Bottom type MTJ – magnetization switching properties and domain structure

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Introduction

Magnetization switching is a key for optimal operation of magnetic random access memory devices. In this paper particular attention will be paid to the analysis of magnetization reversal process and domain structure of as deposited and annealed Magnetic Tunnel Junction (MTJ), in the form of extended sample. The structure of investigated MTJs was composed of buffer layers Ta(5)/Cu(10)/Ta(5)/NiFe(2)/Cu(5), antiferromagnetic (AF) layer of IrMn(10), "pinned" ferromagnetic (FP) layer of CoFe(2.5), insulator spacer Al_2O_3(1.5), "free" ferromagnetic (FF) layer of CoFe(2.5)/NiFe(t = 10, 30 and 100nm) and Ta(5) capping layer.

Experiment

MTJs were prepared in magnetic field 2.4 kA/m on thermally oxidized Si wafers using DC magnetron sputtering with ultra clean Ar(9N) as the process gas, in a chamber with base pressure of $4{\cdot}10^{-9}$ hPa (for details see [1]). The samples were annealed in vacuum at 300°C for 1 hour in the external magnetic field of 80 kA/m, followed by field cooling. Magnetization reversal process was analyzed on the base of hysteresis loops measured by means of R-VSM [2] and MOKE [3]. Real time image processing of domain patterns was performed by magnetooptical Kerr microscope [4].

Magnetization process

In Figure 1 are shown hysteresis loops of magnetization, recorded in easy direction, for as deposited and annealed MTJs with different thickness of NiFe part of FF layer. As-deposited MTJs are characterized by quasi-symmetrical switching of FP layer (major loop), similar to pseudo-spin valve, and by small shift with respect to H=0 of minor hysteresis loop of FF layer (Fig.1a). Magnetization reversal process of annealed structures manifests spin valve effect with exchange biased hysteresis loop of FP, due to field cooling of AF layer [5].

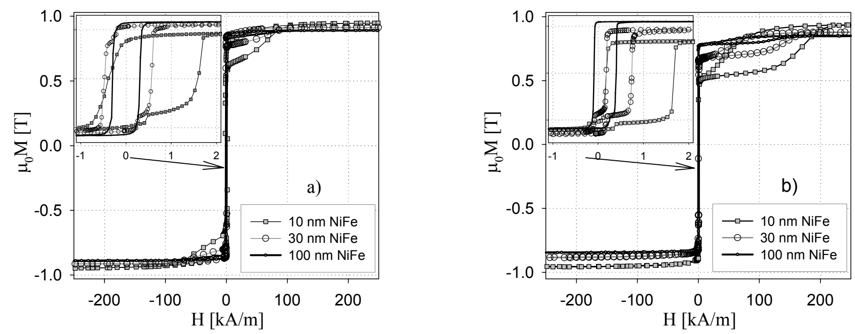

Fig. 1. The major hysteresis loops of MTJs measured by R-VSM (a) as-deposited and (b) annealed at 300°C. The inset shows minor loops.

In addition, one can see larger interlayer coupling field, smaller coercivity, better quality of switching process of FF layer, and good remanence and coercive squareness, due to changes in microstructure after annealing treatment [6].

Following the Stoner-Wohlfarth (S-W) model for hysteresis loop calculation, the total surface energy can be expressed as

$$E(\theta_1,\theta_2,\theta_3,\theta_{AF}) = -J\cos(\theta_2-\theta_1) - J_{EB}\cos(\theta_1-\theta_{AF}) + E_{Z1}(\theta_1) + E_{Z2}(\theta_2) + E_{Z3}(\theta_3) - K_1 t_1\cos^2\theta_1 - K_2 t_2\cos^2\theta_2 - K_3 t_3\cos^2\theta_3 - \hat{K}_{AF} t_{AF}\cos^2\theta_{AF} \quad (1)$$

where Zeeman energy of i-th ferromagnetic layer can be written as

$$E_{Zi}(\theta_i) = -t_i\mu_0 M_{Si}(H_X\cos\theta_i + H_Y\sin\theta_i)\,.$$
(2)

Here θ_1, θ_2, θ_3 are the angles of FF, FP and additional thin NiFe buffer layer magnetization with respect to the easy axis, respectively. θ_{AF} is the angle of AF magnetization sublattice with respect to the anisotropy axis of AF layer. t_i, M_{Si} and K_i are thickness, saturation magnetization and anisotropy energy of the i-th ferromagnetic layer, respectively. H_X, H_Y are field components parallel and perpendicular to the easy axis. $\hat{K}_{AF}$ is an effective anisotropy energy of AF layer (determined by fitting of the S-W model to the experimental data) and differs from the intrinsic anisotropy energy of AF grains. J is an interlayer coupling energy between FP and FF layers, J_{EB} is an interfacial exchange energy between AF and FP layers. Energy constants were computed by minimization of total surface energy with respect to the experimental $M(H)$ hysteresis loops [7]. The obtained $\hat{K}_{AF}t_{AF}$ values are less than J_{EB} energy for as-deposited samples, in contrast to the annealed samples for which $\hat{K}_{AF}t_{AF} = 500\cdot 10^{-6}\,\mathrm{J/m^2}$ is greater than $J_{EB} = 360\cdot 10^{-6}\,\mathrm{J/m^2}$, due to higher magnetic order of AF layer [5]. In such condition the FP layer is "pinned" due to frozen direction of AF magnetization sublattices.

