Purpose of the visit

During my short visit of the Theoretical Physics Department at Loughborough University we included Prof. Kusmartsev's PHD student Mike Forrester in our collaboration and had numerous stimulating and fruitful discusssions. We eventually wrote a draft for a paper to be submitted to the Journal of Applied Physics with the title

TUNNEL JUNCTIONS FOR MAGNETIC NON-VOLATILE MEMORIES

The draft has still to be completed with rather convincing numerical micro-magnetic simulations performed by Mike Forrester.

Short description about the project

We propose a stack of two or more isolated diskshape particles as an element for magnetic memory storage as well as for magnetic field sensors. The tunneling across the device depends on the magnetic arrangement of the magnetic moments of the individual magnetic particles and is appreciably higher when the magnetic moments are aligned parallel to one another. Such a device is characterised by a few stable states separated by large barriers. The switching between different states may be induced by an applied spin-polarised current or magnetic field. We present a complete theoretical study of the magnetic phase diagram as a function of the field for arbitrary strength of the anisotropy. We classify all possible magnetic hysteresis loops and show the dependence of the corresponding magnetic moments on the external field. We further discuss the stability of the information stored and determine the critical magnetic switching fields.

see also:

K.E. Kürten, Invited talk: "Phase transitions and hysteresis in a system of two coupled magnetic nanoparticles", proceedings of the XXIX International Conference on Condensed Matter Theories, held in September 2005 in Kyoto, Nova Science Publishers, N.Y., Vol. **21** (2006)

For completeness I include the current version of our paper.

Future collaboration with the host institution

The long lasting collaboration Vienna-Loughborough with Prof. Kusmartsev is intended to be continued in the future. Considering that the subject is of high actuality, especially in the range of technical applications, we plan to do further joint work in the field of magnetic nanoparticles as well as in the field of arrays of Josephson junctions.

Tunnel junctions for magnetic non-volatile memories

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(Dated: October 21, 2006)

We propose to use a stack of isolated two or more diskshape particles as an element for magnetic memory,ie as magnetic tunnel junction. Such an element is characterised by a few stable states separated by large barriers. The switching between the states may be induced by an applied spin-polarised current or magnetic field. We have described the behaviour of the stable states states of the stack in magnetic field, their energies, magnetisations as well as all possible types of hysteresys loops which such an element may have. We discuss the stability of the information stored in the element and determine a critical magnetic field where the switching of the element occurs.

PACS numbers:

Recent emerging technology known as spintronics is going to make a step towards the use of spin degrees of freedom. On the other hand the magnetic memory structures have a tendency to be made of smaller and smaller elements. Magnetoresistive random access memory (MRAM) uses the magnetic tunnel junction (MTJ) to store information[9]. There the MTJ stack consists of two ferromagnetic layers separated by a thin dielectric barrier. Usually a magnetic polarization of one layer is fixed, while other is used for information storage. MRAM stores data utilizing the magnetic polarity of a ferromagnetic layer[10]. The reading of information is performed by measuring the current, which is determined by the rate of electron quantum tunneling through the MTJ stack, which is affected by the mutual polarity of the layers[11–13]. In other terms the MTJ resistance is measured across the stack to determine the cell state. The free layer polarization is changeable: thus parallel or antiparallel magnetic moments give low or high resistances which can be interpreted as "0" or "1."

The MRAM will be a non-volatile, power-saving, high-speed memory in future[15]. In MRAM, thermal agitation combined with either digit or word disturb limits the operation field margin, causes unexpected switching, and affects the stability of the memory states. New structure is necessary to be developed to increase the operation field margin for effective reading and writing in MRAM[16]. In most of proposals, from Goto's model to tri-layer model, energy barrier becomes lower with the increasing of applied magnetic field. Thermal agitation combined with field disturbances in easy direction may cause unexpected switches.

