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INFLUENCE OF Fe DISTRIBUTION IN THE FECR LAYER ON THE MAGNETIC BEHAVIOR OF THE Fe/Cr/FeCr/Cr/Fe CURIE SWITCH

Spintronics is one of the most promising fields of modern electronics. It originated with the discovery of the giant magnetoresistance (GMR) effect and has played a vital role in the development of information recording, storage, and playback systems. Over time, it has become evident that the potential of spintronics is significant: spintronic devices can offer substantial advantages in speed, energy efficiency, and miniaturization compared to their semiconductor counterparts.

Many spintronic devices are based on magnetic multilayer structures consisting of magnetic and non-magnetic (a few nanometers thick) metallic layers. The magnetic layers in such structures are coupled by indirect exchange interaction, mediated by conduction electrons. The magnitude and sign of this exchange interaction determine whether the magnetic moments of adjacent ferromagnetic layers, separated by a non-magnetic spacer, align parallel or antiparallel to each other. These properties depend on structural parameters, most notably the thickness of the non-magnetic spacer.

The primary challenge is that the spacer thickness is fixed during the fabrication process and cannot be altered during operation. One solution to this problem is the use of Curie switches, which exhibit temperature-dependent exchange interaction due to a diluted magnetic layer embedded within the non-magnetic spacer. Fe(2)/Cr(0.4)/FeCr(0.8)/Cr(0.4)/Fe(2) structures are well-studied; they have demonstrated a reversal of the exchange coupling sign upon heating, resulting in a change in magnetoresistance. This can be achieved through external heating or even via Joule heating.

This work investigates the influence of the morphology of the diluted Fe_{17.5}Cr_{82.5} spacer on its magnetic properties. It is shown that spacer clustering leads to an increased ferromagnetic contribution, the appearance of a small hysteresis loop, and remanent magnetization, which gradually decreases with increasing temperature and causes a shift in the phase transition temperature of the entire Cr/FeCr/Cr spacer. As the temperature increases further, the clusters transition into a superparamagnetic state.

It can be concluded that cluster inhomogeneities affect the interlayer exchange interaction: at low temperatures, by inducing direct ferromagnetic interaction through ferromagnetic clusters; at higher temperatures, through their contribution to indirect exchange due to the clusters' transition to the superparamagnetic state, as well as by shifting the paramagnetic transition point of the entire Cr/FeCr/Cr spacer.

Key words: spintronics, structural defects, magnetic multilayer.

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ВПЛИВ РОЗПОДІЛУ Fe В ШАРІ FeCr НА МАГНІТНУ ПОВЕДІНКУ КЮРІ ПЕРЕМИКАЧА Fe/Cr/FeCr/Cr/Fe

Спінтроніка є одним із найперспективніших напрямів сучасної електроніки. Вона почалась з відкриття ефекту гігантського магнітоопору (ГМО) та відіграла важливу роль у розвитку систем запису, зберігання й відтворення інформації. З часом стало зрозуміло, що потенціал спінтроніки є значним: спінтронні пристрої можуть мати суттєві переваги у швидкодії, енергоефективності та мініатюризації порівняно з напівпровідниковими аналогами.

В основі багатьох спінтронних пристроїв лежать магнітні багатошарові структури, що складаються з магнітних і немагнітних (товщиною декілька нанометрів) металевих шарів. Магнітні шари в таких структурах пов'язані непрямою обмінною взаємодією, носіями якої є електрони провідності. Величина та знак обмінної взаємодії визначають, як магнітні моменти сусідніх феромагнітних шарів, розділених немагнітним прошарком, будуть орієнтуватися один відносно іншого (паралельно чи антипаралельно), і залежать від структурних параметрів, серед яких виділяють товщину немагнітного прошарку.

