7th International Conference on
Superconductivity and Magnetism
21st -27th October 2021, Bodrum, Turkey

SPINTECH

Layered nanostructures for superconducting spintronics

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SPINTECH

The "SPINTECH" has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 810144

Coordinator - Institute of Electronic Engineering and Nanotechnologies, Chisinau, Moldova – in a tight collaboration with partners:

Valdimir Krasnov
Stockholm University

Alexander Golubov,
Twente University

Mikhail Kupriyanov,
Nikolai Klenov,
Moscow, Russia

Vasily Stolyarov,
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Izhevsk, Russia

Lenar Tagirov
Kazan, Russia

Bernhard Keimer
Yurii Khadukov,
Stuttgart, Germany

Horst Hahn
Karlsruhe, Germany

partner project: MELON (France) – coordinator Igor Lukyanchuk https://www.melon.ferroix.net/

Goals of the HORIZON-2020 project “SPINTECH”

- “Boosting the scientific excellence and innovation capacity of the D. GHITU Institute of Electronic Engineering and Nanotechnologies in the field of spintronics”,

– especially in the development of advanced technologies for design and production of superconducting spintronic devices and base elements for novel computer with non-von Neumann architecture – brain like artificial networks.

State of the art

- As the base of the project serves the book:

- are summarised results of theoretical and experimental investigation of nanostructures Superconductor/Feromagnet, novel technologies of their fabrication and characterization methods,

in: Functional Nanostructures and Metamaterials for Superconducting Spintronics. Ed. by A.Sidorenko,“Springer”, 2018, 270p.

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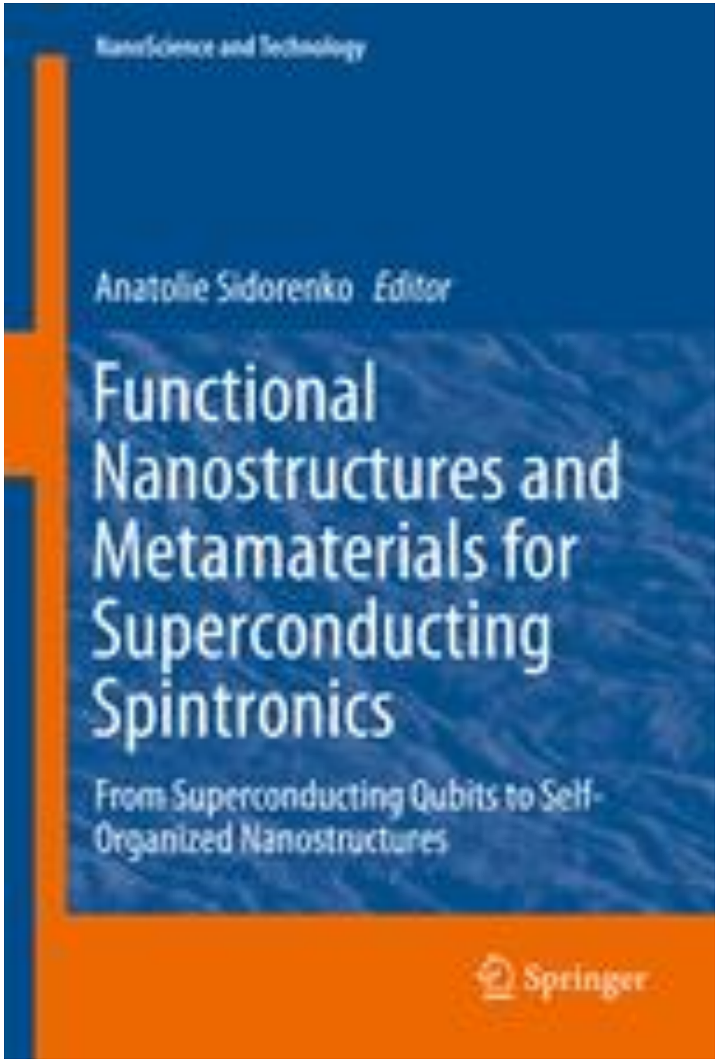


Motivation of the work: **Limits of semiconducting technology**

- **LARGE size and huge Power consumption**

Data Centers: Facebook Data Center

Luleå, Sweden

- 2014 completion target
- Cost: ~760 M$
- Nearby Lule River generates 9% of Sweden's electricity (~4.23 GW)
- Average annual temperature: 1.3 °C

	Specifications
Performance*	27-51 PFLOP/s
Memory*	21-27 PB RAM 1900-6800 PB disk
Power	84 MW avg* (120 MW max)
Space	290,000 ft^2 (27,000 m^2)
Cooling*	~1.07 PUE

* estimated

IEEE Advancing Technology

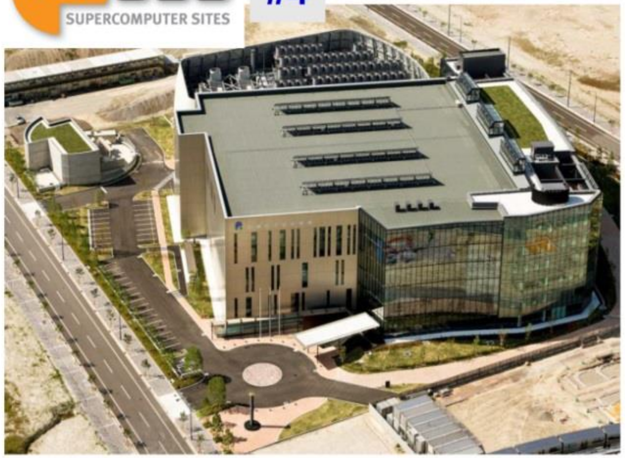
Courtesy of S. Holmes

Data Centers:
- Cloud computing
- Banking
- Shopping
- Social Networks
- Search Engines....

