ARCHIVES OF METALLURGY AND MATERIALS
Volume 50 2005 Issue 2

J. KANAK[*, **], T. STOBIECKI[*], G. REISS[***], H. BRÜCKL[***]

MICROSTRUCTURE AND TEXTURE OF Ir-Mn BASED MAGNETIC TUNNEL JUNCTIONS

MIKROSTRUKTURA I TEKSTURA MAGNETYCZNYCH ZŁĄCZ TUNELOWYCH NA BAZIE Ir-Mn

Magnetic tunnel junctions (MTJs) with the structure: substrate Si(100)/SiO_x 47nm/ system of seed-buffer layers /IrMn 12nm/CoFe 15nm/AlO_x 1.4nm/NiFe 3nm/Ta 5nm were prepared with four different buffers: (a) Cu 25nm, (b) Ta 5nm/Cu 25nm, (c) Ta 5nm/Cu 25nm/Ta 5nm/Cu 5nm and (d) Ta 5nm/Cu 25nm/Ta 5nm/NiFe 2nm/Cu 5nm in order to enhance crystal texture of the MTJs. The annealed in vacuum at 275°C junctions were characterized by XRD θ-2θ-scans, rocking curve (ω-scans) and pole figures, in order to establish the correlation between texture and magnetic exchange bias coupling of IrMn/CoFe. The texture degree in the stack of MTJ depends on material, which was used for the buffer layers, and sequence of the layers. The strongest texture has been obtained if the seed layer of Ta was used (buffer (b)). The multilayer stack is textured in columnar-like fashion, which produces roughness. It was found, from the analysis of magnetic hysteresis loops and rocking curves of the CoFe layer, that the exchange bias and coercivity fields of CoFe pinned layer increase about two times in the case of using strong textured seed-buffer system (b). The design of seed-buffer layers allows to optimize the exchange bias coupling in magnetoelectronics devices.

Keywords: MTJ magnetic tunnel junction; XRD; texture; interfacial magnetic properties; magnetic exchange bias coupling.

Magnetyczne złącza tunelowe o strukturze wielowarstwowej: podłoże Si(100)/SiO_x 47nm/warstwy buforowe /IrMn 12nm/CoFe 15nm/AlO_x 1.4nm/NiFe 3nm/Ta 5nm zostały napylone z użyciem czterech różnych układów warstw buforowych: (a) Cu 25nm, (b) Ta 5nm/Cu 25nm, (c) Ta 5nm/Cu 25nm/Ta 5nm/Cu 5nm oraz (d) Ta 5nm/Cu 25nm/Ta 5nm/NiFe 2nm/Cu 5nm w celu poprawy tekstury złącza. Na złączach wygrzanych w próżni w temperaturze 275°C wykonano pomiary dyfrakcyjne: pomiar θ-2θ, pomiar ω (*rocking curve*) oraz pomiar figur biegunowych w celu znalezienia korelacji pomiędzy teksturą a

---

[*] KATEDRA ELEKTRONIKI, AKADEMIA GÓRNICZO-HUTNICZA, 30-059 KRAKÓW, AL. MICKIEWICZA 30
[**] WYDZIAŁ FIZYKI I INFORMATYKI STOSOWANEJ, AKADEMIA GÓRNICZO-HUTNICZA, 30-059 KRAKÓW, AL. MICKIEICZA 30
[***] UNIVERSITY OF BIELEFLD, DEPARTMENT OF PHYSICS, NANODEVOICES GROUP, P.O. BOX 10031, 33501 BIELEFELD, GERMANY

magnetycznym sprzężeniem wymiennym pomiędzy warstwami IrMn i CoFe. Stopień steksturowania złącza zależy od materiałów zastosowanych na warstwy buforowe jak również od sekwencji ich ułożenia. Najsilniejszą teksturę otrzymano dla bufora typu (b) z warstwą Ta naniesioną bezpośrednio na podłoże. Warstwy rosną w postaci kolumn, które generują szorstkości. Z korelacji pomiarów magnetycznych oraz pomiarów *rocking curve* otrzymano, że wymienne sprzężenie magnetyczne typu *exchange bias* między warstwami CoFe i IrMn oraz pole koercji wzrastają dwukrotnie w przypadku użycia silnie steksturowanego bufora (b). Wybór właściwego układu warstw buforowych pozwala na optymalizację sprzężenia *exchange bias* w wielowarstwowych urządzeniach magnetoelektroniki.