The memory consists of an array of the MRAM cells. Increasing density of MRAM array is possible only with the decreasing sizes of MTJ. However with small sizes there are issues such as thermal instability of the cell states[21]. As size decreases, barrier energy drops as well, decreasing stability. Cannot just raise Hc, because increases current. In some proposal one uses the thermal heat itself to help select cell for writing[18–20]. As material approaches Curie point, Hc drops, so that less current is needed to write the information[17]. At cooler temperatures, the energy potential well can be deeper, this will lead to increasing stability of the MRAM cell states and of the keeping of the stored information. We have to avoiding thermal instabilities by increasing barrier heights. In some proposals the free layer is in fact a Synthetic Antiferromagnetic tri-layer stack (SAF)[18–20]. The magnetic moments of the top and bottom layers are nearly balanced. The direction of magnetization of the ferromagnetic (FM) sense layer with respect to the pinned FM layer determines the resistance state of the bit. The direction of the top FM layer and the sense FM layer are set by Savtchenko switching. Savtchenko switching is named after the late Leonid Savtchenko at Motorola. Savtchenko switching is a method to toggle bit between high and low resistance states. The SAF rotates its magnetic axis perpendicular to the applied field. The bit is oriented 45 degrees with respect to the write lines. The 45 degree bits results in higher memory storage densities.

We propose to use small magnetic diskshape particles to built up a MTJ. In a most simple construction MTJ can consist of two monodomain ferromagnets separated by insulator or normal metal. The monodomain nanodots can be made of NiZn with a diameter about d 40 nm or made of supermalloy with a diameter d 100nm and thickness h 10nm. The magnetism at small length scales has been a rapidly growing area of physics. Small magnetic particles and artificial thin-film structures based on ferro- or anti-ferromagnetic layers separated by non-magnetic spacers are the basic structural elements for an enormous scope of technical applications in the area of data storage and magnetic sensors found in a variety of everyday products[18**?** –20].

The giant magnetoresistant (GMR) effect in anti-ferromagnetically coupled multilayers forming a MTJ the heart of many specific applications [1, 2]. On the other hand, nanomagnets provide an experimental systems for studying fundamental phenomena in spintronics. Because of the hierarchy of competing interactions different from bulk materials,

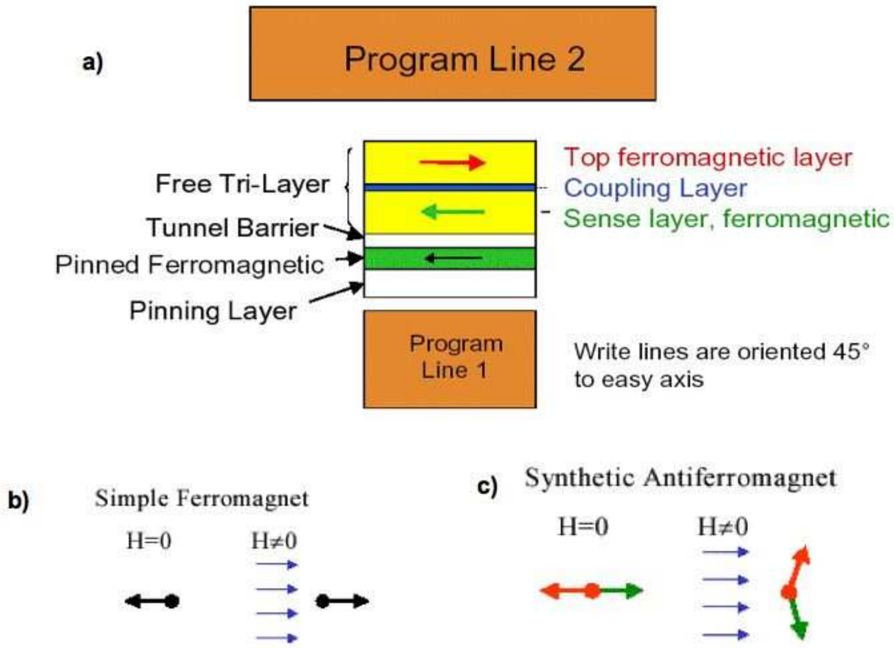

FIG. 1: a) Schematic structure of the work of the Magnetoresistive Access Memory (MRAM) cell consisting of magnetic tunnel junction formed by two ferromagnetic and one insulating layers From the top and bottom from the memory cell there are to programm lines which responsible for reading and writing information into the cell.