Lulea data center: 120 MW (max power)

Supercomputers: K-Computer (Japan)

TOP500 SUPERCOMPUTER SITES #4 www.top500.org



Top500 No. 4 supercomputer: K-computer (Japan): 10.51 petaflop/s, 12.7 MW

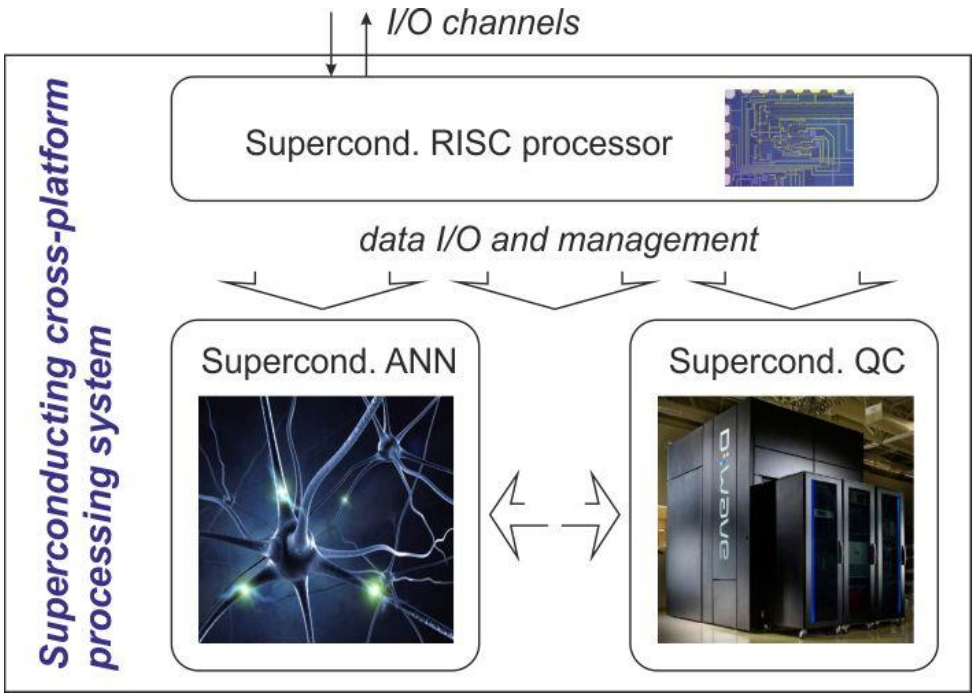
Top500 No. 1: Tianhe-2 (China): 33.9 petaflop/s, 17.8 MW

TOP500 SUPERCOMPUTER SITES *rating updated in June 2014*

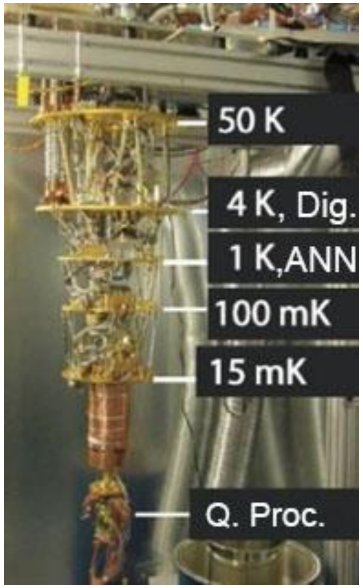
After O. A. Mukhanov, HYPRES Inc, USA

Superconducting solution -

Rapid and energy-efficient platform for neural network and quantum comuter with non-von Neumann architecture



The same base elements!



Temperature levels of operating ANN and Quantum Computer

Starting point of the work:

Beasley's Superconducting Memory Element (BSME)

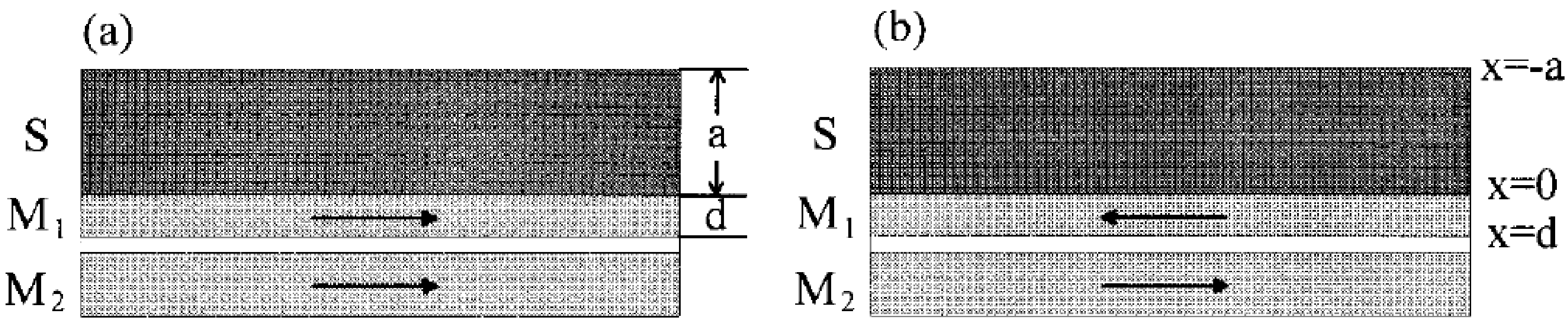
[Applied Physics Letters 71, 2376 (1997)]