Проблема полягає в тому, що товщина прошарку задається під час виготовлення структури і не може змінюватися в процесі її роботи. Одним із варіантів розв'язання цієї проблеми є перемикачі Кюрі, які демонструють температурно-залежну обмінну взаємодію завдяки наявності розбавленого магнітного шару, розташованого всередині немагнітного прошарку. Структури Fe(2)/Cr(0.4)/FeCr(0.8)/Cr(0.4)/Fe(2) добре вивчені; для них продемонстровано зміну знаку обміну за рахунок нагрівання і, як наслідок, зміну магнітоопору. Це може бути зроблено шляхом зовнішнього нагрівання, або навіть за рахунок нагрівання Джоулевім теплом.

У роботі досліджено вплив морфології розбавленого прошарку Fe_{17.5}Cr_{82.5} на його магнітні властивості. Показано, що кластеризація прошарку призводить до зростання феромагнітного внеску, появи малої петлі гістерезису та залишкової намагніченості, яка поступово зменшується зі зростанням температури і спричиняє зміну температури фазового переходу всього прошарку Cr/FeCr/Cr. За подальшого підвищення температури кластери переходять у суперпарамагнітний стан.

Можна зробити висновок, що кластерні неоднорідності впливають на міжшарову обмінну взаємодію: при низьких температурах шляхом виникнення прямої феромагнітної взаємодії через феромагнітні кластери; при вищих температурах через внесок у непрямої обмін завдяки переходу кластерів до суперпарамагнітного стану, а також через зміщення точки переходу в парамагнітний стан усього прошарку Cr/FeCr/Cr.

Ключові слова: спінтроніка, структурні дефекти, магнітні багатошарові плівки.

Relevance of the problem. Interlayer exchange coupling (IEC) in magnetic multilayers is a crucial phenomenon underlying the Giant Magnetoresistance (GMR) effect (Bruno, 1995). The discovery of GMR played a pivotal role in the development of modern electronics and computing, enabling a revolutionary advance in the miniaturization of data storage devices (Grünberg, 2008). Since then, spintronics has been regarded as a highly promising research field, expected to lead to new classes of devices characterized by high speed, energy efficiency, and scalability. These include advanced magnetic sensors, logic elements, memory devices, and spin-torque nanosensors (STNOs) (Khalili, 2024; Bhatti, 2017; Apalkov, 2016; Dieny, 2020).

The IEC effect is based on the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction (Kasuya, 1956; Yosida, 1957; Ruderman, 1954), which couples adjacent magnetic layers separated by a nonmagnetic spacer via conduction electrons. The magnitude and sign of this exchange interaction depend on structural parameters such as layer thicknesses and interface quality. As a result, the system can be engineered so that the magnetic layers align either parallel or antiparallel.

Analysis of recent research and publications.

A challenge is that the exchange coupling can typically be tuned only once, during fabrication. An interesting possibility is the ability to control the magnitude of the exchange coupling through external stimuli, such as heating or current application during device operation. Several studies have addressed this topic. Curie switches Fe/Cr/Fe_xCr_{1-x}/Cr/Fe have been well-studied, demonstrating the possibility of controlling exchange coupling via heating (Polishchuk, 2017). Furthermore, switching these devices using current-induced Joule heating has also been demonstrated (Iurchuk, 2023).

Aim of the study. It has been established that, as in other multilayer systems, the magnitude and sign of the exchange coupling depend strongly on layer thicknesses, interface quality, and iron concentration in the spacer layer. These structures Fe/Cr/Fe_xCr_{1-x}/Cr/Fe must be carefully optimized and fabricated with high structural quality. Interestingly, the role of the spatial distribution of iron within the spacer layer has not yet been systematically investigated (Polishchuk, 2017).

Methodology and computational approach. To study the effect of Fe_{17.5}Cr_{82.5} spacer

morphology on the magnetic properties of Cr/Fe_{17.5}Cr_{82.5}/Cr performed Monte Carlo simulations on a three-dimensional cubic lattice comprising 30 × 30 × 12 monolayers (10⁴ atomic sites).

Each lattice site is defined by a spin state $S_i = \pm 1$ and an atomic species $\tau_i \in \{\text{Fe}, \text{Cr}\}$. To model the thin-film geometry, periodic boundary conditions were applied in the in-plane directions (x and y), while open boundary conditions were imposed along the out-of-plane direction (z).