1. Introduction

Magnetic tunnel junction (MTJ) is subject of intensive fundamental and applied research, since the successful fabrication of MTJs that show relative large tunnel magnetoresistance effect at room temperature (about 15%) [1, 2]. One of the most important results of this research is design of the magnetoelectronics devices as: read heads of hard disc drives, magnetic random access memory (M-RAM) and magnetic field sensors [3], in the form of magnetic multilayer structure characterizes by two distinct high and low resistance states which usually represent "0" and "1" bits that can be electronically read and write. The typical multilayer structure of MTJ is composed of oxidized Si substrate, the system of metal seed-buffer layers that create the bottom electrode of MTJ, next the system of magnetic layers: antiferromagnets, pinned ferromagnetic layer insulating barrier, ferromagnetic free layer and the system of metal protection layers that create together the top electrode of MTJ. In the magnetic layers system of MTJ are observed two exchange coupling effects, very important for operation of MTJ, interfacial exchange bias coupling between antiferromagnet and ferromagnetic pinned layers and interlayer exchange coupling between pinned and free layers through insulator barrier.

The phenomenon of magnetic exchange bias coupling between antiferromagnetic and ferromagnetic thin film [4] is utilized in the so called magnetic spin valve device. In the spin valve junction, exchange biased field (H_{EB}), high tunnel magnetoresistance and high blocking temperature of the antiferromagnets are required. The antiferromagnets as Ir-Mn has been found as a very promising material due to its high exchange bias energy ($J_{EB} \approx 4 \cdot 10^{-4} J/m^2$), high blocking temperature ($T_b \approx 590K$) and low critical thickness ($\sim 7nm$) [5]. The exchange coupling between antiferromagnetic/ferromagnetic layers, which has been shown primarily an interfacial phenomenon, should be dependent on the microstructural characteristics of the films such as crystal texture, grain size and roughness [6]. All these factors influence the interface microstructure and are closely linked to the structure of the seed-buffer layers, which are used in designed multilayers. The metal layers are typically polycrystalline and tend to grow in a columnar-like fashion. If the columns of seed layers are oriented perpendicular to the substrate they can induce strongly textured growth of antiferromagnetic layer.

In this study, we report the relationship between texture degree of antiferromagnetic and ferromagnetic pinned bilayer, induces by different seed-buffer layers, and the exchange bias field. It was found that the strong textured, in contrast to the weak textured, MTJs are characterized by large exchange bias and large coercivity fields of pinned ferromagnetic layer, which are crucial for stable switching of M-RAM cells or other magnetoelectronic applications.

2. Experimental details

The investigated multilayers were deposited, in Ar as the process gas under the pressure of 0.2 hPa, on the oxidized Si wafers by dc magnetron sputtering in a chamber with the base pressure 3.5×10^{-7} hPa. All samples were annealed in vacuum (10^{-7} hPa) at 548 K (275°C) for 1 hour under a magnetic field of 80 kA/m, followed by field cooling in order to induce unidirectional exchange bias anisotropy of ferromagnetic CoFe layer. These are optimum annealing conditions to obtain a maximum of the tunneling magnetoresistivity ratio [7], besides annealing reduces the defects and stresses in the whole multilayer sample. In order to find the correlation between microstructure and magnetic parameters, the samples have been characterized by XRD experiments, using a Philips diffractometer type X'Pert- MPD with Cu anode. The XRD measurements were done in θ-2θ geometry, by measuring rocking curve (scan-ω) and pole figures. Roughness of the films was measured with an atomic force microscope (AFM) in tapping mode using a scan area of 500×500 nm. Magnetic hysteresis loops were measured by magnetooptical Kerr magnetometer [8].

MTJs are composed in the following sequence of layers: substrate Si(100)/SiO_x 47nm/ system of seed-buffer layers /IrMn 12nm/CoFe 15nm/AlO_x 1.4nm/NiFe 3nm/Ta 5nm. To enhance texture of MTJ four different systems of seed-buffer layers have been investigated: (a) Cu 25nm, (b) Ta 5nm / Cu 25nm, (c) Ta 5nm / Cu 25nm / Ta 5nm / Cu 5nm and (d) Ta 5nm / Cu 25nm / Ta 5nm / NiFe 2nm / Cu 5nm.