these many particle systems display rather rich and interesting collective behaviour not found in bulk crystalline magnets. Networks of elementary interacting small magnetic particles, smaller than the bulk domain size, are potential future candidates for MRAM to store and to propagate information. The states are signalled by the magnetization direction of single-domain magnetic particles coupled to their nearest neighbours through magnetostatic interactions. A new memory may consists of a network or a one-dimensional chain of circular or elliptic pairs of diskshape monodomain particles forming a MTJs made from a commonly used magnetic supermalloy on a single-cristal silicon substrate. Cowburn et al. have shown experimentally that circular nanomagnets made from supermalloy behave like single domains if their diameter is less than 100nm and their thickness is not more than 10nm [3]

2. THE MODEL SYSTEM

Consider a thin film sandwich structure with two ferromagnetic layers separated by an insulating layer. Depending on the thickness of the spacer the two layers can be ferromagnetically or antiferromagnetically coupled. We start with the Hamiltonian of the classic anisotropic Dirac-Heisenberg model

$$H = -J \sum_{<i,j>} \mathbf{S}_i \cdot \mathbf{S}_j + K \sum_{i=1}^{N} (\mathbf{S_i} \cdot \mathbf{e}_y)^2 - \mathbf{H} \cdot \sum_{i=1}^{N} \mathbf{S}_i \qquad (1)$$

where the spin operators are substituted by the unit vectors S_i corresponding to the spin on site i. H is the uniform magnetic field applied in a direction of the angle β with respect to the easy axis. The quantity $K > 0$ specifies the strength of the uniaxial unisotropy, while the quantity J describes the strength of the nearest-neighbor exchange interaction. We remark that the dipole-dipole interaction inside the particles is neclected, since for small spherical particles this energy contribution is small compared with the contribution to the exchange interactions. The same argument holds for the shape anisotropy such that the anisotropy contribution mainly stems from surface effects. The locally energy minima of the system whose stabilities are crucial for hysteresis effects can be determined from the

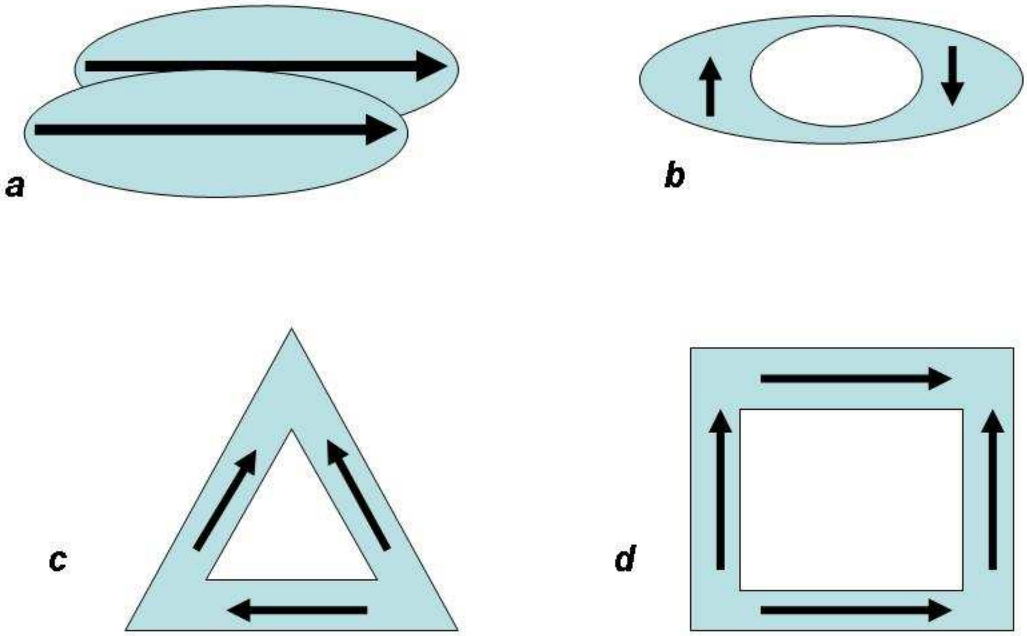

FIG. 2: Different elements for magnetic memory.