The system's magnetic energy was described using the Ising Hamiltonian:

$$H = -\sum_{\langle i,j \rangle} J_{\tau_i \tau_j} S_i S_j - \mu_o H \sum_i S_i, \quad (1)$$

where the summation runs over nearest neighbors, H is the external magnetic field, and $J_{\tau_i \tau_j}$ is the exchange interaction integral. Heisenberg Hamiltonian was also evaluated; it significantly increased computational complexity and complicated the parameter fitting process. Consequently, the Ising Hamiltonian was selected due to its phenomenological success, which is fundamentally justified by the system's structural geometry and in-plane anisotropy (Kozlov, 2025).

The exchange interaction constants were physically justified and derived from the ratio of the bulk magnetic ordering temperatures (the Néel and Curie temperatures, $\frac{T_N^{\text{Cr}}}{T_C^{\text{Fe}}} \approx 0.3$). Expressed in dimensionless units, the exchange parameters were set to $J_{\text{Fe-Fe}} = 1.0$ (ferromagnetic), $J_{\text{Cr-Cr}} = -0.3$ (antiferromagnetic) and $J_{\text{Fe-Cr}} = -0.5$ to properly account for interface frustration.

Magnetic hysteresis loops were simulated using the Metropolis algorithm:

$$\Delta E = 2s_i \left(J \sum_{j \in \langle i \rangle} s_j + H \right). \quad (2)$$

The probability of spin flip on each step:

$$W(s_i \rightarrow -s_i) = \min \left(1, \exp \left(-\frac{\Delta E}{T} \right) \right). \quad (3)$$

The total magnetization of the system is defined as:

$$M = \sum_{i=1}^N s_i. \quad (4)$$

The external field was varied cyclically, with an increased density of points near $H = 0$.

The magnetic susceptibility χ was calculated directly from the thermodynamic fluctuations of the magnetization during the Monte Carlo sampling, using the standard relation:

$$\chi = \frac{1}{T} (M^2 - \langle M \rangle^2), \quad (5)$$

where T is the temperature, and M is the total magnetization of the system

I consider two types of structural morphology:

Homogeneous structure: characterized by a completely uniform distribution of iron within the FeCr layer. In the generated sample, iron atom clusters have a mean linear size of 0.37 nm, $\sigma_l = 0.07$ nm and a maximum size of 0.77 nm.

Clustered structure: where iron atoms are distributed non-uniformly using a three-dimensional Gaussian distribution (6) with multiple centers (7):

$$F(x, y, z) = \sum_{k=1}^{N_c} \exp \left(-\frac{d_x^2(x, x_k) + d_y^2(y, y_k) + d_z^2(z, z_k)}{2\sigma^2} \right); \quad (6)$$

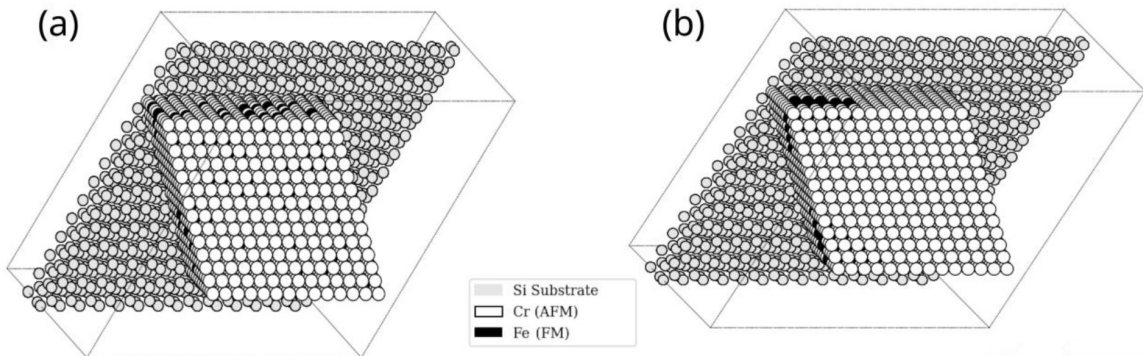


Fig. 1. Visualization of the simulated magnetic lattice Fe/FeCr/Fe cut:
(a) A homogeneous structure with a uniform distribution of Fe atoms in the central FeCr spacer;
(b) A granular structure with a Gaussian spatial distribution of Fe atoms

