Materials Science-Poland, Vol. 24, No. 3, 2006

Week interlayer exchange coupling in Fe–Zr and Fe–Ti layered structures

L. SMARDZ[1*], K. SMARDZ[2]

[1]Institute of Molecular Physics, Polish Academy of Sciences,
M. Smoluchowskiego 17, 60-179 Poznań, Poland

[2]Institute of Materials Science and Engineering, Poznań University of Technology,
pl. Skłodowskiej-Curie 5, 60-965 Poznań, Poland

20 nm Fe/d_{Zr} Zr/20 nm Fe and 20 nm Fe/d_{Ti} Ti/20 nm Fe trilayers with wedged Zr and Ti sublayers were prepared at room temperature using UHV (5×10^{-10} mbar) RF/DC magnetron sputtering. The reesults showed that the Fe sublayers are ferromagnetically coupled up to a Zr or a Ti spacer thickness of about 1.5 or 2 nm, respectively. Furthermore, a weak antiferromagnetic (ferromagnetic) coupling of the Fe sublayers was observed for a Zr (Ti) thickness range of 1.5–3 nm (2–3.4 nm). The Fe sublayers are very weakly exchange coupled or decoupled for $d_{Zr} > 3$ nm and $d_{Ti} > 3.4$ nm. The small decoupling Ti and Zr thickness can be explained by the spontaneous formation of a quasi-amorphous structure of paramagnetic spacer during the deposition process.

Key words: *magnetic film;, multilayers; exchange coupling*

1. Introduction

In our previous papers, we have shown that polycrystalline Co sublayers are ferromagnetically (FM) coupled up to Ti [1] and Zr [1, 2] spacer thicknesses of about 2 and 2.5 nm, respectively. Furthermore, a weak antiferromagnetic (AFM) coupling of the Co sublayers was observed for a Ti (Zr) thickness range of 2–2.7 nm (2.5–3.2 nm). The Co sublayers were very weakly exchange coupled or decoupled for $d_{Ti} > 2.7$ nm and $d_{Zr} >$ 3.2 nm. The rapid decrease of interlayer exchange coupling with Ti and Zr spacer thickness could be explained by its strong damping due to the spontaneous formation of a non-magnetic quasi-amorphous Ti–Co and Zr–Co alloy layer at the interface during the deposition process. The above behaviour is also in agreement with experimental results for interlayer coupling studies across amorphous metallic $Cu_{65}Zr_{35}$ spacers [3].

*Corresponding author, e-mail: smardz@ifmpan.poznan.pl

In this paper, we report on the magnetic exchange coupling of polycrystalline ($d_{Fe} > d_{crit}$) Fe sublayers across a paramagnetic noncrystalline spacer in Fe/Zr/Fe and Fe/Ti/Fe trilayers. Very recently we have shown that iron sublayers grow on sufficiently thick zirconium [4, 5] ($d_{Zr} > 0.7$ nm) and titanium [6] ($d_{Ti} > 0.6$ nm) sublayers in the soft magnetic nanocrystalline phase up to a critical thickness of $d_{crit} \sim 2.3$ nm. For thicknesses greater than d_{crit}, the Fe sublayers undergo a structural transition to the polycrystalline phase with a much higher coercivity. On the other hand, it is well known that suitable annealing of Fe/Zr and Fe/Ti MLs leads to the formation of an amorphous phase due to a solid state reaction [7, 8]. Therefore, the spontaneous formation of an amorphous or nanocrystalline nonmagnetic Zr–Fe and Ti–Fe spacer between Fe sublayers is very likely to proceed during the deposition of the Fe/Zr(Ti)/Fe trilayer or Fe/Zr (Fe/Ti) multilayers.

