Simulation of magnetic properties of different types of spin-valve nanostructures

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Nanostructures, in which GMR effects are manifested, have found wide application in magnetic field sensors, read heads of hard disks, and magnetoresistive random access memory (MRAM) [1]. Spin valves are one of the most widespread such nanostructures. At present time, various types of spin valve structures have been developed (simple, complicated, symmetrical spin valves), which are characterized by high sensitivity to a magnetic field at room temperature [2-3]. In this work, we simulated the temperature characteristics and the effects of magnetization hysteresis and the magnetoresistance in spin valves.

[1] Drovorub E.V., Prudnikov V.V., Prudnikov P.V. // Bulletin of the Russian Academy of Sciences: Physics 2022. V. 86. №2. P. 109-114.

[2] Dieny B. // J. Magn. Magn. Mater. 1994. Vol. 136. P. 335359.

[3] Freitas P.P., Ferreira R., Cardoso S. and Cardoso F. // J. Phys. Condens. Matter. 2007. V. 19 P. 1-21.

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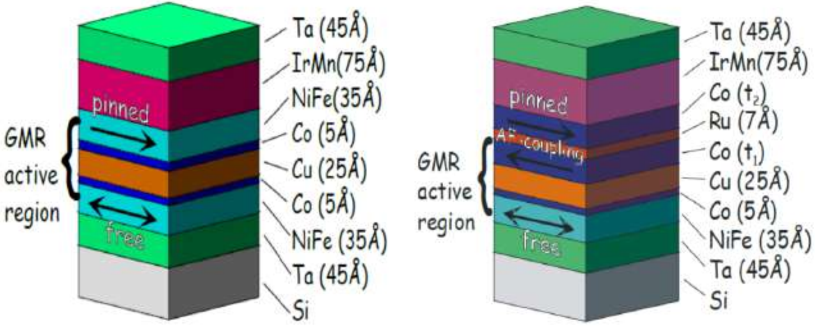

Fig 1: Model of a simple spin valve (on the left) and complicated spin valve (on the right) [4].

[4] Marrows C.H., Stanley F.E., Hickey B.J. // J. Appl. Phys. 2000. V. 87. No. 9. Art. No. 5058.

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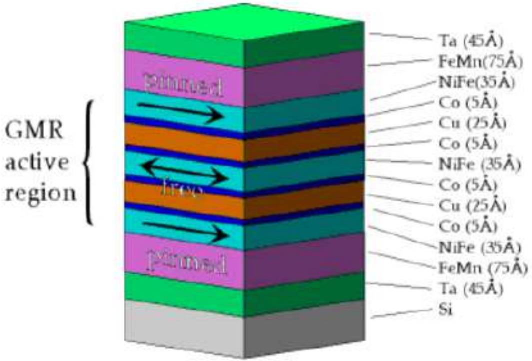

Fig 2: Model of a symmetrical spin valve [4].

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Hamiltonian of a system with «easy plane» anisotropy [5]:

$$H = -\sum_{<i,j>} J_{ij}\{S_i^x S_j^x + 0.8 \cdot S_i^y S_j^y + (1-\Delta(N))S_i^z S_j^z\} - h\sum_i S_i^x, \quad (1)$$

$S_i = (S_i^x, S_i^y, S_i^z)$ - is the classical three-dimensional unit vector of a spin fixed in the i-th center of the FCC lattice of a ferromagnetic cobalt films. $\Delta(N)$ - parameters of the effect anisotropy caused by the crystalline field of the substrate has on the magnetic properties of a film consisting of N monolayers. Parameter $h = g\mu_B H$ characterizes the effect of an external magnetic field oriented in the plane of a film with weak anisotropy along axis x to remove degeneracy. J_{ij} - the exchange integral characterizing the interaction of nearest spins in the film.

[5] Prudnikov P. V., Prudnikov V. V., Menshikova M. A., Piskunova N. I. // J. Magn. Magn. Mater. 2015. Vol. 387. P. 77–82.