$$N_c = \frac{L^2 \cdot d_{active}}{\sigma}, \quad (7)$$

where L denotes the linear system size in the x and y directions, d_{active} is the thickness of the active layer along the z -axis, and σ the Gaussian width parameter that determines the characteristic correlation length of the generated field. The coordinates (x_k, y_k, z_k) of each center are uniformly distributed within the system volume. Distances in the x and y directions are calculated using periodic boundary conditions. We use the precision control to keep concentration of Fe equal to 17.5 %

Cluster sizes are estimated by the linear dimension $L = aN^{1/3}$, where N is the number of iron atoms forming the cluster and $a = 0.25$ nm is the characteristic interatomic distance for iron.

- $\sigma = 2.5$: mean cluster size of 1.42 nm, $\sigma_l = 0.53$ nm, maximum size of 2 nm;
- $\sigma = 5$: mean cluster size of 0.77 nm, $\sigma_l = 0.389$ nm, maximum size of 1.97 nm;
- $\sigma = 10$: mean cluster size of 0.48 nm, $\sigma_l = 0.176$ nm, maximum size of 1.3 nm

Presentation of the main research findings. Magnetization loops for a homogeneous (Fig. 2, *a*)

structure show a transition from a metamagnetic state – displaying contributions from both ferromagnetic (FM) and antiferromagnetic (AFM) sublattice – to a paramagnetic state. In the case of clusters (Fig. 2, *b*) a minor hysteresis loop appears due to the contribution of iron clusters. This loop gradually vanishes with increasing temperature, shifting the transition from the metamagnetic to the paramagnetic state to higher temperatures. At the same time, a pronounced increase in magnetic susceptibility is observed near zero field, indicating that the iron clusters have entered a superparamagnetic state (Fig. 2, *b*, $T = 360$ K). The presence of a soft magnetic step near $H \approx 0$ in the clustered system serves as a direct signature of the unblocked superparamagnetic fraction. In these systems, a direct proportionality is known to exist between the IEC and the magnetic susceptibility of the paramagnetic spacer in layered structures. The appearance of paramagnetic centers strongly influences the exchange between Fe layers through Fe/FeCr/Fe.

Figure 3 shows the temperature dependence of the magnetic susceptibility for different morphological configurations. A comparison

