can be easily magnetized except SmFeO$_3$ [26]. Therefore, YbFeO$_3$/STO(100) film, oriented in (001) direction, exhibited higher saturation magnetization than YbFeO$_3$ films oriented in other direction.
In summary, YbFeO$_3$ thin films have not been reported yet. In order to investigate the influence of substrate selection on magneto-optical properties of YbFeO$_3$ film, the MCD spectra of YbFeO$_3$/quartz-glass, YbFeO$_3$/sapphire(0001), YbFeO$_3$/MgO(111), YbFeO$_3$/YSZ(111), YbFeO$_3$/STO(100) and YbFeO$_3$/SiO$_2$(0001) films have been collected at room temperature. Figure 10 presents the MCD spectra of YbFeO$_3$ films on different substrates after annealing at 800 °C. MCD spectra of YbFeO$_3$ films exhibit four main peaks, located at 437 nm, 461 nm, 546 nm and 599 nm. According to the Tanabe-Sugano diagram of Fe$^{3+}$ ions in iron oxide octahedron [27], the peaks at 437 nm can be attributed to $^6A_g \rightarrow ^2A_{2g}^\pi T_{1g}$ transition, whereas the peaks at 461 nm, 546 nm and 599 nm can be ascribed to $^6A_g \rightarrow ^4T_{2g}$, $^4T_{1g}$ and $^6A_{1g}$ transitions, respectively. In addition, the MCD spectra of YbFeO$_3$ films deposited on different substrates, are similar in shape, but with different peak intensities. The MCD peak intensity of (001)-oriented YbFeO$_3$/STO(100) film is lower than other films, whereas YbFeO$_3$/quartz-glass film has shown the highest peak intensity. These results indicate the presence of magneto-optical anisotropy in as-deposited YbFeO$_3$ films. In general, the magneto-optical effect of (001)-orientation YbFeO$_3$ film is lower than other films. This phenomenon may be due to the stress of film changed with different substrates, and then the crystal field environment of Fe$^{3+}$ ions in the films changed, which results in different MCD signals. The different properties of films is just in line with the theme of this paper. The key point of this paper is to highlight that the inducing effect of substrates on films leads to different structures of films on different substrates, which leads to different properties of films.

### 3.6. MCD properties

MCD signal is caused by the different absorption coefficients for left and right handed polarizations in the magnetic field, which is an important method to characterize the magneto-optical properties of films and nanomaterials. It is worth mentioning that the magneto-optical properties the YbFeO$_3$ films have not been reported yet. In order to investigate the influence of substrate selection on magneto-optical properties of YbFeO$_3$ film, the MCD spectra of YbFeO$_3$/quartz-glass, YbFeO$_3$/sapphire(0001), YbFeO$_3$/MgO(111), YbFeO$_3$/YSZ(111), YbFeO$_3$/STO(100) and YbFeO$_3$/SiO$_2$(0001) films have been collected at room temperature.

Figure 10 presents the MCD spectra of YbFeO$_3$ films on different substrates. The transmission spectra of YbFeO$_3$ films are similar in shape, but with different peak intensities. The MCD peak intensity of (001)-oriented YbFeO$_3$ film is lower than other films, whereas YbFeO$_3$/quartz-glass film has shown the highest peak intensity. These results indicate the presence of magneto-optical anisotropy in as-deposited YbFeO$_3$ films. In general, the magneto-optical effect of (001)-orientation YbFeO$_3$ film is lower than other films. This phenomenon may be due to the stress of film changed with different substrates, and then the crystal field environment of Fe$^{3+}$ ions in the films changed, which results in different MCD signals. The different properties of films is just in line with the theme of this paper. The key point of this paper is to highlight that the inducing effect of substrates on films leads to different structures of films on different substrates, which leads to different properties of films.