2. Experimental

Fe/Zr/Fe and Fe/Ti/Fe trilayers with wedged Zr and Ti sublayers were prepared on glass substrates at room temperature using UHV (5×10^{-10} mbar) DC/RF magnetron sputtering [1]. The Fe layers (d_{Fe} = 20 nm) were deposited using a DC source. RF source was used to prepare the wedged Zr and Ti layers ($0 < d_{Zr(Ti)} < 10$ nm). Typical deposition rates for the Fe and Zr sublayers were 0.1 and 0.05 nm/s, respectively. After outgassing the glass substrate at 500 K for 30 minutes, we first deposited a Fe layer. A wedged Zr or Ti spacer layer was then grown immediately on the Fe layer. Finally, a 3 nm Au cap layer was deposited to prevent the oxidation of the top Fe sublayer. The chemical composition and the purity of all layers was checked *in situ* immediately after deposition, after transferring the samples to an UHV (4×10^{-11} mbar) analysis chamber equipped with X-ray photoelectron spectroscopy (XPS). The structures of the samples with step-like wedge forms (areas with Fe and Zr sublayers of constant thickness) was examined *ex situ* by standard θ–2θ X-ray diffraction using CuK_α radiation. The magnetic characterisation of the wedged Fe/Zr MLs was carried out at room temperature using the magnetooptical Kerr effect and a vibrating sample magnetometer.

3. Results and discussion

Results of systematic high-angle X-ray diffraction studies as a function of Fe and Zr sublayer thickness for 20 nm Fe/d_{Zr} Zr/20 nm Fe, and 20 nm Fe/d_{Ti} Ti/20 nm Fe trilayers with d_{Zr} (d_{Ti}) greater than ~3 nm showed only (110) and (002) reflections of bcc Fe and hcp Zr (Ti) in the patterns, respectively. Only a broad peak related to Fe sublayers was observed for trilayers with d_{Zr} (d_{Ti}) < ~3 nm, in agreement with the X-ray diffraction studies for Co/Zr, Co/Ti, and Fe/Ti multilayers reported in Refs.

[4–6]. The absence of Zr and Ti reflections for d_{Zr} (d_{Ti}) < ~3 nm is consistent with UHV STM images [9] which showed randomly oriented nanocrystalline grains with an average size D of ~3–5 nm.

In situ XPS analyses of freshly deposited Fe and Zr layers revealed no contamination elements such as oxygen and carbon. In the XPS experiment, we have also studied Fe layer growth on a 10 nm Zr underlayer and Zr layer growth on a 10 nm Fe underlayer. From the exponential variation of the XPS Fe-2p and Ti-2p and Zr-3d integral intensities with increasing layer thickness, we conclude that the Fe, Ti, and Zr sublayers grow homogeneously during the deposition of the trilayers [9, 10].

In the case of wedged trilayers, the bottom Fe layer was deposited on a rather rough glass substrate. Such a layer showed a greater coercivity compared to the top Fe layer, which was deposited on a quasi-amorphous Zr–Fe (Ti–Fe) interlayer, formed spontaneously during the deposition process [1, 2]. For a sufficiently small Zr–Fe (Ti–Fe) thickness, however, the FM exchange coupling energy of the Fe layers across the paramagnetic spacer is large enough for the simultaneous magnetisation reversal process of the bottom and top sublayers. On the other hand, for a weaker interlayer exchange coupling (d_{Zr} > ~1.5 nm, d_{Ti} > ~2 nm), we have observed step-like hysteresis loops due to different coercivities of the bottom and top Fe layers.

