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FeGa/MgO/Fe/GaAs(001) magnetic tunnel junction: Growth and magnetic properties

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ABSTRACT

Research on spintronics and on multiferroics leads now to the possibility of combining the properties of these materials in order to develop new functional devices. Here we report the integration of a layer of magnetostrictive material into a magnetic tunnel junction. A FeGa/MgO/Fe heterostructure has been grown on a GaAs(001) substrate by molecular beam epitaxy (MBE) and studied by X-ray magnetic circular dichroism (XMCD). The comparison between magneto optical Kerr effect (MOKE) measurements and hysteresis performed in total electron yield allowed distinguishing the ferromagnetic hysteresis loop of the FeGa top layer from that of the Fe buried layer, evidencing a different switching field of the two layers. This observation indicates an absence of magnetic coupling between the two ferromagnetic layers despite the thickness of the MgO barrier of only 2.5 nm. The in-plane magnetic anisotropy has also been investigated. Overall results show the good quality of the heterostructure and the general feasibility of such a device using magnetostrictive materials in magnetic tunnel junction.

1. Introduction

Research in multiferroics is gaining interest, [1,2] and relevance as these materials make it possible to control magnetic order through an applied electric field. This has been achieved in magnetoelectric materials among which $BiFeO_3$. [3] However $BiFeO_3$ has a little magnetoelectric coupling that has prevented up to now the use of this material in real devices [4]. Therefore the scientific community is in search of other paths to couple magnetic and electric orders. One possibility is the preparation of nanostructures composed by different layers where properties of each layer are combined. Following this strategy, researchers have shown the properties of ferromagnetic/ferroelectric interfaces [5] or even ferromagnetic/multiferroic interfaces [1]. Magnetostrictive materials, with the intrinsic coupling between strain and ferromagnetism, have attracted interest for growing bilayers piezoelectric/magnetostrictive in which the magnetization can be governed by an external electric field. In this context, epitaxial magnetostrictive materials are nowadays subject of intense research and in particular galfenol ($Fe_{1-x}Ga_x$) for its potential industrial applications having one of the largest known magnetostrictive coefficients apart from rare earth alloys [6].

On another hand, research is also addressing spintronics [7] and the magnetic tunnel junctions (MTJ) that were the first potential devices [8]. The MTJ has quickly evolved to industrial applications, however research is still going on to improve its performances [9] or to use them as spin filter and injection devices also in combination with diluted magnetic semiconductors [10]. Thus the integration into magnetic tunnel junctions of new properties such as magnetostriction would be of great interest in the perspective of controlling the resistance of the junction through the control of the strain. As the Fe/MgO interface has shown great efficiency for tunnel magnetoresistance [11], we propose here the following heterostructure: $Fe_{1-x}Ga_x$/MgO/Fe/GaAs(001). We discuss the first results obtained on these heterostructures regarding the growth protocol and the measured magnetic properties.

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2. Experimental details

A heterostructure of $Fe_{0.8}Ga_{0.2}$(20 nm)/MgO(2.5 nm)/Fe(5 nm) ultra-thin layers has been grown on GaAs(001) substrate (Fig. 1) in two stages. In the first stage, performed in the MBE chamber of APE beamline at Elettra in Trieste, the surface oxide layer of a commercial undoped GaAs(001) crystal was removed by cycles of bombardment with Ar+ at 600 eV of kinetic energy and annealing at 850 K until a 1 × 1 LEED pattern with sharp spots was observed. On this surface, we evaporated Fe (5 nm) and MgO (2.5 nm) from e-beam evaporators at room temperature. The deposition rate was about 1 Å/min determined with a quartz crystal balance. Fe and MgO epilayers showed the same (001) out-of-plane orientation and with in-plane MgO[100] axis aligned with the [110] crystalline direction of Fe layer [12] (while Fe[110] layer axes are epitaxied with GaAs[110] substrate axes). The thickness of the Fe bottom layer has been chosen to ensure the continuity of the layer and hence the ferromagnetism of the layer [13] while the thickness of the MgO film was chosen close to the maximum of the tunneling magnetoresistence in Fe/MgO/Fe structures [11]. Once prepared, the MgO/Fe epilayers on GaAs(001) substrate, they were removed from vacuum chamber and shipped to the University of Paris. In the second stage, the growth of $Fe_{1-x}Ga_x$ films on MgO/Fe epilayers were performed in a molecular beam system. Before the growth, the MgO/Fe epilayers on GaAs(001) substrate was cleaned in UHV by heating to 120 °C to remove organic surface contamination. The substrate temperature is gradually increased until 180 °C, the surface MgO/Fe epilayer showed a weak 1 × 1 streak-like RHEED diffraction pattern. On this MgO/Fe epilayer surface 20 nm-thickness of $Fe_{0.8}Ga_{0.2}$ thin films were deposited by molecular beam epitaxy with growth rate of 0.2 nm per minute and with an appropriate stoecchiometry proportion of the beam equivalent pressures of Fe and Ga [14]. At the early stage of the growth, the surface of $Fe_{1-x}Ga_x$ film showed 3D-spot-like features and once the coverage increases the spots were accompanied with steaks patterns, indicating the improvement of the crystalline film quality. This ordered $Fe_{1-x}Ga_x$(001) surface has in-plane aligned cubic axes with the respective MgO layer axes; azimuthal orientation relationship: $Fe_{1-x}Ga_x$[110]||MgO[100] and $Fe_{1-x}Ga_x$[1–10]||MgO[010] (Fig. 1). Following the growth, the films were covered by a protective 6 nm Au capping layer at room temperature. The same procedure was used for growing another $Fe_{1-x}Ga_x$ heterostructure with $x=0.14$.