### 4. Conclusions

In summary, YbFeO$_3$ thin films have been deposited on quartz-glass, sapphire(0001), MgO(111), YSZ(111), SrTiO$_3$(STO)(100) and SiO$_2$(0001) substrates by using radio frequency magnetron sputtering. The film quality and growth orientation of the films are remarkably influenced by choice of the substrate due to the difference in the degree of lattice mismatch between the substrate and YbFeO$_3$ film. The large degree of lattice mismatch led the formation of surface cracks and hindered the preferred growth orientation. The transmission spectra of YbFeO$_3$/STO(100) film showed small interference effect due to the refractive index of YbFeO$_3$ and STO(100) substrate is relatively close. Moreover, the YbFeO$_3$ films exhibited an obvious magnetic anisotropy, where (001)-oriented YbFeO$_3$/STO(100) films have shown the maximum saturation magnetization. In addition, the YbFeO$_3$ films have demonstrated large coercivity of ~882 Oe. For the first time, the magneto-optical properties of YbFeO$_3$ films have been characterized by MCD spectra, which exhibited four prominent peaks corresponding to $^6A_g \rightarrow ^2A_{2g}^\pi T_{1g}$ transition, and $^6A_g \rightarrow ^4T_{2g}$, $^4T_{1g}$ and $^6A_{1g}$ transitions, respectively. Furthermore, the magneto-optical properties of YbFeO$_3$ films have also exhibited an obvious anisotropy, where (001)-oriented YbFeO$_3$ films have shown far lower magneto-optical properties than other films. In conclusion, from the
magneto-optical effect and economic point of view, quartz glass may be a better candidate for the integrated magneto-optical equipment.

Acknowledgments

This project was supported by Science and Technology Foundation of Guizhou Province (Qiankehejichu [2018] 1007), Youth Scientific and Technological Talent Growth Project of Education Department of Guizhou Province (Qianjiaohe KY [2016]251), Major Construction Project of First-rate University in Guizhou Province (2017158134), Discipline and Master’s Site Construction Project of Guiyang University by Guiyang City Financial Support Guiyang University [HC-2019], Academic new seedling cultivation and innovation exploration special project, Heavy Duty Friction Material Special Adhesive Processing Pilot Production Base of Guiyang University (Guiyang Tianlong) (K1631000117).

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References

[1] Lyubutin I S, Dmitrieva T V and Stepin A S 1999 J. Exp. Theor. Phys. 88 590–7
[2] Vilarinho R et al 2019 Phys. Rev. B 99 064109
[3] Jeong Y K et al 2012 J. Am. Chem. Soc. 134 1450–3
[4] Ye J L et al 2014 J. Alloy. Compd. 617 850–4
[5] Zhang X Z et al 2017 J. Phys.: Condens. Matter 29 164001
[6] Anju A et al 2018 ACS Appl. Nano Mater. 1 3196–203
[7] Wang Z Q et al 2019 Mater. Res. Express. 6 055605
[8] Wang Y B et al 2011 J Cryst Growth. 318 927–31
[9] Gnatchenko S L et al 1989 J. Magn. Magn. Mater. 81 125–32
[10] Auluck S V 2008 J. Korean Phys. Soc 53 806–11
[11] Schmool D S et al 1999 J. Appl. Phys. 86 5712–7
[12] Lin N X et al 2017 J. Am. Ceram. Soc. 100 2952–8
[13] Gabey P A et al 2018 Nano Lett. 18 579–85
[14] Liu H et al 2018 Appl. Surf. Sci. 442 742–9
[15] Boudiar T et al 2004 J. Magn. Magn. Mater. 284 77–85
[16] Berenov A et al 2008 Solid State Ionics 179 1090–3
[17] Bramfitt B L 1970 Metallurgical Transactions 1 1987–95
[18] Kim Y J et al 2008 J. Mater. Sci. Technol. 24 143–4
[19] De Ligny D and Richet P 1996 Phys. Rev. B 53 3013–22
[20] Li Y P et al 2013 Appl. Surf. Sci. 264 538–44
[21] MÁrquez E et al 1992 J. Phys. D: Appl. Phys. 25 535–41
[22] Rajendran M, Krishna M G and Bhattacharya A K 2001 Thin Solid Films 385 230–3
[23] Thomas R and Dube D C 2000 Jpn. J. Appl. Phys. 39 1771–1775
[24] Tabakovic I, Inturi V and Riemer S 2002 J. Electrochem. Soc. 149 C18–22
[25] Bhat M et al 2006 Nucl. Instr. and Meth. in Phys. Res. B 243 134–42
[26] Kuze’menko A V et al 2003 J. Magn. Magn. Mater. 257 327–34
[27] Gavriliuk A G, Lyubutin I S and Struzhkin V V 2007 J. Exp. Theor. Phys. Lett. 86 532–6