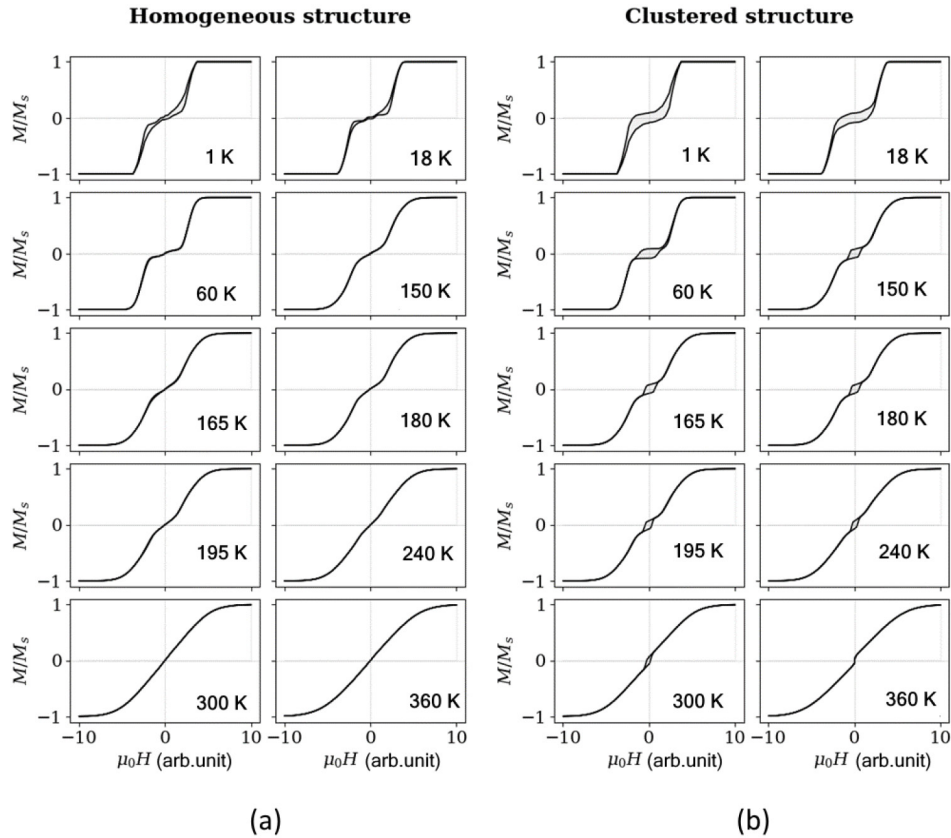


Fig. 2. Simulated magnetization loops for the (a) homogeneous and (b) clustered spacer morphologies $\sigma = 5$

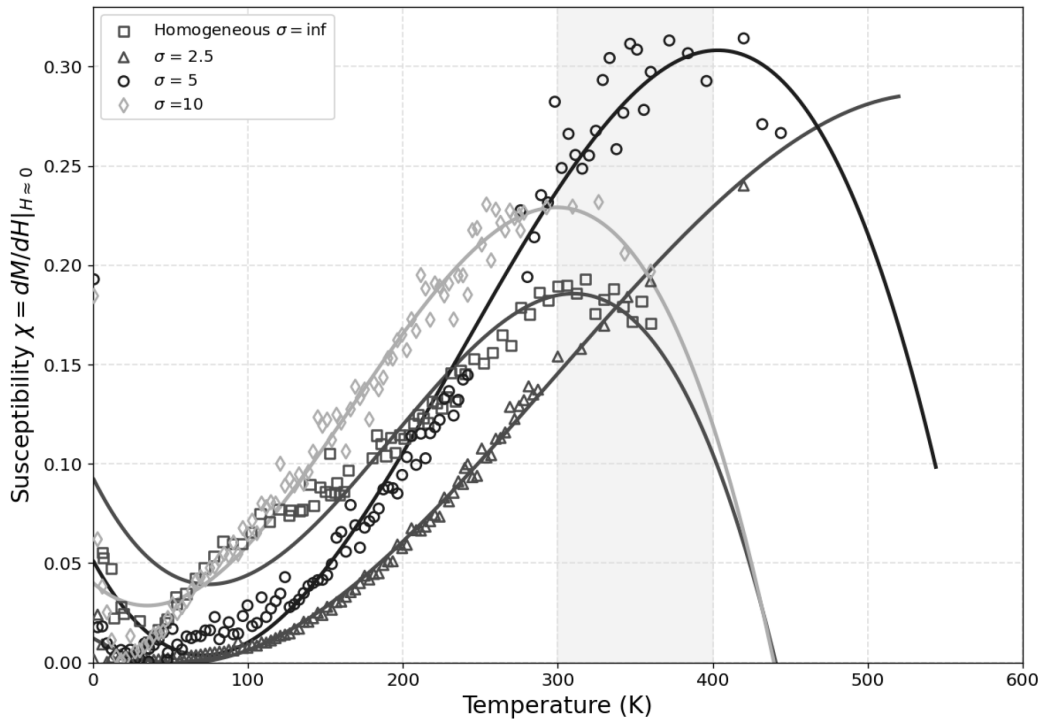


Fig. 3. Temperature dependence of the magnetic susceptibility χ (at $H \approx 0$)