Magnetization switching

Energy values (such as interlayer coupling energy and anisotropy energy constant), obtained from S-W model were used to simulate series of hysteresis loop in order to determine switching fields of FF layer for annealed sample with t_{NiFe} = 10 nm. Each hysteresis loop was

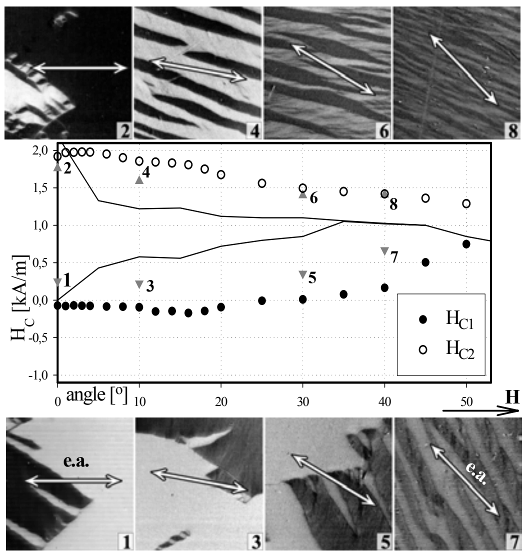

Fig. 2. Switching fields (H_{C1}, H_{C2}) of MOKE hysteresis loop as a function of angle between external magnetic field and easy axis. Numbers on the domain patterns correspond to H_{C1} and H_{C2} switching field values and field angle during picture acquisition. Lines represent S-W model.

calculated along the easy-axis (H_X) with fixed hard-axis field (H_Y). Switching fields of FF layer were also measured by MOKE magnetometer using above mentioned H_X-H_Y scanning method. Simulated and measured, in external magnetic field aligned at different angles with respect to the easy axis, switching fields are shown in Fig. 2., as well as domain images corresponding to the certain switching fields.

The domain patterns correspond to the switching states indicated by numbers. Domain patterns for both branches of hysteresis are complementary only for field parallel to easy axis. One can notice, that high switching field H_{C2} is smoothly decreasing when angle between field and easy axis is increasing, whilst low switching field H_{C1} is blocked around zero field up to 30^o. Domain images corresponding to H_{C2} show that domain structure smoothly changes from large domains superimposed by crossed stripes to the narrow stripes and finally to ripple structure [9] for angles larger than 40^o. Domain images corresponding to H_{C1} exhibit domains blocking mechanism. Large domains split to stripes for angles larger than 30^o, which leads to increase of the H_{C1}.

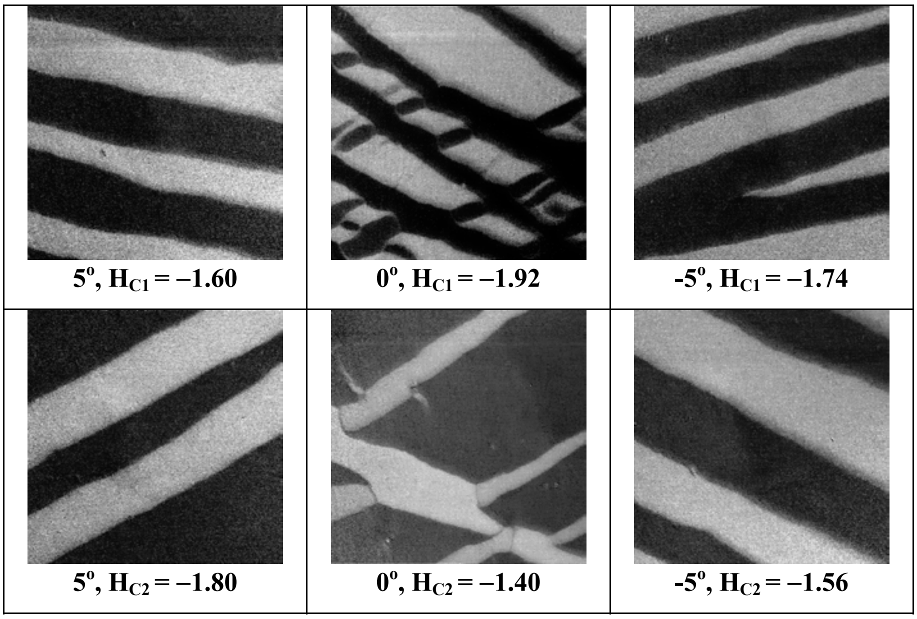

Fig. 3. Domain patterns at switching fields H_{C1}, H_{C2} [kA/m] for different angles between external magnetic field and easy axis.