integration of the Landau Lifshitz Gilbert equation [4]

$$\dot{\mathbf{S}}_{\mathbf{i}} = \mathbf{S}_{\mathbf{i}} \times \frac{\partial H}{\partial \mathbf{S}_{\mathbf{i}}} - \alpha \mathbf{S}_{\mathbf{i}} \times (\mathbf{S}_{\mathbf{i}} \times \frac{\partial H}{\partial \mathbf{S}_{\mathbf{i}}}) \tag{2}$$

with the relaxation parameter α, which is often known from experimental studies. Assuming that within each layer all magnetic moments are ferromagnetically aligned but with an orientation that differs from layer to layer, we consider the particles as elementary mono-domain units which take the shape of very flat spheres. Under these assumptions the preferential orientations of the magnetizations are in-plane such that we can reduce our problem to the study of one-dimensional chains of small magnetic particles. Introducing planar polar coordinates $\mathbf{S}_i = (\cos(\phi_i), \sin(\phi_i))$, where the magnetization direction of particle i is described by the variable ϕ_i. the total energy of the system is given by the two-particle Hamiltonian

$$H = -2J\cos(\phi_1 - \phi_2) + \frac{K}{2}\left(\sin^2(\phi_1) + \sin^2(\phi_2)\right) - H\left(\cos(\phi_1 - \beta) + \cos(\phi_2 - \beta)\right) \tag{3}$$

The quantity β specifies the angle of the external field with the easy axis, The dynamical behaviour of the particles is governed by three competing energy terms, which can give rise to multistability and coexistence of various physical phases. The first term defines the exchange energy, specified by nearest-neighbour interactions, while the next two terms are due to the anisotropy. The last two terms specify the Zeeman energy. Since H and K can be scaled by J we can choose $|J| = 1$. The set of Landau Lifshitz Gilbert equations collapses to the two coupled ordinary differential equations

$$\dot{\phi}_1 = -\alpha \frac{\partial H}{\partial \phi_1} \qquad \text{and} \qquad \dot{\phi}_2 = -\alpha \frac{\partial H}{\partial \phi_2} \tag{4}$$

Discretization of Eqs. (4) leads to a gradient descent procedure as commonly practised. Here, depending on the initial condition, the system relaxes to the "closest" local or global minimum. According to the variational principle, the necessary conditions for the existence of a local minimum of the Hamiltonian are the force equilibrium equations

$$\frac{\partial \mathbf{E}}{\partial \phi_1} = 2J\sin(\phi_1 - \phi_2) + H\ \sin\ (\phi_1 - \beta) + K\ \sin(\phi_1)\cos(\phi_1) = 0 \tag{5}$$

and

$$\frac{\partial \mathbf{E}}{\partial \phi_2} = 2J\sin(\phi_2 - \phi_1) + H\ \sin\ (\phi_2 - \beta) + K\ \sin(\phi_2)\cos(\phi_2) = 0 \tag{6}$$

In addition, the smallest eigenvalue λ_{min} of the Hessian matrix, the Jacobi matrix of the derivatives of the energy Eq.(3), has to be positive.