A superconductive magnetoresistive memory element using controlled exchange interaction

Sangjun Oh and D. Youm
Department of Physics, Korea Advanced Institute of Science and Technology, Kusung-Dong, Yusung-Gu, Taejon 305-701, Korea

M. R. Beasley[a)]
Department of Applied Physics, Stanford University, Via Palou, Stanford, California 94305-4085

(Received 14 January 1997; accepted for publication 24 July 1997)



Beasley's Superconducting Memory Element (BSME)

[Applied Physics Letters 71, 2376 (1997)]

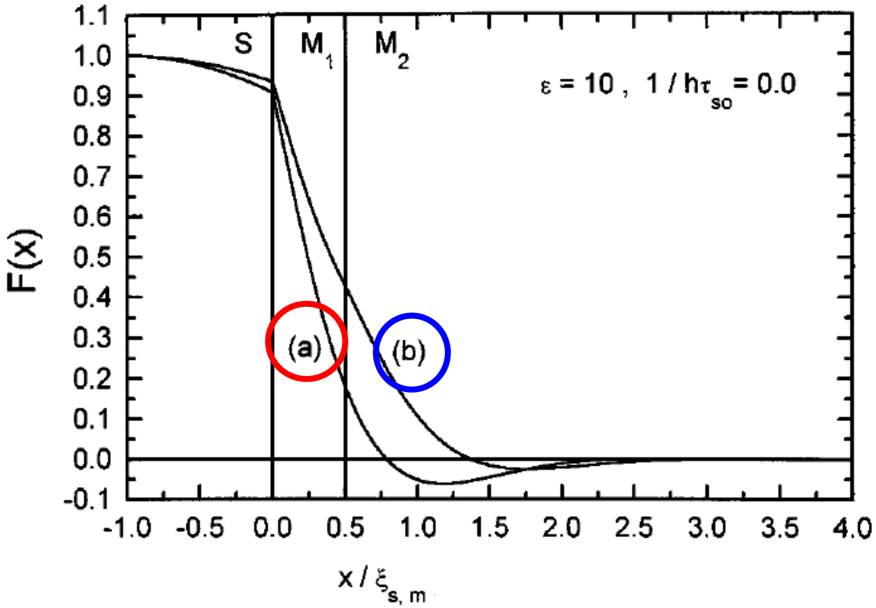
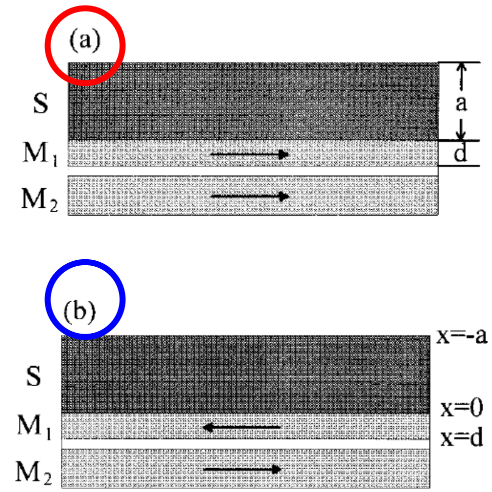


FIG. 2. Normalized pair wave functions, $F(x)=\Sigma_{\omega}[f_{-}(\omega,x)+f_{+}(\omega,x)]$,