Schematic representation of structures

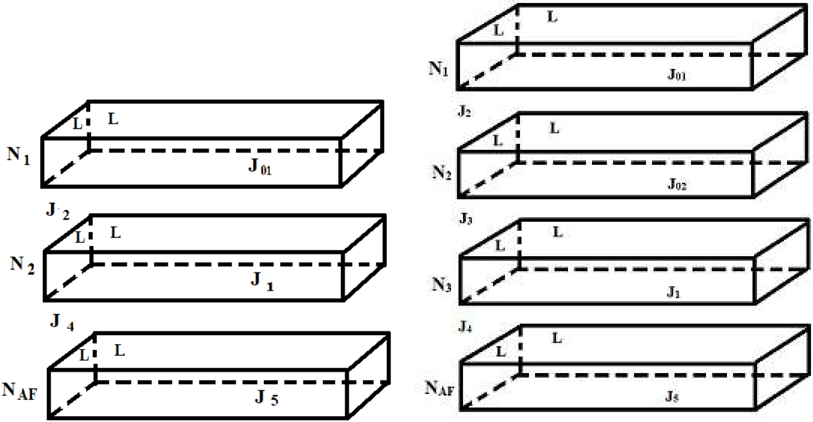

Fig 3: Schemes of simple SV (on the left) and complicated SV (on the right). L, N_1, N_2, N_3 and N_{AF} - linear sizes of the films, $J_{01}, J_{02}, J_1, J_2, J_3, J_4, J_5$ - exchange integrals.

Schematic representation of structures

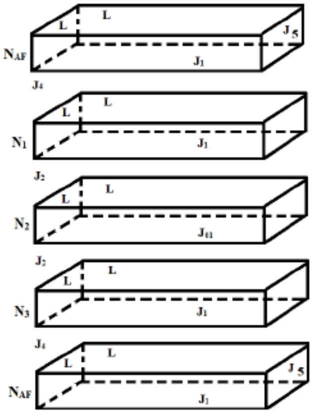

Fig 4: Scheme of symmetric SV. L, N_1, N_2, N_3 and N_{AF} - linear sizes of the films, $J_{01}, J_1, J_2, J_4, J_5$ - exchange integrals.

Simulation parameters

- Face-centered cubic lattice: $L * L * N$;
- Linear size: $L = 32$;
- Periodic boundary conditions in the film plane;
- The values of the exchange integrals of the intralayer interaction were set as $J_1/k_bT = 1$, $J_{01}/J_1 = 1.0$, while interlayer interaction $J_2/J_1 = 0.01$. To model the properties of an antiferromagnetic, the negative integral of the intralayer intersublattice interaction is introduced $J_5/J_1 = -2.0$. The interlayer interaction of an antiferromagnetic and a pinned film is described using the exchange integral $J_4/J_1 = -3.0$;
- Metropolis Algorithm.

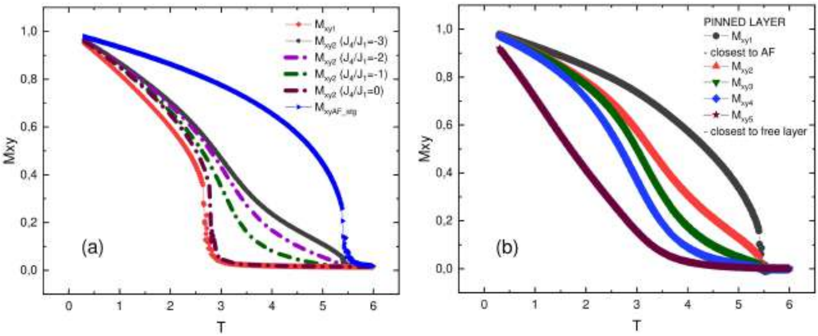

Fig 5: Temperature dependences of the spontaneous magnetization M_{xy} and staggered magnetization M_{xyAF_stg} of films in the simple spin-valve structure with magnetization in the film planes and thicknesses $N_1 = N_2 = 5$ ML: (a) for separate films in structure and different values of interlayer exchange interaction $J_4/J_1 =$ -3, -2, -1, 0; (b) for separate monolayers in pinned film with $J_4/J_1 =$ -3.