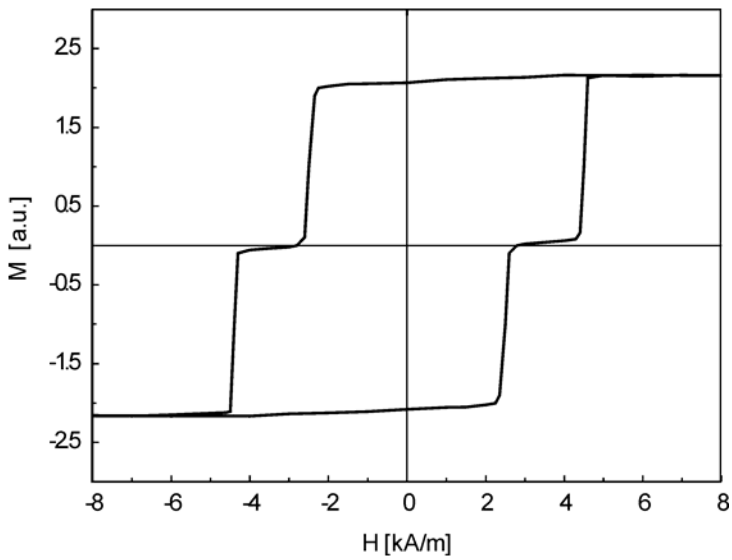

Fig. 1. A hysteresis loop of the 20 nm –Fe/2 nm – Zr/20 nm – Fe trilayer

Figure 1 shows an example of a step-like hysteresis loop measured for the Fe/Zr/Fe trilayer with d_{Zr} = 2 nm. In the intermediate case between fully coupled and independent (i.e. fully decoupled) Fe layers, the exchange field felt by each layer due to the presence of the second layer decreases (increases) the observed switching field of the soft (hard) magnetic layer in the case of AFM coupling, and vice versa for FM coupling [1]. The two observed significantly different coercive fields in Fig. 1, H_{c1} and H_{c2}, originate from the soft and hard magnetic Fe layers, respectively [1, 2].

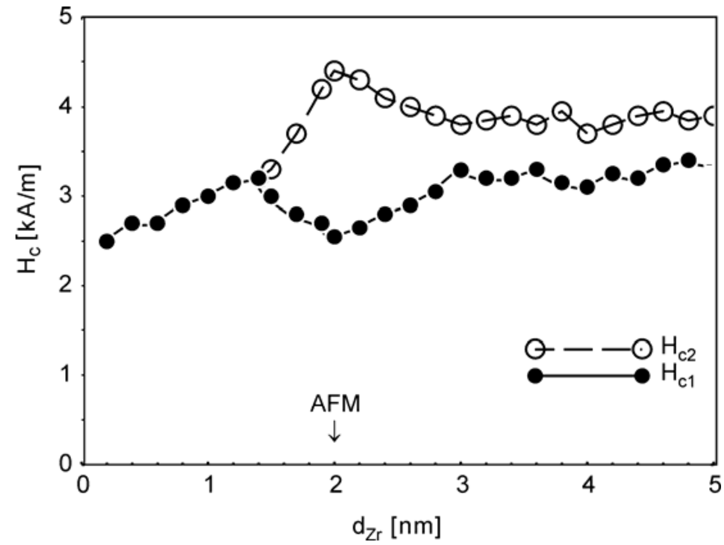

Fig. 2. Two different coercive fields H_{c1} and H_{c2} as functions of Zr interlayer thickness for a wedged 20 nm Fe/d_{Zr} Zr/20 nm Fe trilayer

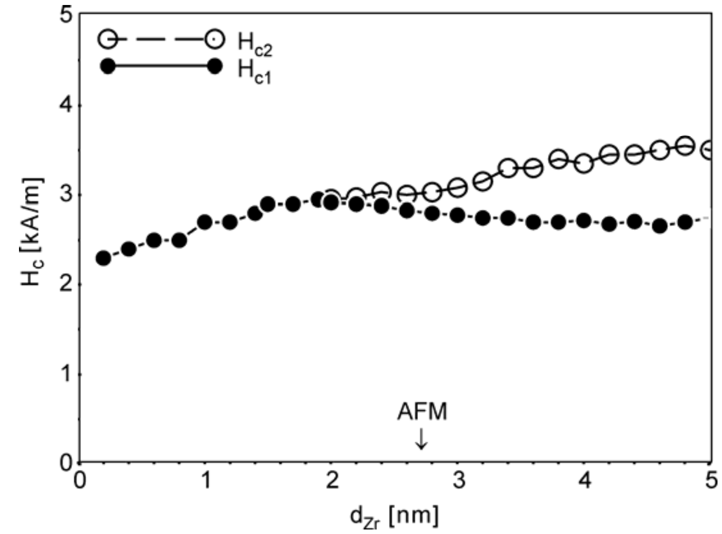

Fig. 3. Two different coercive fields H_{c1} and H_{c2} as functions of Ti interlayer thickness for a wedged 20 nm Fe/d_{Ti} Ti/20 nm Fe trilayer