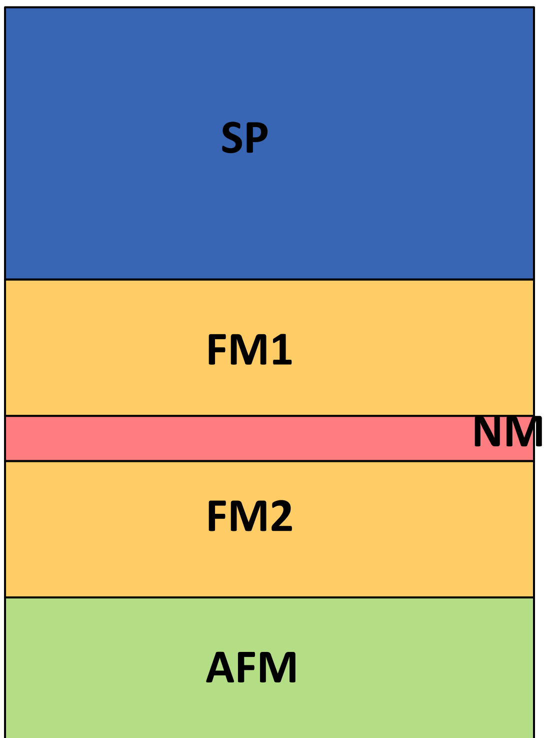


Coined as “Standard”, or “Direct” switching

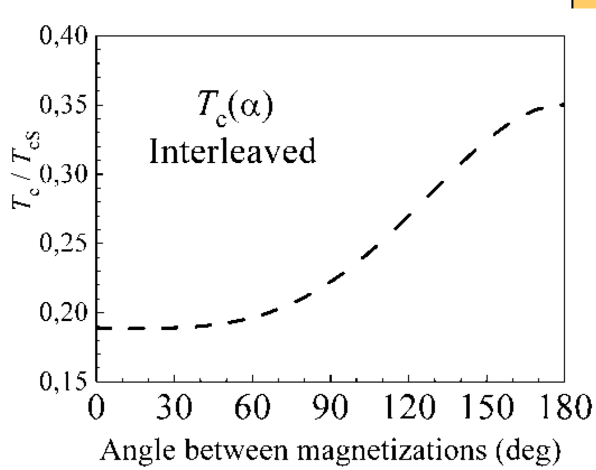
Augsburg-2002

Two designs of superconducting spin-valves based on the superconductor-ferromagnet proximity effect