is presented between data for a homogeneous distribution (squares) and cluster structures with different parameters: 2.5 (triangles), 5.0 (circles), and 10.0 (diamonds). Markers represent t the obtained data points, while solid lines show the corresponding fitting results. The shaded area ($300 < T < 400$ K) corresponds to the Curie-switch range. The inflection points of the susceptibility for the Cr/Fe_{17.5}Cr_{82.5}/Cr structure strongly depend on the clustering of the layer. We observe that minor clustering ($\sigma = 10$) does not significantly affect the shift in the Curie switching temperature. In the Curie switching region, this clustered structure behaves almost like a homogeneous one, with the only difference being that its susceptibility is higher due to the contribution of superparamagnetic particles. As the particle size increases ($\sigma = 2.5$, $\sigma = 5$), the transition region shifts toward higher temperatures, and both the number and the contribution of superparamagnetic particles increase significantly.

Conclusions and Future Work. It can be concluded that cluster-induced inhomogeneities modify the effective exchange interaction in several ways: by providing an additional channel of direct ferromagnetic coupling at low temperatures; by contributing to the effective indirect exchange through thermally activated superparamagnetic centers; and by shifting the transition temperature to the paramagnetic phase in Cr/FeCr/Cr spacers. As mentioned, the model is phenomenological; it does not account for long-range order or the change in the exchange interaction magnitude during the phase transition. Nevertheless, it describes certain features observed experimentally: the presence of a small peak on the hysteresis loops (Kozlov, 2025), the Curie-switch temperature (Polishchuk, 2017), and several other phenomena that will be discussed in future work, such as establishing a correlation between the interlayer exchange interaction and the magnetic susceptibility of the modeled structure.

BIBLIOGRAPHY:

1. Bruno P. Theory of interlayer magnetic coupling. *Physical Review B*. 1995. Vol. 52, no. 1. P. 411–439. DOI: <https://doi.org/10.1103/physrevb.52.411>
2. Grünberg P. A. Nobel Lecture: From spin waves to giant magnetoresistance and beyond. *Reviews of Modern Physics*. 2008. Vol. 80, no. 4. P. 1531–1540. DOI: <https://doi.org/10.1103/revmodphys.80.1531>
3. Khalili Amiri P., Phatak C., Finocchio G. Prospects for Antiferromagnetic Spintronic Devices. *Annual Review of Materials Research*. 2024. DOI: <https://doi.org/10.1146/annurev-matsci-080222-030535>
4. Spintronics based random access memory: a review / S. Bhatti et al. *Materials Today*. 2017. Vol. 20, no. 9. P. 530–548. DOI: <https://doi.org/10.1016/j.mattod.2017.07.007>

5. Apalkov D., Dieny B., Slaughter J. M. Magnetoresistive Random Access Memory. *Proceedings of the IEEE*. 2016. Vol. 104, no. 10. P. 1796–1830. DOI: <https://doi.org/10.1109/jproc.2016.2590142>
6. Opportunities and challenges for spintronics in the microelectronics industry / B. Dieny et al. *Nature Electronics*. 2020. Vol. 3, no. 8. P. 446–459. DOI: <https://doi.org/10.1038/s41928-020-0461-5>
7. Kasuya T. A Theory of Metallic Ferro- and Antiferromagnetism on Zener's Model. *Progress of Theoretical Physics*. 1956. Vol. 16, no. 1. P. 45–57. DOI: <https://doi.org/10.1143/ptp.16.45>
8. Yosida K. Magnetic Properties of Cu-Mn Alloys. *Physical Review*. 1957. Vol. 106, no. 5. P. 893–898. DOI: <https://doi.org/10.1103/physrev.106.893>
9. Ruderman M. A., Kittel C. Indirect Exchange Coupling of Nuclear Magnetic Moments by Conduction Electrons. *Physical Review*. 1954. Vol. 96, no. 1. P. 99–102. DOI: <https://doi.org/10.1103/physrev.96.99>
10. Thermally induced antiferromagnetic exchange in magnetic multilayers / D. M. Polishchuk et al. *Physical Review B*. 2017. Vol. 96, no. 10. DOI: <https://doi.org/10.1103/physrevb.96.104427>
11. All-Electrical Operation of a Curie Switch at Room Temperature / V. Iurchuk et al. *Physical Review Applied*. 2023. Vol. 20, no. 2. DOI: <https://doi.org/10.1103/physrevapplied.20.024009>
12. Thermally-controlled interlayer exchange and field-induced anisotropy in synthetic antiferromagnets. *arXiv.org*. DOI: <https://doi.org/10.48550/arXiv.2512.10511>