3. PHASE DIAGRAM FOR $\beta = 0$

For $\beta = 0$ the external magnetic field is parallel to the direction of the easy axis. We find two ferromagnetic phases, $\mathbf{F}^{\uparrow\uparrow}$ and $\mathbf{F}^{\downarrow\downarrow}$ specified by the angles $\phi_1 = \phi_2 = 0$ and $\phi_1 = \phi_2 = \pi$, respectively. The corresponding energies are $E_F = 2 - 2H$ and $E_F = 2 + 2H$. The two ferromagnetic phases $\mathbf{F}^{\uparrow\uparrow}$ and $\mathbf{F}^{\downarrow\downarrow}$ are stable for $H > 4 - K$ and $H < K - 4$, respectively. We further find the anti-ferromagnetic phase **AF** characterized by the angles $\phi_1 = 0$ $\phi_2 = \pi$, and $\phi_1 = \pi$ $\phi_2 = 0$ with the corresponding constant energy $E_{AF} = -2$. The antiferromagnetic phases are stable for $|H| < \sqrt{K(4+K)}$. Eventually there exists a scissored phase SC specified by the angle relation $\phi_1 = -\phi_2$ with $\phi_1 = \text{Arccos} H/(4-K)$. Note that his phase is often referred to as the spin-flop phase [7]. The corresponding energy takes the value $E_{SC} = (K-2) - H^2/(4-K)$. This phase is stable for $|H| < 4 - K$ and $|H| > (4-K)\sqrt{K/(4+K)}$. Note that the scissored phase exists only for $K < 4$. According to Fig. 3 we can have coexistence of two and more phases, respectively. Moreover, we have the triple points $P_3 = (\frac{4}{3}, \pm\frac{8}{3})$, where three phases exist, while at $P_4 = (4, 0)$ we have coexistence of all four phases. These critical points will be decisive in order to give a proper classification of all possible hysteresis loops. The evolution of the two magnetization angles ϕ_1 and ϕ_2 as a function of the magnetic field for an anisotropy strength below the critical point $K = \frac{4}{3}$ is illustrated in Fig. 4. We start with a sufficiently large positive field and drive the field slowly down. The first transition occurs, when the $F^{\uparrow\uparrow}$ phase becomes unstable. ($P_{F^{\uparrow\uparrow}\rightarrow SC} = (1, 3)$). This second order transition is a pitchfork bifurcation. Then the SC phase becomes unstable and there is a discontinuous transition at $P_{SC\rightarrow AF} = (1, \frac{3}{5}\sqrt{5})$. Then the AF phase becomes unstable and we reenter the SC phase at $P_{AF\rightarrow SC} = (1, -\sqrt{5})$. Eventually the SC phase becomes unstable at $P_{SC\rightarrow F^{\downarrow\downarrow}} = (1, -3)$ and we enter continuously the complementary ferromagnetic phase $F^{\downarrow\downarrow}$.

In contrast to the evolution of the magnetization angles in Fig. 4 we restart with a negative large saturation and drive the field slowly up to the positive saturation again. Thus, in contrast to Fig. 4, Fig. 5 is symmetric to the axis of magnetization, since we drive the saturated field forth and back, giving rise to a closed hysteresis loop. The evolution of the two magnetization angles for anisotropy strength K with $\frac{4}{3} < K < 4$ between the two critical points is similar, however the system enters directly from the AF phase into the $\mathbf{F}^{\downarrow\downarrow}$ without passing through the **SC** phase. In fact, this behavior is well known from experiments with antiferromagnetic materials.

Figure 4 shows the corresponding evolution of the hysteresis loop, which can also be extracted completely from our phase diagram depicted in Fig. 3. According to the phase diagram depicted in Fig. 3, for $K > 4$, we only have transitions from the ferromagnetic phase $F^{\uparrow\uparrow}$ to the complementary ferromagnetic $F^{\downarrow\downarrow}$ phase and vice versa. We stress that a complete classification of all possible hysteresis curves is of fundamental importance in any kind of technical application. Moreover, in the same manner, the qualitative behaviour of all possible magnetoresistance curves can directly be extracted from the phase diagram depicted in Fig. 3.