Another example of the crossed stripes pattern was observed by means of MOKE microscope in Ta(5)/Cu(30)/Ta(20)/Cu(5)/MnIr(12)/CoFe(3)/AlO_x(1.6)/NiFe(8)/Ta(10) MTJ sample deposited in Thin Films and Nanostructures laboratory at Bielefeld University in Germany (courtesy of G. Reiss). As can be observed in Fig. 3, crossed domain pattern of soft FF layer appears only when is magnetized in the field parallel to easy axis.

Domains in free layer

Domain images of free layer for different thickness of NiFe are shown in Fig. 4a. (as-deposited structures) and in Fig. 4b. (after annealing) and minor loops of magnetic moment for comparison. Both as-deposited and annealed structures with t_{NiFe} = 100nm exhibit similar images of huge magnetic domains and similar hysteresis loops with low coercivity and small shift field, due to domination of magnetostatic energy of thick permalloy over interlayer

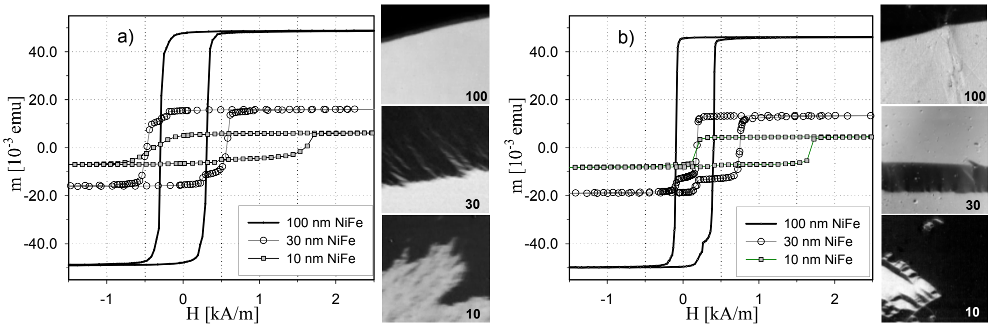

Fig. 4. Hysteresis loops of samples with different thickness of NiFe sublayer and corresponding to the switching field domain images of the FF layer, a) as-deposited b) annealed sample.

coupling energy. Annealed sample with t_{NiFe} = 10 nm has large domains superimposed by crossed stripes and more rectangular hysteresis loops in comparison to as-deposited one. The domain structure of as-deposited sample is characterized by fuzzy domains with fine irregular "patches" pattern [8]. Interlayer coupling energy is less for as-deposited samples ($J = 8.5\cdot10^{-6}$ J/m^2) then for annealed samples ($J = 10.4\cdot10^{-6}$ J/m^2).

Conclusions

Annealing treatment at 300° C, due to the changes in the microstructure in AF and FF layers, improved quality of magnetization reversal process of free layer and led to smaller coercive force, faster switching and regular domain structure. Coherent rotation of magnetization is disturbed by domain blocking mechanism, occurred in free layer. The observed different types of domain pattern and domain walls depend on FF/FP layer interlayer coupling energy and FF layer magnetostatic energy.

[1] M. Tsunoda, K. Nishigawa, S. Ogata and M. Takahashi, Appl. Phys. Lett. 80 (2002) 3135.
[2] J. Wrona, M. Czapkiewicz, T. Stobiecki, J. Magn. Magn. Mat. 196, 935 (1999).
[3] J. Wrona, T. Stobiecki, R. Rak, M. Czapkiewicz, F. Stobiecki, L .Uba, J. Korecki, T. Ślęzak, J. Wilgocka-Ślęzak, M. Roots, phys. stat. sol. 196, 161 (2003).
[4] M. Żołądź, S. Knappmann, M. Otto, K. Röll, T. Stobiecki, phys. stat. sol. (a) 189, 791 (2002).
[5] M. Tsunoda, M. Takahashi, J. Appl. Phys. 87, 4957 (2000).
[6] T. Stobiecki, J. Kanak, J. Wrona, M. Czapkiewicz, C.G. Kim, C.O. Kim, M. Tsunoda, M. Takahashi, phys. stat. sol. (a), to be published.
[7] M. Czapkiewicz, PhD Thesis, UMM Kraków (1999).
[8] M. Tsunoda, Y. Tsuchiya, T. Hashimoto, and M. Takahashi, J. Appl. Phys. 87, 4375 (2000).
[9] A. Hubert, R. Schäfer, "Magnetic Domains. The Analysis of Magnetic Micro-structures", Springer (1998).

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