Adjacent

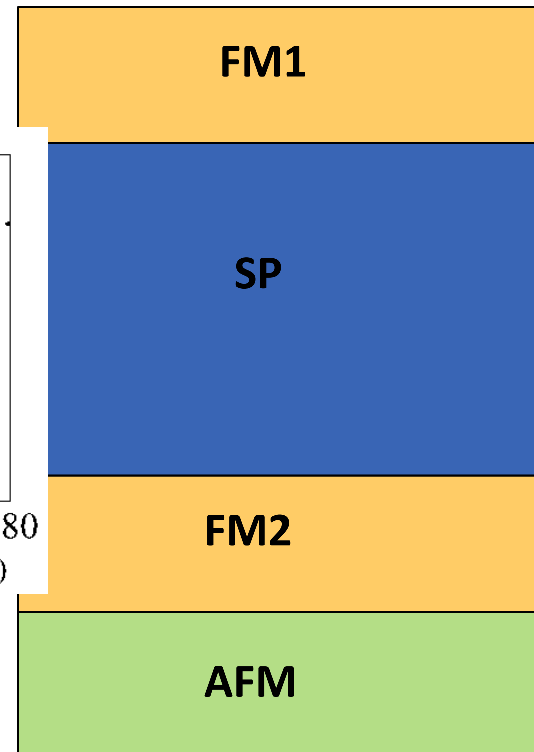


Oh, Youm, Beasley/1997



Alexander Golubov, Mikhail Kupriyanov et al. /JETPL-2003

Interleaved

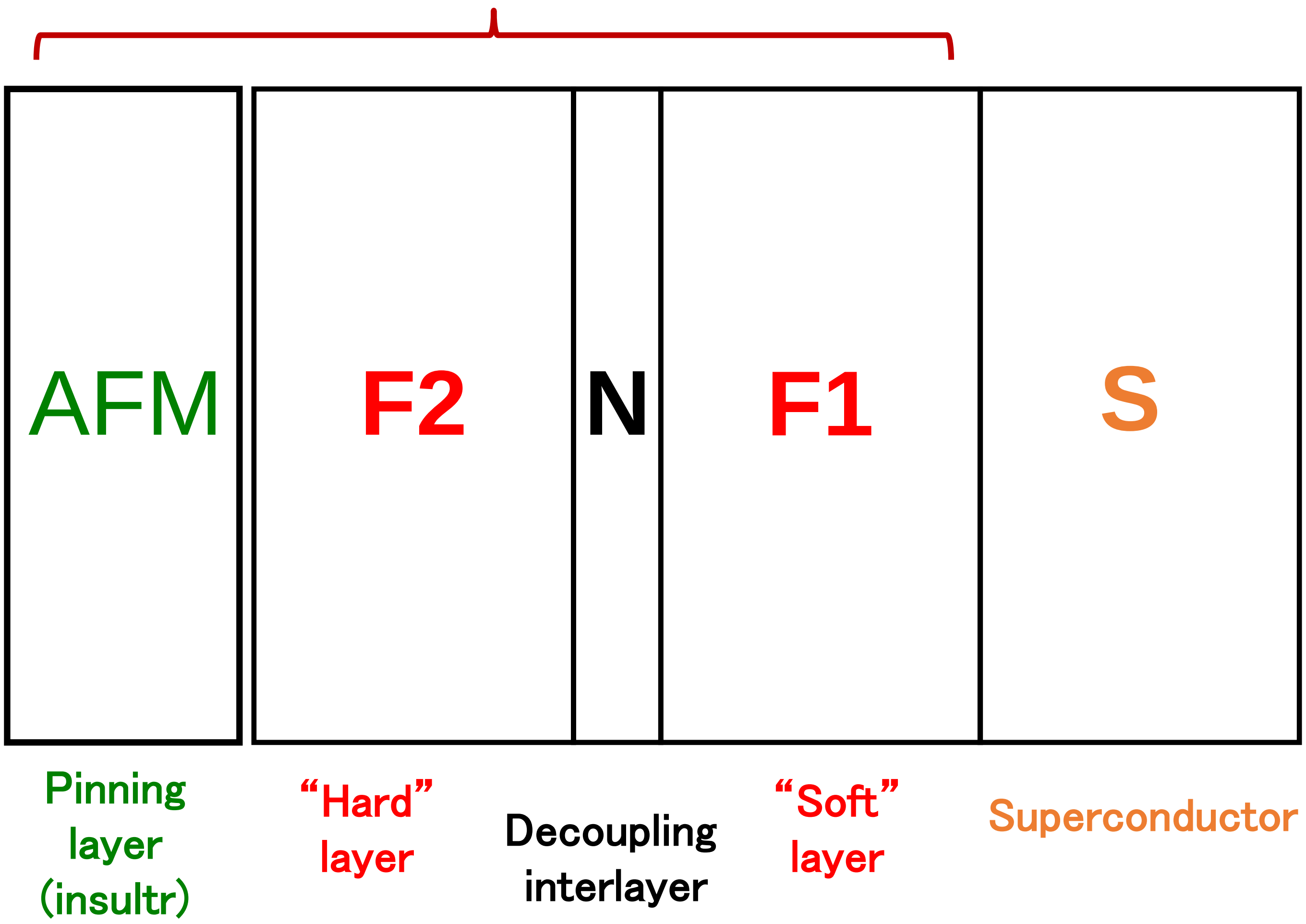


Lenar Tagirov, Alexander Buzdin et al./1999

Triplet spin-valve

General model of SSV (adjacent)

Conventional spin-valve **(the actuator)**



Triplet Pairing

Generation of the triplet components of pairing in superconductor-ferromagnet hybrids (like FSF) at non-collinear magnetic configurations

$$f_3 \sim \langle \psi_\uparrow \psi_\downarrow \rangle - \langle \psi_\downarrow \psi_\uparrow \rangle,$$

Even in freq. singlet WF

$$f_0 \sim \langle \psi_\uparrow \psi_\downarrow \rangle + \langle \psi_\downarrow \psi_\uparrow \rangle,$$

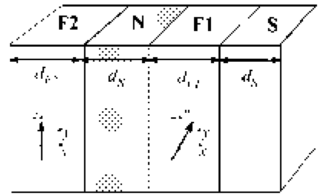
Even triplet WF with zero projection (*E*ex +AP mag.)

$$f_1 \sim \langle \psi_\uparrow \psi_\uparrow \rangle \sim \langle \psi_\downarrow \psi_\downarrow \rangle.$$

Odd triplet WF with ±1 projection (Long-Range, *E*ex +non-coll. mag.)

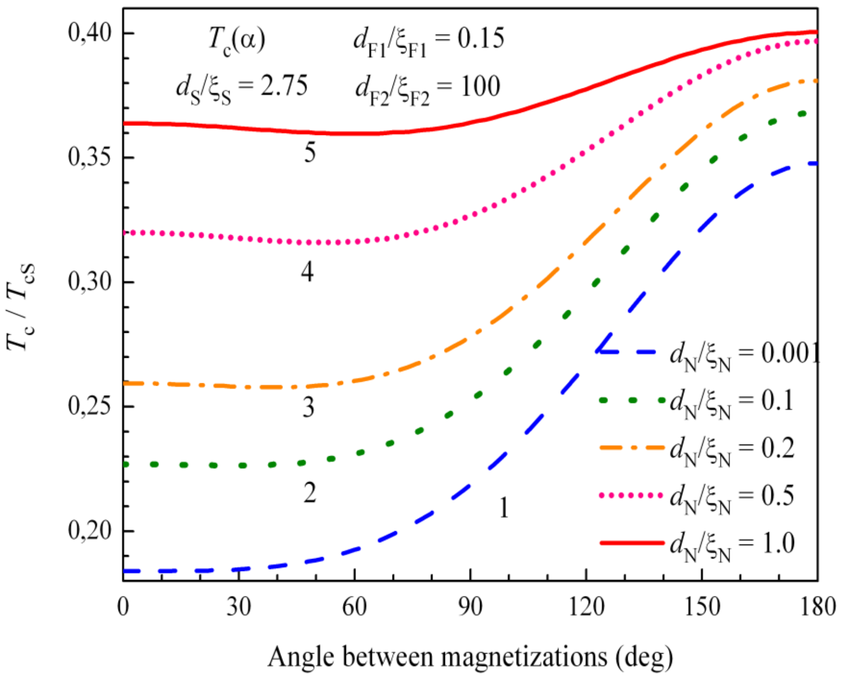
F.S. Bergeret, A.F. Volkov and K.B. Efetov, PRL **86**, 4096 (2001);
A.F. Volkov, F.S. Bergeret and K.B. Efetov, PRL **90**, 117006 (2003);
Alexander Golubov, Mikhail Kupriyanov et al. / JETPL (2003);