SUMMARY

We studied properties of two interacting magnetic particles subjected to exchange interaction J, anisotropy parameter K and an external magnetic field H with an arbitrary angle β with respect to the easy axis. We further present a complete theoretical study of magnetic phase diagrams as a function of the field for arbitrary strength of the anisotropy. We classify all possible magnetic hysteresis loops and show the dependence of the corresponding magnetic moments on the external field. These studies can give answers to the problem of finding adequate materials for practical

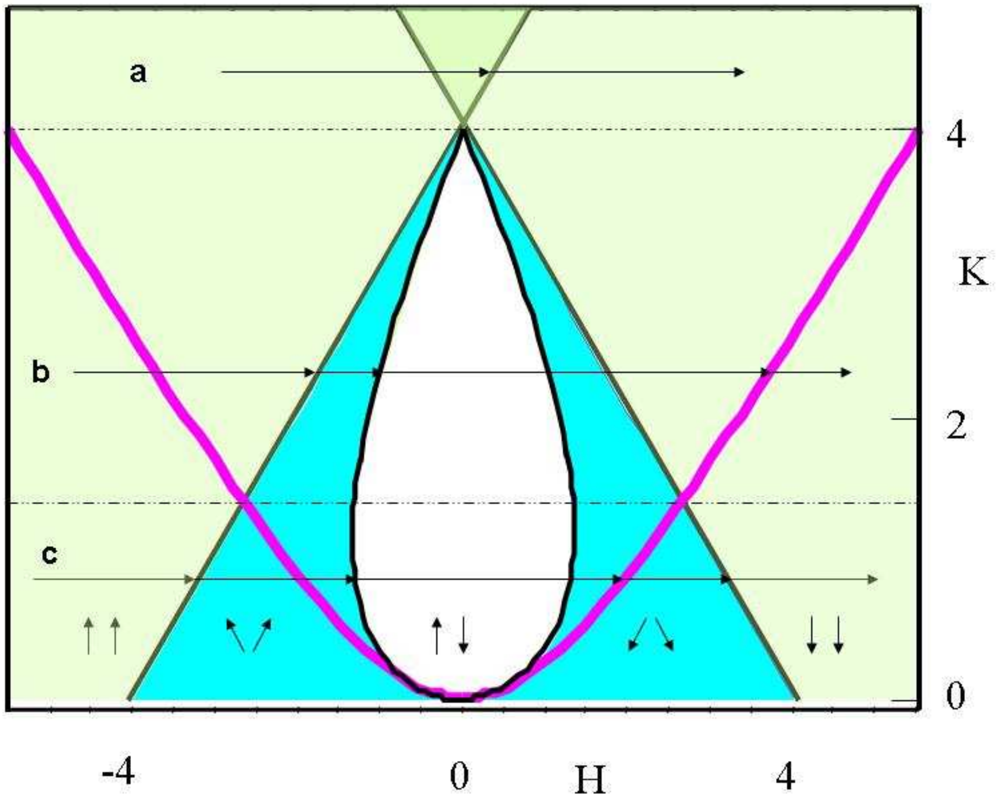

FIG. 3: A diagramm of different states existing in magnetic tunnel junction as a function of external magnetic field applied in the plane parallel to ferromagnetic layers and the shape of the particles associated with the parameter K. Large positive value of K indicate that the monodomain particles are strongly elongated along X-direction.

applications such as sensor, storing or recording devices. We remark that for larger number of particles the problem of multistability is highly complex and can lead to fractal properties seen in all physical variables [8].

In conclusion, we have demonstrated the behavior of MTJ consisting of pair of diskshape monodomain particles separating by an insulator. We have studied the stability of the MTJ states and a hysteresis loop both analytically and numerically and made a detailed analysis of the possible hysteresys loops of the proposed MTJ. We have determined a phase diagramm in the magnetic field -shape anisotropy plane. The numerical calculations are in good agreement with our theoretical predictions.

The proposed MTJ may entail a range of applications. Development of new magnetoelectronic devices are probable and innovations in information processing and THz technology can be anticipated. The possible applications may include models for MRAM constructions and logic gates. The novel magnetoelecronic devices may embrace memory cells for storing binary data and even a construction for logic gates. Many interconnected transmission lines made of MTJ can be designed into networks – nano MTJ networks. These considerations lead to future development of a novel hardware and a new technology based on the nano- MTJs.