3. Structural Properties

Figure 1a shows θ-2θ profiles, in wide range of diffraction angle, for annealed samples with seed-buffer layers: (a) and (b). Sample with seed-buffer type (a), in comparison to the sample with seed-buffer (b), characterizes by significantly lower intensities of cubic structure (111)$Ir_{17}Mn_{83}$, (111)Cu and (110)$Co_{70}Fe_{30}$. Two order higher intensities of IrMn, Cu and CoFe peaks indicate strong texture of the system (b) where seed layer was 5 nm of Ta. Figure 1b shows the evolution from high to low intensities of (111)IrMn, (111)Cu and (110)CoFe peaks in dependence on the type of buffer which indicates that seed-buffer layers cause textured growth, in the form of perpendicular oriented columns, with different texture degree in IrMn and CoFe layers. In order to determine texture degree and how the crystallites planes of particular magnetic sublayers are oriented in space, pole figures (Fig. 2) and rocking curves of these samples have been recorded (Figs. 3a – c).

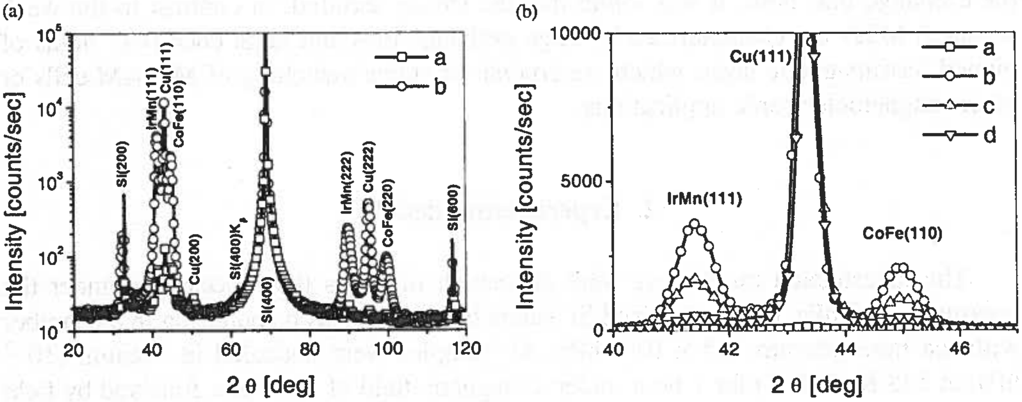

Fig. 1. θ-2θ profiles of MTJs with the structure: substrate Sai (100)/SiO$_x$ 47 nm/ system of seed-buffer layers: (a), (b), (c), (d) /IrMn 12nm/CoFe 15nm/AlO$_x$ 1.4nm/NiFe 3nm/Ta 5nm, where (a) Cu 25nm, (b) Ta 5nm/Cu 25nm, (c) Ta 5nm/Cu 25nm/Ta 5 nm/Cu and (d) Ta 5nm/Cu 25nm/Ta 5nm/NiFe 2nm/Cu 5nm

The pole figures for all kind of buffers (Fig.2) represent central [111] and [110] spots and spread rings around angle ψ = 70° and 60° for Cu, IrMn and CoFe, respectively. Diffuses spots and rings are observed for buffer (a), and narrow high intensity spots and rings for buffer (b), (c) and (d). It means that the layers have sheet texture with no crystallographic orientation in the film plane. The intensity of spots and rings of (111)Cu are for buffers (b), (c) and (d) constant, however gradually decreases of intensity in the case of (111)IrMn and (110)CoFe is observed. In pole figure of CoFe four spots in position of angle Ψ = 45° come from (110)Si of single crystal substrate-wafer of Si. Position of (110)Si is close to (110)CoFe, hence four spots in pole figure of CoFe are strong in the intensity. The positions of (111)Cu and (111)IrMn are far from Si(110), thus single crystal spots are not visible in the pole figure images of IrMn and Cu.

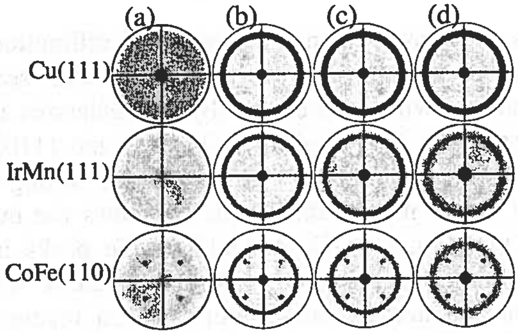

Fig. 2. Pole figures for samples with different buffers: (a), (b), (c) and (d). Four spots at angle ψ = 45° are from (110)Si single crystal substrate

In order to determine more quantitatively texture degree, rocking curves have been measured (Figs. 3a – c) and fitted by gaussian distribution function. The standard deviation coefficients 2σ obtained from fitting procedures of rocking curve profiles are compiled together with FWHM (Full Width at Half Maximum) of (111)Cu, (111)IrMn and (110)CoFe determined from θ-2θ-scans and interfacial roughness from AFM, in Table. The FWHM of (111)Cu, (111)IrMn and (110)CoFe is inversely proportional to grain size, narrower profile width indicates the formation of a larger grain size. This fact shows, that for all types of buffers the coefficient 2σ is proportional to FWHM, it means that higher texture degree originates from lager grains formed in columns perpendicular oriented to the substrate. In consequence, the textured columns induce interfacial roughness that RMS amplitude (Root Mean Square) depends on the texture degree (see Table).