Results of computer simulation

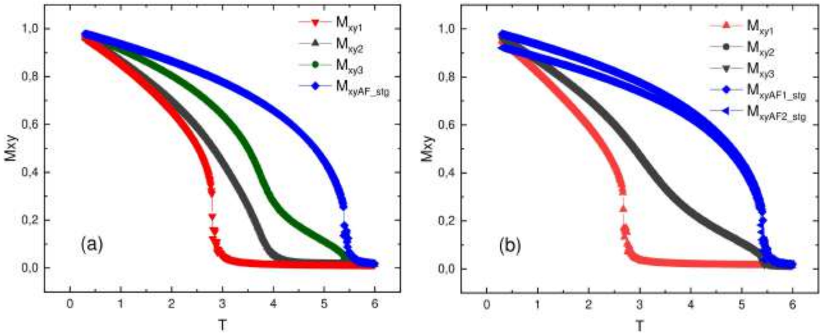

Fig 6: Temperature dependences of the spontaneous magnetization M_{xy} and staggered magnetization M_{xyAF_stg} of films (a) in spin-valve structure with synthetic antiferromagnetic layers (SVAF), (b) in dual symmetrical spin-valve structure (DSV) with thicknesses $N_1 = N_2 = N_3 = 5$ ML and $J_4/J_1 = -3$.

Results of computer simulation

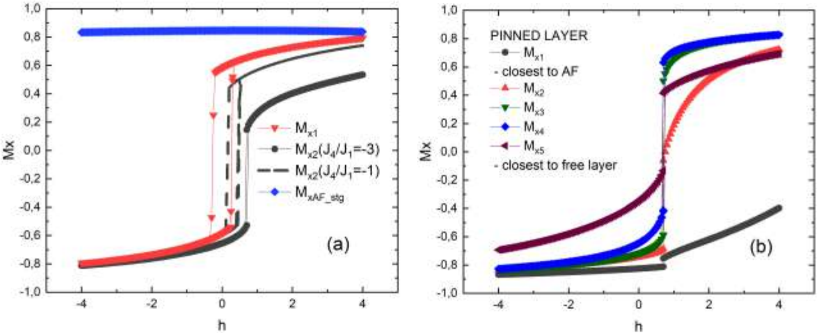

Fig 7: Hysteresis loops in a simple spin-valve structure (a) for the magnetization of individual ferromagnetic films with thicknesses $N_1 = N_2 = 5$ ML and antiferromagnetic film with N_{AF}=16 ML and (b) for separate monolayers in pinned film. Value of interlayer exchange interaction J_4/J_1 = -3. Temperature of system is $T = 2.25\ J_1/k_B$. Dashed lines in panels (a) show results for reduced interlayer exchange coupling with J_4/J_1 = -1.

Results of computer simulation

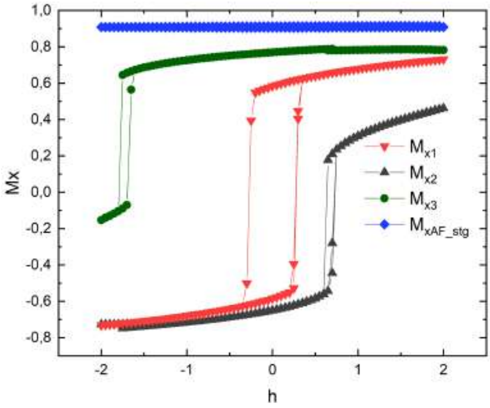

Fig 8: Hysteresis loops in spin-valve structure with synthetic antiferromagnetic layers (SVAF) for the magnetization of individual ferromagnetic films with thicknesses $N_1 = N_2 = N_3 = 5$ ML and antiferromagnetic film with N_{AF}=16 ML. Value of interlayer exchange interaction J_4/J_1 = -3. Temperature of system is $T = 2.25 J_1/k_B$.