ACKNOWLEDGMENTS

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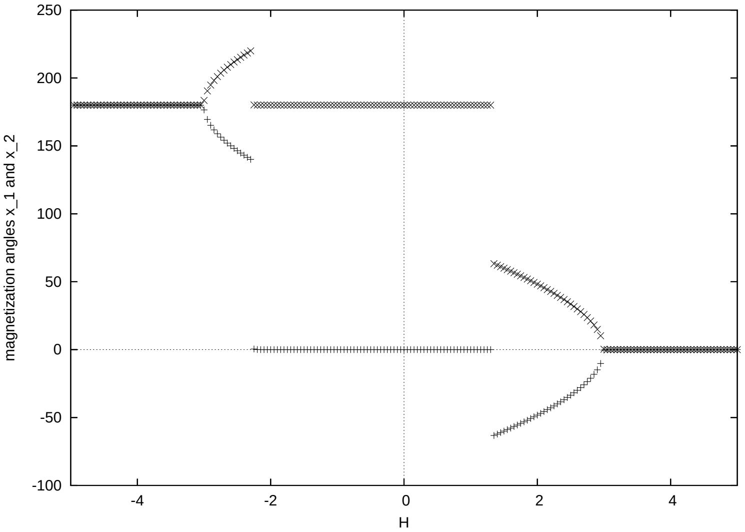

FIG. 4: Magnetization angles for $K = 1$ as a function of the magnetic field H .

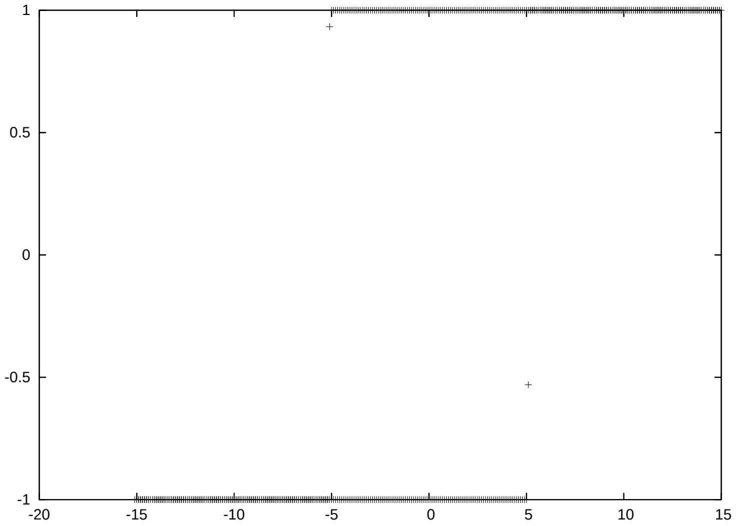

FIG. 5: Hysteresis loop for anisotropy strength $K = 8$.

"Arrays of Quantum Dots and Josephson Junctions".

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[1] M. A. Howson, *Contemporary Physics*, **35**, (5) 347-359 (1994)
[2] P. Grünberg, *Physics Today*, May 2001
[3] R. P. Cowburn and M. E. Welland, Science, **287**, 1466 (2000)
[4] D. Suess, T. Schrefl, W. Scholz, and J. Fidler, Journal of Magnetism and Magnetic Materials, **242-245**,426-429 (2002)
[5] D. C. Worledge, Appl. Phys. Lett. **84**, 2847 (2004)
[6] Z. Szabo and A. Ivanyi, Journal of Magnetism and Magnetic Materials, **215-216**, 33-36 (2000)
[7] C Micheletti, R.B. Griffiths and J.M. Yeomans, Phys.Rev. **B 59**, 6239 (1999)
[8] K. E. Kürten and F.V Kusmartsev, Phys.Rev. **B 72**, 014433 (2005)
[9] Daughton, J.; Magnetoresistive Random Access Memory; 2000.
[10] Klein, L.; Single-layer PHE-based MRAM; 2005.