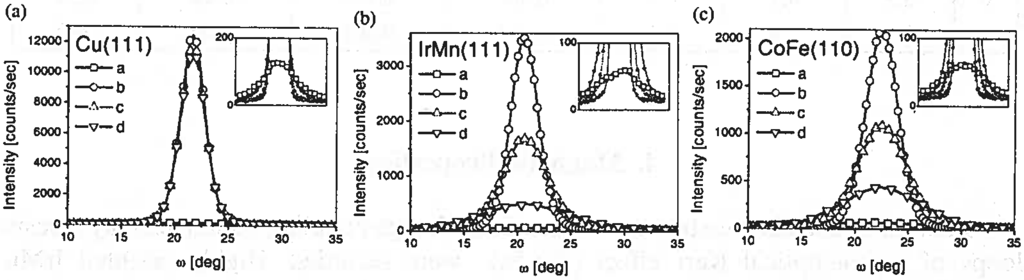

Fig. 3. Rocking curves (ω-scan) recorded in Bragg positions of (111)Cu, (111)IrMn and (110)CoFe. Letters in legend relate to appropriate buffers. Insert enlargement ω-scans of buffer (a)

Figure 4 shows the roughness obtained by AFM measurements detected on the top of the Ta surface, from the system of seed-buffers (a), (b), (c) and (d). Tantalum top layer was used to protect very sensitive IrMn surface against corrosion. The RMS amplitude of roughness depends on the type of the buffer. Weak textured buffer (a) and high textured buffer (b) characterize by small and large RMS amplitude, respectively. Buffers (c) and (d) have medium RMS amplitude of roughness (see Table). The seed-buffer metal layers can be, in dependence on sequences layers in buffer, strongly

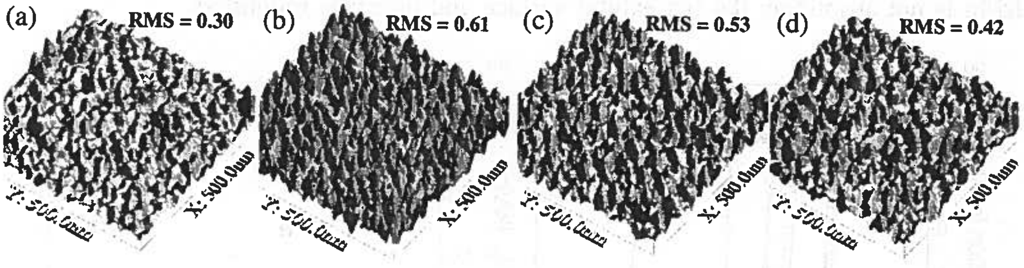

Fig. 4. AFM images on the top of IrMn protected by Ta(5 nm) layer, (a), (b), (c) and (d) relate to appropriate buffers

textured and tend to grow in a columnar- like fashion. This produce a roughness, that in turn, propagates into the whole MTJ. The roughness and texture modified very strongly exchange coupling effects in the MTJs.

TABLE

Standard deviation coefficients 2σ of rocking curve profiles and FWHM of θ-2θ scans of (111)Cu, (111)IrMn and (110)CoFe, and RMS amplitude of IrMn roughness

	XRD rocking curve			XRD $\theta-2\theta$			AFM
buffer	(111)Cu 2σ [deg]	(111)IrMn 2σ [deg]	(110)CoFe 2σ [deg]	(111)Cu FWHM [deg]	(111)IrMn FWHM [deg]	(110)CoFe FWHM [deg]	roughness RMS [nm]
a	11.7	15.9	14.5	0.502	0.842	0.824	0.30
b	2.4	2.8	3.0	0.370	0.700	0.642	0.61
c	2.3	4.1	4.6	0.366	0.774	0.684	0.53
d	2.3	7.9	7.5	0.361	0.801	0.745	0.42

4. Magnetic Properties

In order to correlate texture and magnetic exchange coupling parameters, hysteresis loops of magnetoptical Kerr effect (Fig.5a) were recorded. Highly oriented IrMn crystallites from textured seed-buffer layers cause high exchange bias coupling and coercivity fields of pinned CoFe layer. It was found, from the analysis of CoFe rocking curves, that the exchange bias and coercivity fields of CoFe pinned layer increase about two times (Fig.5b) if strong textured seed-buffer system (b) is used.