XAS (X-ray Absorption Spectroscopy) and XMCD (X-ray Magnetic Circular Dichroism) measurements have been carried out at the APE beamline on the Elettra synchrotron light source. [15] The X-ray beam is provided by an Apple-II undulator which is able to produce a high flux of linearly or circularly polarized light. The overall energy resolution of incident radiation during measurement was set around $E/\Delta E=3000$. Spectra were recorded with 75% circularly polarized X-rays on the samples by total electron yield (TEY). The experimental chamber is equipped with a magnet providing an external magnetic field along an in-plane axis of the sample and collinear to the plane of incident X-ray beam. During measurements we fixed the angle between the X-ray beam and the normal at the sample surface to 45°. XMCD spectra are recorded in total electron yield at remanence reversing the magnetization at each point of the XAS spectra. Magneto-optic kerr effect (MOKE) has been performed ex-situ. The hysteresis loops were measured with MOKE magnetometer using a p-polarized 633 nm He–Ne laser light (5 mW maximum power), whose intensity was modulated at 50 kHz with a chopper (Hinds Instruments). All the measurements were performed in longitudinal geometry i.e. with field applied into both the film and the light scattering plane.

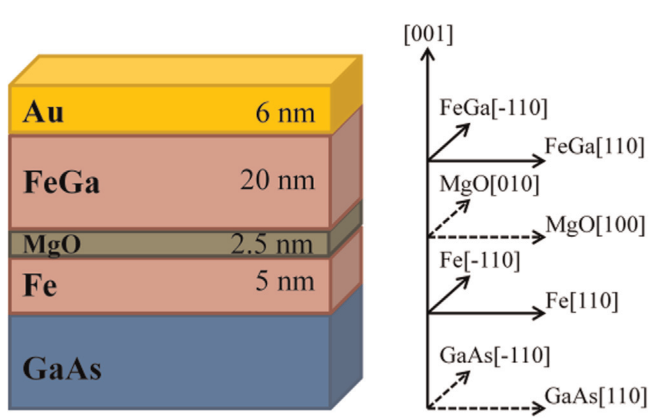

Fig. 1. Scheme of the heterostructure.

3. Results and discussion

The samples have been first studied by X-ray absorption spectroscopy. Fig. 2 shows the Fe $L_{2,3}$ absorption spectra (black and red curves) and the subsequent XMCD curves (blue) of the two $Fe_{1-x}Ga_x$ samples with $x=0.20$ (Fig. 2a) and $x=0.14$ (Fig. 2b). All the spectra have been acquired by collecting the total electron yield excited by the X-ray absorption and secondary decays and therefore, due to the limited escape depth of photoelectrons [16,17], are mostly representatives of the $Fe_{1-x}Ga_x$ top layer.

First, one can observe that both spectral shapes are “band-like”, without sharp peaks indicating localized states, and therefore indicate the metallic character of the two $Fe_{1-x}Ga_x$ layers. In

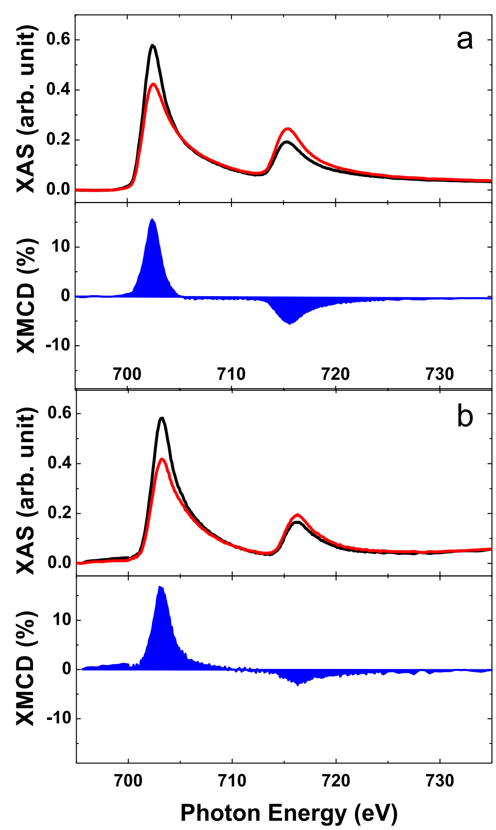

Fig. 2. XAS spectra of (a) $Fe_{0.8}Ga_{0.2}$ and (b) $Fe_{0.86}Ga_{0.14}$ at remanence after positive (black) and negative (red) magnetic impulse (200 Oe) and the difference (XMCD signal in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).