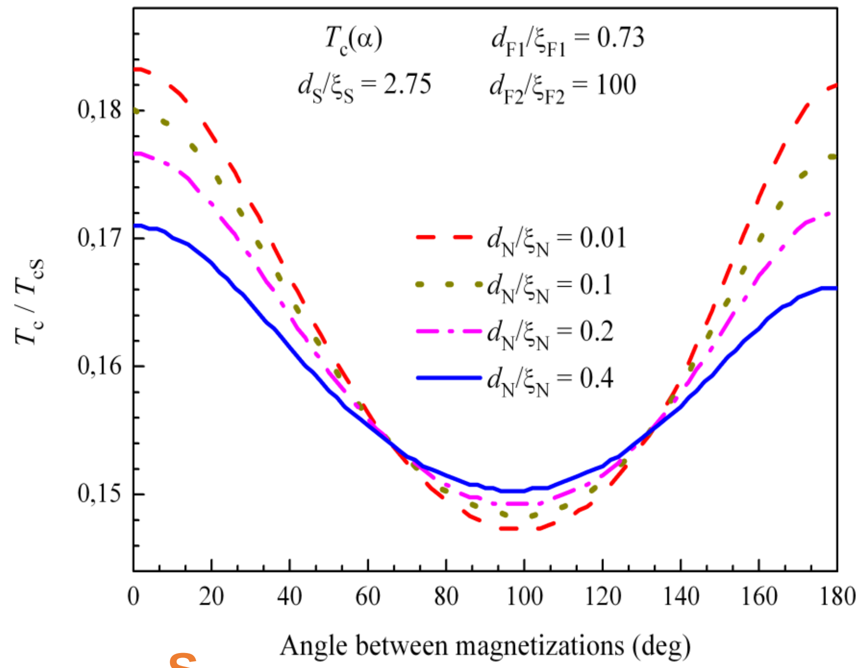
General model – influence of the norm. metal spacer (N)

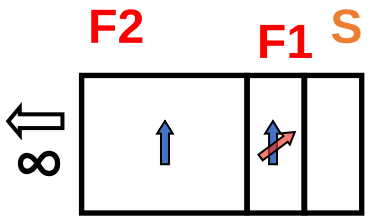


«Direct» switching

«Triplet » switching



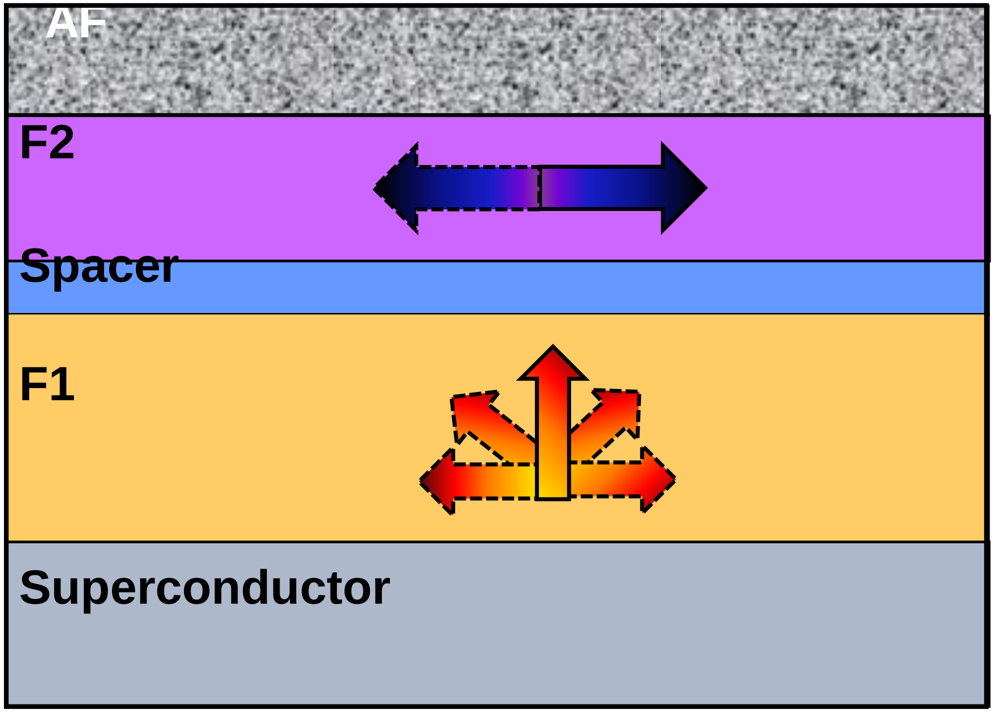




Golubov-Karminskaya-Kupriyanov-Deminov-Tagirov, JETPL 91, 308 (2010)

The experiment idea and the sample design

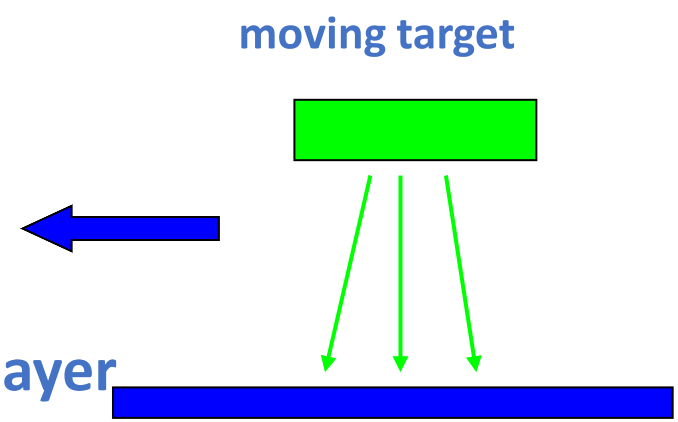
F1 – soft Perp.Anis. FM, F2 – In-Plane Anis. FM