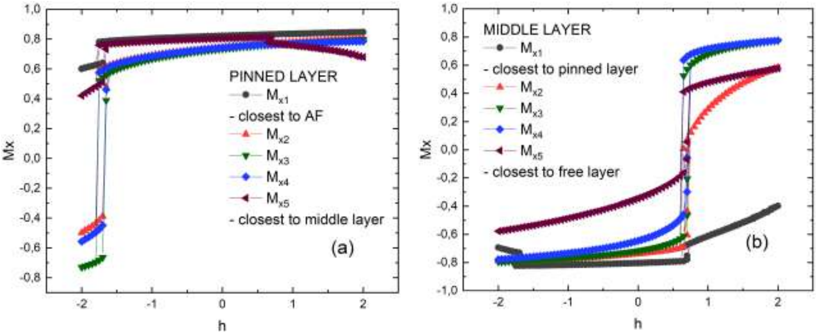

Fig 9: Hysteresis loops in spin-valve structure with synthetic antiferromagnetic layers (SVAF) (a) for separate monolayers in pinned film; (b) for separate monolayers in middle film. Value of interlayer exchange interaction $J_4/J_1 =$ -3. Temperature of system is $T = 2.25 J_1/k_B$.

Results of computer simulation

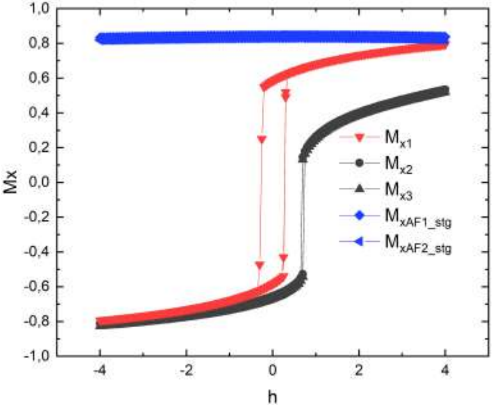

Fig 10: Hysteresis loops in dual symmetrical spin-valve (DSV) for the magnetization of individual ferromagnetic films with thicknesses $N_1 = N_2 = N_3$ =5 ML and antiferromagnetic film with N_{AF}=16 ML. Value of interlayer exchange interaction J_4/J_1 = -3. Temperature of system is $T = 2.25 J_1/k_B$.

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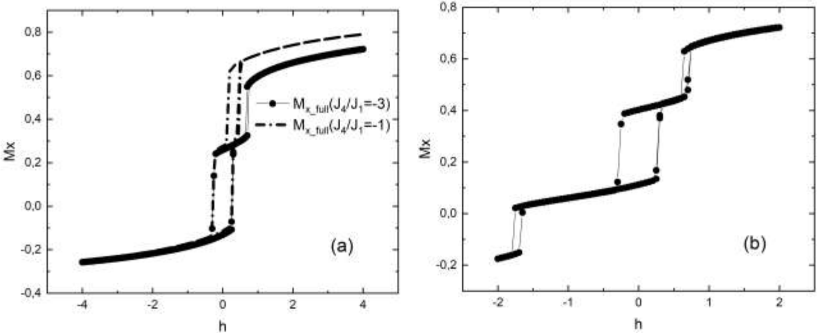

Fig 11: Hysteresis loops in a simple spin-valve structure (a) and in a spin-valve structure with synthetic antiferromagnetic layers (b) for the magnetization of throughout SV structure. Value of interlayer exchange interaction $J_4/J_1 =$ -3. Temperature of system is $T = 2.25 J_1/k_B$.