REFERENCES

1. Bruno, P. (1995). Theory of interlayer magnetic coupling. *Physical Review B*, 52(1), 411–439. <https://doi.org/10.1103/physrevb.52.411>
2. Grünberg, P. A. (2008). Nobel Lecture: From spin waves to giant magnetoresistance and beyond. *Reviews of Modern Physics*, 80(4), 1531–1540. <https://doi.org/10.1103/revmodphys.80.1531>
3. Khalili Amiri, P., Phatak, C., & Finocchio, G. (2024). Prospects for Antiferromagnetic Spintronic Devices. *Annual Review of Materials Research*. <https://doi.org/10.1146/annurev-matsci-080222-030535>
4. Bhatti, S., Sbiaa, R., Hirohata, A., Ohno, H., Fukami, S., & Piramanayagam, S. N. (2017a). Spintronics based random access memory: a review. *Materials Today*, 20(9), 530–548. <https://doi.org/10.1016/j.mattod.2017.07.007>
5. Apalkov D., Dieny B., Slaughter J. M. Magnetoresistive Random Access Memory. *Proceedings of the IEEE*. 2016. Vol. 104, no. 10. P. 1796–1830. URL: <https://doi.org/10.1109/jproc.2016.2590142>
6. Dieny, B., Prejbeanu, I. L., Garello, K., Gambardella, P., Freitas, P., Lehndorff, R., Raberg, W., Ebels, U., Demokritov, S. O., Akerman, J., Deac, A., Pirro, P., Adelman, C., Anane, A., Chumak, A. V., Hirohata, A., Mangin, S., Valenzuela, S. O., Onbaşlı, M. C.,... Bortolotti, P. (2020b). Opportunities and challenges for spintronics in the microelectronics industry. *Nature Electronics*, 3(8), 446–459. <https://doi.org/10.1038/s41928-020-0461-5>
7. Kasuya, T. (1956). A Theory of Metallic Ferro- and Antiferromagnetism on Zener's Model. *Progress of Theoretical Physics*, 16(1), 45–57. <https://doi.org/10.1143/ptp.16.45>
8. Yosida, K. (1957). Magnetic Properties of Cu-Mn Alloys. *Physical Review*, 106(5), 893–898. <https://doi.org/10.1103/physrev.106.893>
9. Ruderman, M. A., & Kittel, C. (1954). Indirect Exchange Coupling of Nuclear Magnetic Moments by Conduction Electrons. *Physical Review*, 96(1), 99–102. <https://doi.org/10.1103/physrev.96.99>
10. Polishchuk, D. M., Tykhonenko-Polishchuk, Y. O., Holmgren, E., Kravets, A. F., & Korenivski, V. (2017). Thermally induced antiferromagnetic exchange in magnetic multilayers. *Physical Review B*, 96(10). <https://doi.org/10.1103/physrevb.96.104427>
11. Iurchuk, V., Kozlov, O., Sorokin, S., Zhou, S., Lindner, J., Reshetniak, S., Kravets, A., Polishchuk, D., & Korenivski, V. (2023). All-Electrical Operation of a Curie Switch at Room Temperature. *Physical Review Applied*, 20(2). <https://doi.org/10.1103/physrevapplied.20.024009>
12. *Thermally-controlled interlayer exchange and field-induced anisotropy in synthetic antiferromagnets*. (б. д.). arXiv.org. <https://arxiv.org/abs/2512.10511>

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