Sample preparation- Novel Technology :

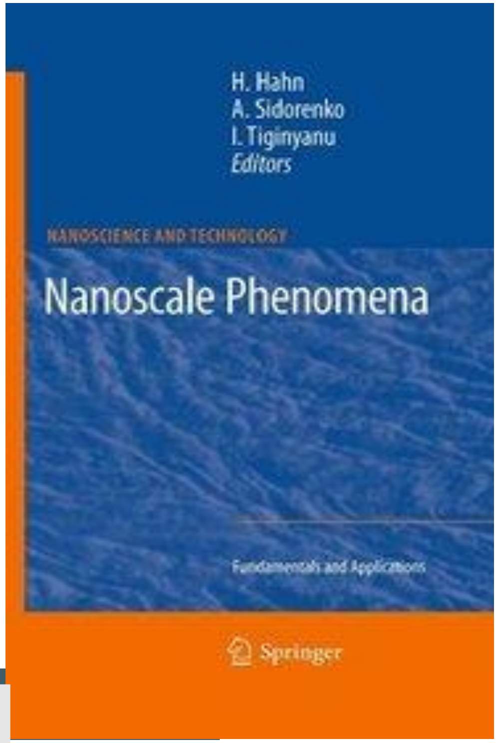
- DC magnetron sputtering with:

a)high deposition rate (2-4 nm/s)
b)moving Nb target- homogenity
c)Deposition of amorphous Si-sublayer
d)Protection of the structure with Si-top layer



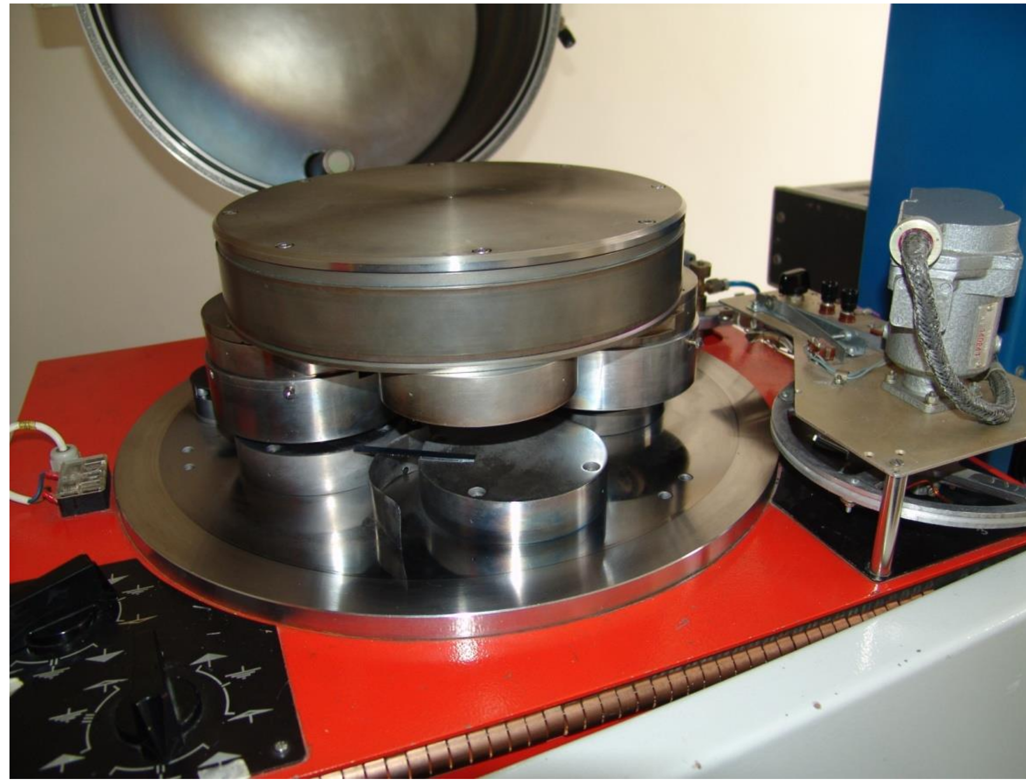
Detailes of the advanced technology are descriebed in:

Nanoscale Phenomena – Fundamentals and Applications.
H.Hahn, A.Sidorenko, I.Tiginyanu,
Springer, 2009, 237p.