The results of systematic studies of coercivity as a function of Zr and Ti interlayer thickness are presented in Figs. 2 and 3, respectively. The spacer thickness dependence of coercivity for wedged trilayers allows us to characterise the week interlayer exchange coupling of Fe sublayers [1, 2]. For $d_{Zr} \approx 2$ nm (Fig. 2), we observe a weak minimum and maximum for H_{c1} and H_{c2}, respectively. The above behaviour possibly indicates weak AFM coupling between Fe layers, with a maximum near $d_{Zr} \approx 2$ nm. The difference between H_{c1} and H_{c2} determined for the Fe/Ti/Fe trilayer (Fig. 3) is rather small for Ti layer thickness between ~2 and ~3.4 nm. The above behaviour could indicate a weak FM coupling between Fe layers for Ti spacer thickness ~2–3.4 nm. The absence of weak AFM coupling for the Fe/Ti/Fe trilayer could be associated with a low density of the ferromagnetic "bridges" between Fe sublayers. Furthermore, coercivity measurements show that Fe layers are very weakly exchange coupled or decoupled for $d_{Zr} > 3$ nm ($d_{Ti} > 3.4$ nm). The small decoupling Zr and Ti thicknesses could be explained by a spontaneous formation of a quasi-amorphous structure in the paramagnetic spacer during deposition [1–3]. In the case of the Fe/Zr/Fe (Fe/Ti/Fe) trilayer, the spacer interlayer consists of a Fe_xZr_{1-x} (Fe_xTi_{1-x}) alloy and pure Zr (Ti) layer. For the ultrathin spacer ($d_{Zr} < 2$nm), the Fe_xZr_{1-x} (Fe_xTi_{1-x}) alloy layer remains practically quasi-amorphous, with a variable concentration (x) in the direction perpendicular to the substrate. This is consistent with the results of our XRD and magnetisation studies for Fe/Zr and Fe/Ti [4–6] MLs. In the case of such a quasi-amorphous structure of the spacer, a strong damping of the interlayer exchange coupling is to be expected from the theory based on the RKKY interaction [3]. The above effect could explain our results of the studies of coercivity as a function of Zr and Ti spacer thickness, shown in Figs. 2 and 3. Furthermore, amorphous Fe–Ti and Fe–Zr alloys approximately fulfil the Nagel–Tauc criterion [1–3] ($2k_F = k_p$), where k_F and k_p denote the Fermi k-vector and ion correlation radius, respectively. Therefore, for Fe –Zr alloy spacers the location of the first weak AFM maximum was detected at $d_{Zr} \approx 2$ nm, in agreement with the large oscillation period of the exchange coupling ($\lambda \approx 1/|2k_F - k_p|$) expected from the theory [3].

In summary, the planar growth of Fe and Zr (Ti) sublayers was confirmed *in situ* by X-ray photoelectron spectroscopy. Furthermore, a weak AFM (FM) coupling of the Fe sublayers was observed for Zr (Ti) thickness between 1.5 and 3 nm (2 and 3.4 nm). The Fe layers are very weakly exchange coupled or decoupled for $d_{Zr} > 3$ nm ($d_{Ti} > 3.4$ nm). The rapid decrease in exchange coupling could be explained by its strong damping due to the formation of a non-magnetic quasi-amorphous alloy layer at the interfaces.

Acknowledgements

This work was financially supported by the Polish Committee for Scientific Research under grant No. PBZ KBN 044/P03/02 2001.

References

[1] SMARDZ L., Sol. State Comm., 112 (1999), 693.
[2] SMARDZ L., Czech. J. Phys., 52 (2002), 209.
[3] BÜRGLER D.E., SCHALLER D.M., SCHMIDT C.M., MEISINGER F., KROHA J., MCCORD J., HUBERT A., GÜNTHERODT H.J., Phys. Rev. Lett., 80 (1998), 4983.

[4] SMARDZ L., SMARDZ K., Mol. Phys. Rep., 40 (2004), 137.
[5] SMARDZ L., J. All. Comp., 389 (2005), 17.
[6] SMARDZ K., SMARDZ L., Mater. Sci.-Poland, 24 (2006), 827.
[7] SAMWER K., Phys. Reports ,161 (1988), 3.
[8] STOBIECKI T., KOPCEWICZ M., CASTAÑO F.J., Chaos, Solitons and Fractals, 10 (1999), 2031.
[9] SMARDZ K., PhD Thesis, Institute of Molecular Physics, Polish Acad. Sci., Poznań (Poland), 1999.
[10] BRIGGS D., [in:] *Handbook of X-ray and Ultraviolet Photoelectron Spectroscopy*, D. Briggs (Ed.), Heyden & Son Ltd., London, 1977, p. 153 and references therein.

Received 1 June 2005
Revised 10 October 2005