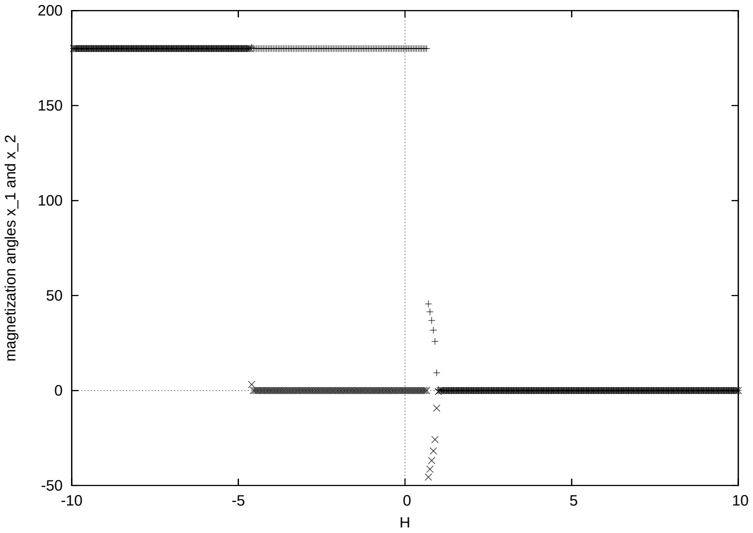

FIG. 6: Magnetization angles for $K = 8$ as a function of the magnetic field H.

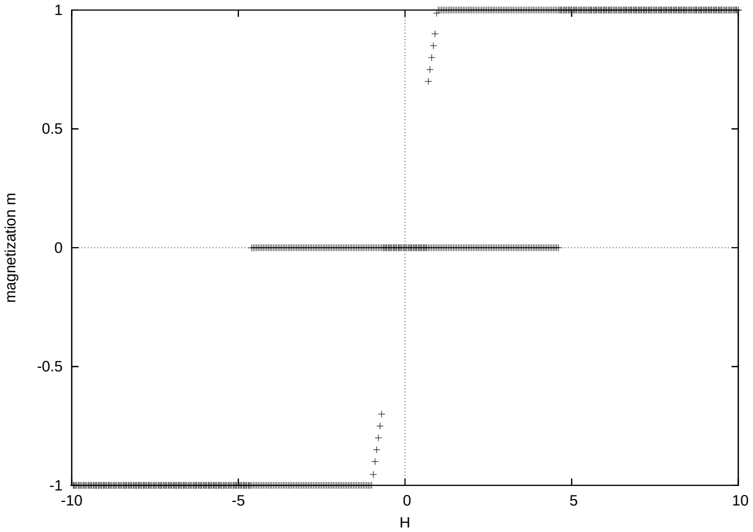

FIG. 7: Hysteresis loop for $K = 3$.

[11] Akerman, J.; Toward a Universal Memory; Science; 308(4), 508-510; 2005.
[12] Mallinson, John; Magneto-Resistive and Spin Valve Heads; Academic Press; 2002.
[13] Hirota E., Sakakima H., Inomata K,; Giant Magneto-Resistance Devices; Springer; 2002.
[14] Hartmann, Uwe (editor); Magnetic Multilayers and Giant Magnetoresistance; Springer; 2000.
[15] Daughton, James M, Advanced MRAM Concepts; NVE Corporation, 2001.
[16] Slaughter J.M et al; Fundamentals of MRAM Technology; Journal of Superconductivity; 15(1), 19; 2002.
[17] Daughton, J.M.; J. Appl. Phys; 81(8), 3758.
[18] Durlam, M et al.; VLSI Symposium 2002.
[19] Durlam, M., et al.; A 0.18um 4Mb Toggling MRAM; Freescale Semiconductor, Inc.; 2003.
[20] Pohm, A.V. et al.; IEEE Transactions on Magnetics; 33(5), 3280.
[21] Slaughter, J.M., et al.; Magnetic Tunnel Junction Materials for Electronic Applications; JOM-e, 52(6); 2000: