Effect of strain in Nickel Ferrite thin films

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Abstract

Nickel ferrite epitaxial thin films grown by PLD technique simultaneously in a series of different thickness varying from 3 to 200 nm on the three (001) orientated substrates $SrTiO_3$ (STO), MgO and $0.72Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.28PbTiO_3$ (PMN-PT) are studied in this paper. The effects of epitaxial strain on the lattice structure, microstructure and magnetization of nickel ferrite thin films have been studied on several types of single-crystalline substrates with different lattice mismatch. The XRD difractograms show only (00l) substrate peaks and peaks that can be assigned to the (00l) reflexes of the spinel phase. The films are out-of-plane epitaxial oriented to the substrate. The thinnest films grown on STO and PMN-PT are under a small compressive strain, especially the films on PMN-PT. Here, the strain relaxation is not complete and the strain that is imposed by the substrates is partially maintained. With increasing thickness the strain relaxation of the films proceeds and the strain turns from compressive to tensile. The magnetic properties of a 200 nm nickel ferrite film deposited on STO, MgO and PMN-PT are investigated and correlated with the strain states of the films. The film grown on MgO has the smallest coercive field (980 Oe), whereas the coercive fields of the films grown on STO (2070 Oe) and PMN-PT (2360 Oe) are larger and of about the same magnitude.

Introduction

Ferrite thin films with spinel structure are potentially interesting and scientifically promising for high frequency devices, where low conductivity and high saturation magnetization are important aspects. The properties of spinel ferrites are of great interest due to its wide implication in magnetic recording media, microwave devices, computer hard disc read/write heads and micro-electromechanical systems and sensors. Among all the ferrites, nickel ferrite ($NiFe_2O_4$) is a ferrimagnetic material used in thin film form efficiently for magnetic cores, opto-magnetic devices, bubble memory devices and vertical recording magnetic materials applications and spintronics [1].

Experimental

The nickel ferrite target was made of a single phase nickel ferrite powder synthesized by the coprecipitation method. The nickel ferrite thin films were deposited on commercial (001) oriented STO, MgO and PMN-PT substrates using the pulsed laser deposition (PLD) technique. The substrates were ultrasonically washed using acetone and methanol before deposition. A KrF excimer laser (248 nm wavelength and 23 ns pulse width, Lambda Physics) was used for ablating the nickel ferrite target with an energy density of about 4 J/cm^2 and a repetition rate of 10 Hz. The laser beam was focused by optical lenses at an angle of about 45 deg to the rotating target and the substrate was placed at a distance of 4 cm to the target. Before deposition, the chamber was evacuated to 0.08 mbar. The films were deposited at a substrate temperature of 650 °C. After deposition, the films were annealed for 15 min and cooled down to room temperature at an oxygen pressure of about 0.5 bar. The crystallinity and orientation of the thin films were determined by X-ray diffraction (XRD) analysis using ω −2θ scans, which were performed by Cu radiation (wavelength of 0.154017 nm) using an Panalytical X'Pert MRD diffractometer. Before each XRD analysis, the sample alignment was performed on STO (002) MgO(002) PMN-PT(002) peaks of the substrate in order to avoid the peak shift due to the sample misalignment. The magnetization of thin films was measured for in-plane (magnetic field applied parallel to the film) configurations using a superconductor quantum interference device (SQUID) magnetometer (Quantum Design, MPMS-5 T). The magnetic hysteresis loops (M–H curves) were obtained after subtracting the diamagnetic contribution of the substrate. Atomic force microscopy (AFM) has been employed to investigate the surface of the films. A *DI Nanoscope III* AFM in tapping mode was used for this purpose.

Results and discussion

The NFO films were grown by on-axis pulsed laser deposition from the $NiFe_2O_4$ target simultaneously on STO, MgO and PMN-PT. The films have been grown in a series of different thickness varying from 3 to 200 nm on the (001) orientated substrates.

In figure 1.a) the reflectivity curves of the films grown on PMN-PT substrates are shown. The thickness of the films is calculated from the distance of the oscillations. The observation of clear thickness fringes is an indication for a good surface roughness of the films.

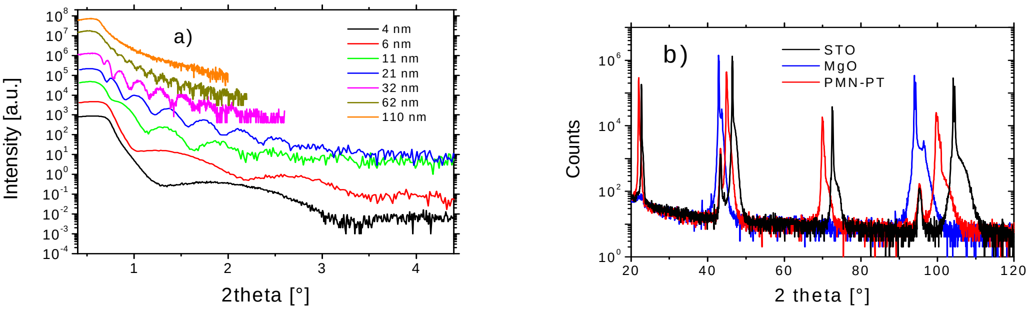


Figure 1. a)The reflectivity curves of the films grown on PMN-PT substrates b) X-ray diffraction patterns (Bragg-Brentano θ-2θ) of the 200nm films grown on STO, MgO and PMN-PT[1].

Wide angle θ-2θ XRD scans of the films grown on STO, MgO and on PMN-PT have been recorded to investigate the phase-purity and epitaxial nature of the films and are plotted in figure 1.b). The scans show only (00l) substrate peaks and peaks that can be assigned to the (00l) reflexes of the spinel phase. The films are out-of-plane epitaxial oriented to the substrate. There are no peaks corresponding to other phases or impurities of films.

Reciprocal space maps (RSM) around the (1 1 3) substrate peak and the (2 2 6) film peak were recorded in order to get further information about the strain states of all the films and lattice parameters are presented in Table 1.We find that the peak positions of thick films reveal a c parameter that almost coincides with the lattice parameter of bulk NFO. This indicates that thick films are essentially strain-relaxed due to the large lattice misfit with STO and PMN-PT (-6.65% and -3.55%). For the thinnest films grown on PMN-PT the peak positions are slightly shifted to the left, i.e. the c lattice parameter is enhanced. Here the films still take up some partial strain from the substrate and the films are not fully relaxed. The RSM reveal that the films grown on MgO substrate are coherent with the substrate, i.e. the film is strained in-plane to the MgO lattice.

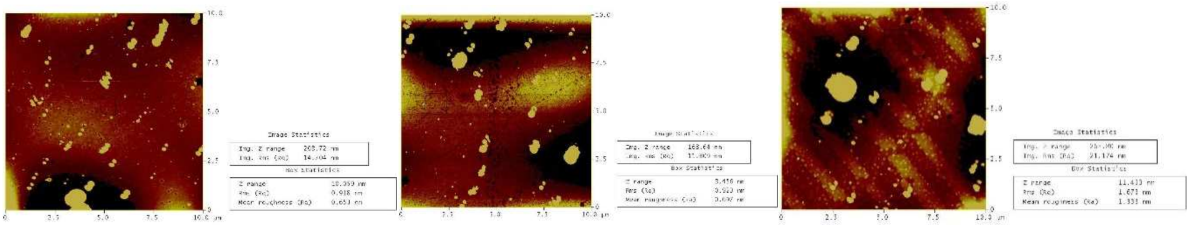
Table 1. In- and out-of-plane lattice parameters of the films [1].

Sample	Substrate	thickness	$a_{substrate}$	strain	c $_{film}$	a $_{film}$
		nm	A	%	A	A
AH520	STO	22	3.905	-0.053	8.348	8.342
AH517	STO	32	3.905	0.0007	8.346	8.346
AH515	STO	62	3.905	0.120	8.344	8.356
AH516	STO	110	3.905	0.246	8.337	8.348
AH521	STO	200	3.905	0.055	8.341	8.344
AH520	PMN-PT	22	4.022	-0.278	8.389	8.323
AH517	PMN-PT	32	4.022	-0.203	8.376	8.329
AH515	PMN-PT	62	4.022	0.184	8.348	8.362
AH516	PMN-PT	110	4.022	0.218	8.329	8.364
AH521	PMN-PT	200	4.022	0.236	8.324	8.365
AH521	MgO	200	4.212	0.895	8.263	8.421

The thickest films of the NFO films all experience a small tensile strain. This tensile strain can be explained by the thermal mismatch between film and substrates [2]. The film on MgO is grown coherent and thus has a quite large tensile strain of about +0.9%. The thinnest films grown on STO on PMN-PT are under a small compressive strain, especially the films on PMN-PT. Here, the strain relaxation is not complete and the strain that is imposes by the substrates is partially maintained. With increasing thickness the strain relaxation of the films proceeds and the strain turns from compressive to tensile.

2 Topography of the Nickel ferrite films

Atomic force microscopy (AFM) was used to investigate the surface of the films. AFM images reveal a film surface that shows a flat film surface but also a large number of droplets. Those droplets are big particles that are formed during the PLD process and are incorporated into the film.

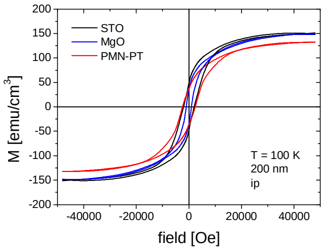


(a) STO (b) MgO (c) PMN-PT

Figure 2: Surface morphology images of 60 nm films of nickel ferrite deposited on a) STO, b) MgO, c) PMN-PT taken by AFM.

3 Magnetic properties of the films

The magnetic properties of the N1 films deposited on STO, MgO and PMN-PT are investigated in this part and correlated with the strain states of the films. The 200 nm thick films have been studied since they provide the largest magnetic signal. Fig. 3 shows the in-plane M–H loops at 100K . From the M-H loops the magnetic parameters, such as remanent magnetization M_r, saturation magnetization M_s and coercive H_c are determined. The parameters are listed in table 2. The saturation magnetizations of the films are found to be in the range 130-150 emu/cm^3. The magnetization of the films is also lower than the bulk value of NFO. This is an experimental observation that was often reported for ferrite spinel films.



Nickel	a [Å]	c [Å]	strain [%]	M_r [emu/ cm3]	M_s [emu/ cm3]	M_r/M_s	H_c [Oe]
PMNPT	8.365	8.324	0.236	37.0	131.5	0.281	2360
STO	8.344	8.341	0.055	47.8	150.2	0.318	2070
MgO	8.421	8.263	0.895	35.1	149.1	0.235	980

Figure 3 In-plane magnetization versus field (M–H) loops at room temperature of 200 nm nickel ferrite–films grown on an STO, MgO respectively PMN-PT substrates. Table 2 Parameters of in-plane measurement of the 200 nm film [1]

The total magnetic moment per formula unit we calculated using to be 1.00 μ_B for PMNPT, 1.153 μ_B for STO and 1.145 μ_B for MgO. A commonly accepted explanation for the reduced Ms found films is the presence of anti-phase boundaries (APB) [3]. The film on PMN-PT has the largest lattice mismatch and is thus likely to have the highest concentration of APBs. The lowest saturation magnetization for the film on PMN-PT is in agreement with this picture.

For all films the magnetic hysteresis curve are slim and the ratio M_r/M_S is small, which indicates that the in-plane measurement is along a magnetic hard axis and that the magnetic anisotropy is out-of-plane. This is in agreement with the tensile strain found in the films. The film on MgO has a significantly lower Mr/M_S and H_c than the films on STO and PMN-PT. This means that the film on MgO has the largest out-of-plane anisotropy. It is a result of the pronounced negative magnetostriction in NFO that forces the easy axis to rotate further into the film normal and enhance the anisotropy under increasing tensile strain. The measurements show that epitaxial strain can be used to tailor magnetic properties of NFO films.

Conclusion

Epitaxial films of nickel ferrite have been grown on single crystalline (001) oriented SrTiO3 and MgO and PMN-PT substrates. We have observed that thin films grown under compression on STO and PMN-PT. The saturated magnetization we observe to be the smallest for the film grown on PMN-PT. We also find a correlation of epitaxial strain and magnetic anisotropy. The results are in agreement with a strain-driven change of the magnetic anisotropy that is based on the large negative magnetostriction of NFO. The results demonstrate that epitaxial strain can be deployed to tune the magnetic properties of nickel ferrite films. This could potentially be used to produce films with properties designed for specific application.

Acknowledgements

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