The crystalline structure of antiferromagnets, in our case IrMn, plays important role in providing a desirable magnetic exchange coupling of MTJ. The film surface of IrMn is not absolutely flat but exhibit surface and interface roughness.

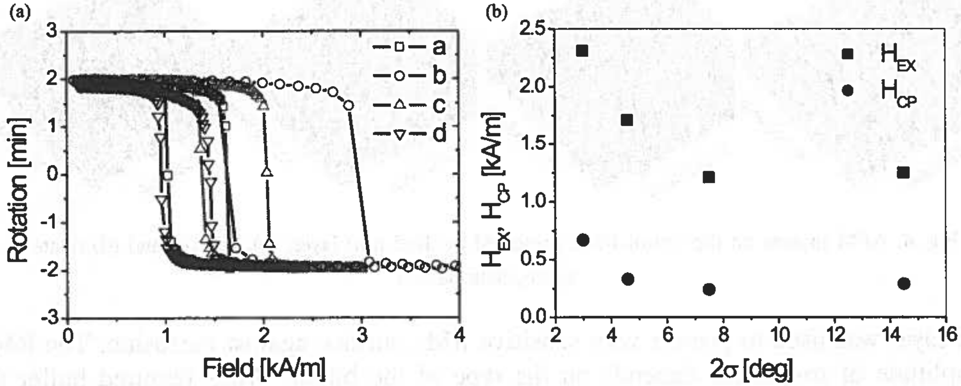

Fig. 5. a) Exchsnge bias hysteresis loops of CoFe pinned layer for different buffers. b) Exchange bias and coercivity fields of CoFe vs. Standard deviation coefficients 2σ

5. Conclusions

We have investigated influence of different systems of seed-buffer layers on structure and bias exchange coupling of MTJs. By using different buffers, the crystal texture and roughness of IrMn and CoFe layers have been varied. Texture degree in the stack of spin valve MTJ depends on material (which was used for buffer layers) and sequence of layers. The strongest texture has been obtained if the seed layer of Ta was used (buffer (b) Ta 5nm/Cu 25nm). The growth of the multilayer stack is textured in columnar-like fashion, which produces roughness. The roughness propagates into the whole MTJ and gives roughness at IrMn/CoFe interface. It was found, from the analysis of CoFe rocking curves, that exchange bias and coercivity fields of CoFe pinned layer increase about two times in the case of using strong textured seed-buffer system (b). The design of seed- buffer layers allows to optimize the exchange coupling bias in magnetoelectronics devices.

Acknowledgements

This work was partially supported by grants of Ministry of Scientific Research and Information Technology Nos. 3 T11B 027 26, 4 T11B 033 24 1111120. 068 and 21. 10. 120. One of the authors (J.K.) would like to thank D. Meyners and D. Brinkmann for help with AFM imaging.

REFERENCES

[1] T. Miyazaki, N. Tezuka, J. Magn. Magn. Mat. **139**, L231 (1995).
[2] J.S. Moodera, L.R. Kinder, T.M. Wong, R. Meservey, Phys. Rev. Lett. 74, 3273 (1995).
[3] G.A. Prinz, J. Magn. Magn. Mat. **200**, 57 (1999).
[4] J. Noguès, I.K. Schuller, J.Magn. Magn. Mat. **192**, 203 (1999).
[5] M. Takahashi, M. Tsunoda, J. Phys. D **35**, 2365 (2002).
[6] T. Stobiecki, J. Kanak, J. Wrona, M. Czapkiewicz, C.G. Kim, C.O. Kim, M. Tsunoda, M. Takahashi, phys. stat. sol. a, **201**, 1621 (2004).
[7] M. Tsunoda, M. Takahashi, J. Magn. Magn. Mater. **239**, 149 (2002).
[8] J. Wrona, T. Stobiecki, M. Czapkiewicz, R. Rak, T. Ślęzak, J. Korecki, C.G. Kim, J. Magn. Magn. Mat. **272-276**, P3, 2294 (2004).

Received: 21 March 2005.