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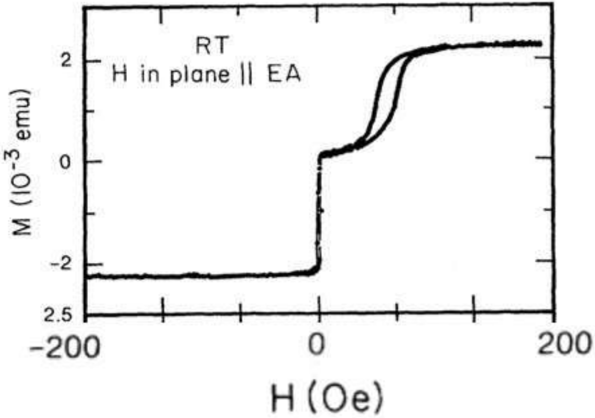

Fig 12: Hysteresis loops for Si/(150-Å NiFe)/(26-Å Cu)/(150-Å NiFe)/ (100-Å FeMn)/(20-Å Ag) structure [2].

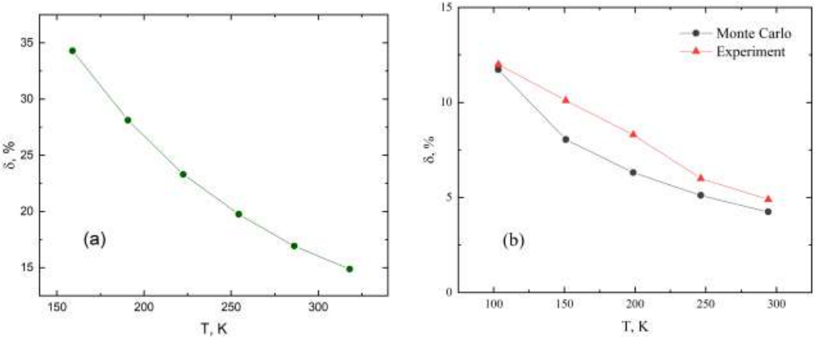

Fig 13: The dependence of the CPP magnetoresistance $\delta(T, N)$ on the temperature (a) in Co/Cu(100)/Co/IrMn structure for thicknesses $N_1 = N_2 = 5$ ML and $J_2/J_1 = 0.01$; (b) in CFAS/Ag/CFAS/IrMn spin-valve with Co based Heusler alloy $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS) for thicknesses $N_1 = N_2 = 23$ ML of the CFAS films and $J_2/J_1 = 0.005$. Comparison with experimental results from [6].

[6] Furubayashi T., Kodama K., Sukegawa H., Takahashi Y.K., Inomata K. and Hono K. // Appl. Phys. Lett. 93, 122507 (2008).

Results of computer simulation

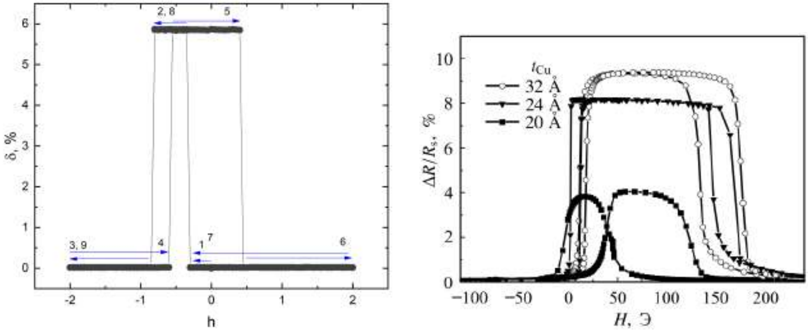

Fig 14: Hysteresis loops of the magnetoresistance for a simple SV (on the left) at a temperature of $T = 2.75$ and experimental results (on the right) at room temperature [7].

[7] Устинова В.В., Мушникова Н.В., Ирхина В.Ю. // Институт физики металлов имени М.Н. Михеева УрО РАН, 2020. - 664 с

Conclusion

- The dependence of the magnetic characteristics of the films on temperature and external magnetic field was obtained for various types of spin valves, which is in good agreement with experiment.
- The factors that make it possible to influence the magnetic properties of ferromagnetic films and the manifestation of hysteresis effects in SV structures are identified.
- The temperature properties of an antiferromagnetic and the effect of an external magnetic field are investigated.
- The dependences of the magnetoresistance on temperature and external magnetic field are obtained.

Thank you for your attention!