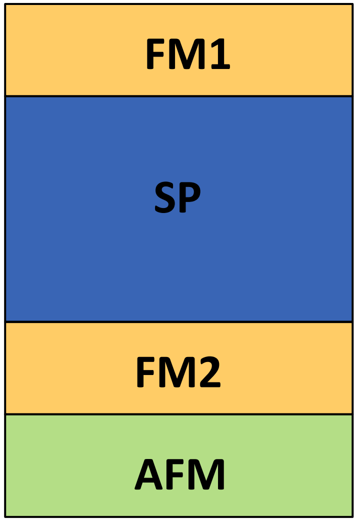
SF- samples

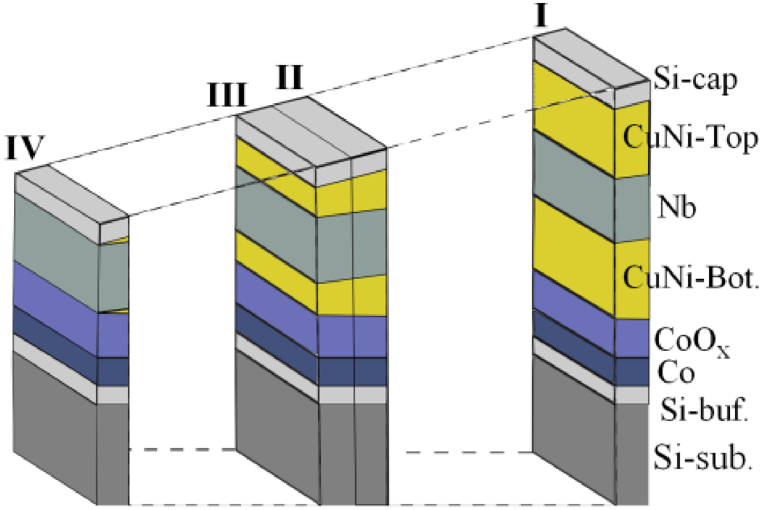
Leybold Z400 magnetron sputtering



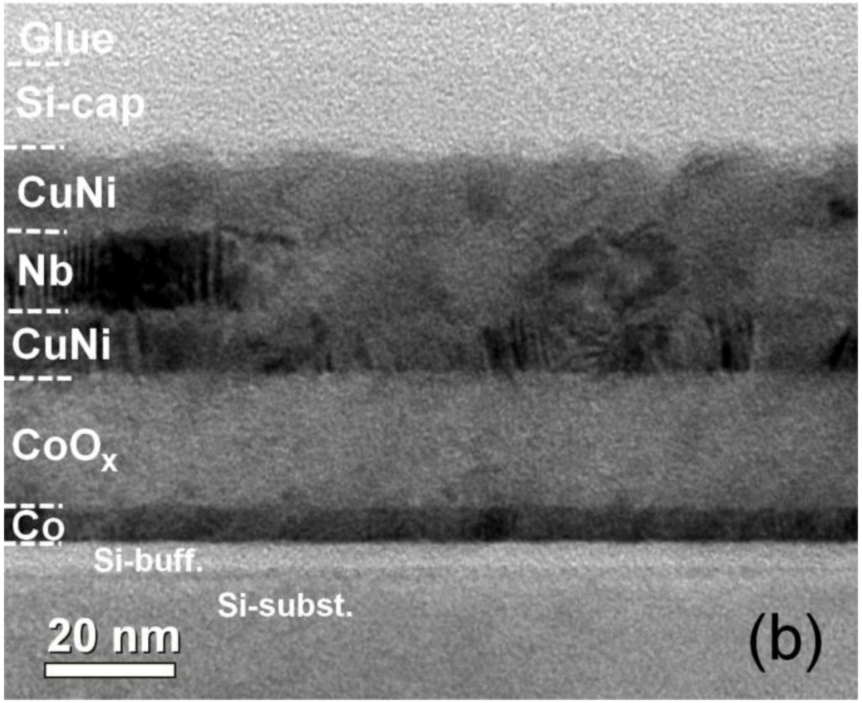
Technology patented: Patent of RM №3135 from 31.08 2006.
Sidorenko A.S., Zdravkov V.I., "Device for thin films preparation"

Spin-valve sample design
$Co/CoO_x/Cu_{41}Ni_{59}/Nb/Cu_{41}Ni_{59}$



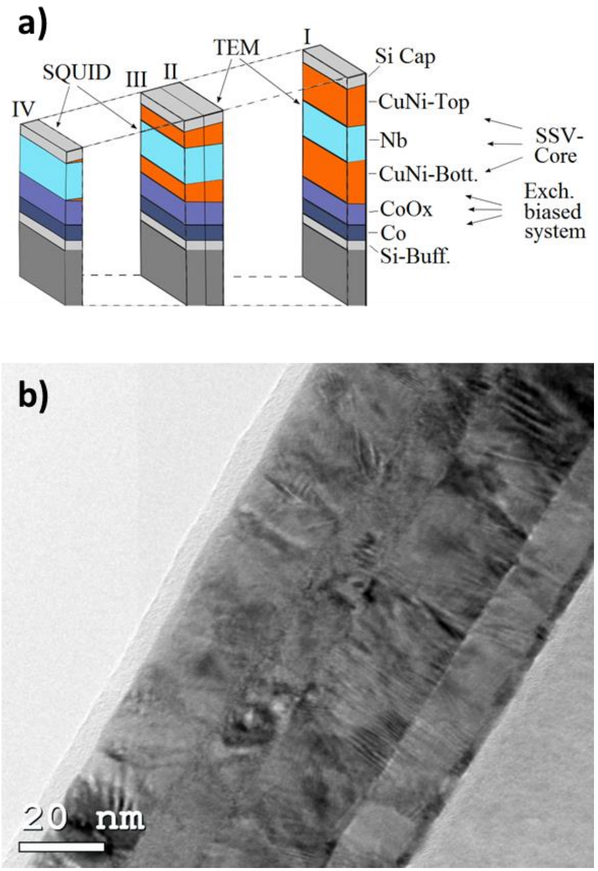


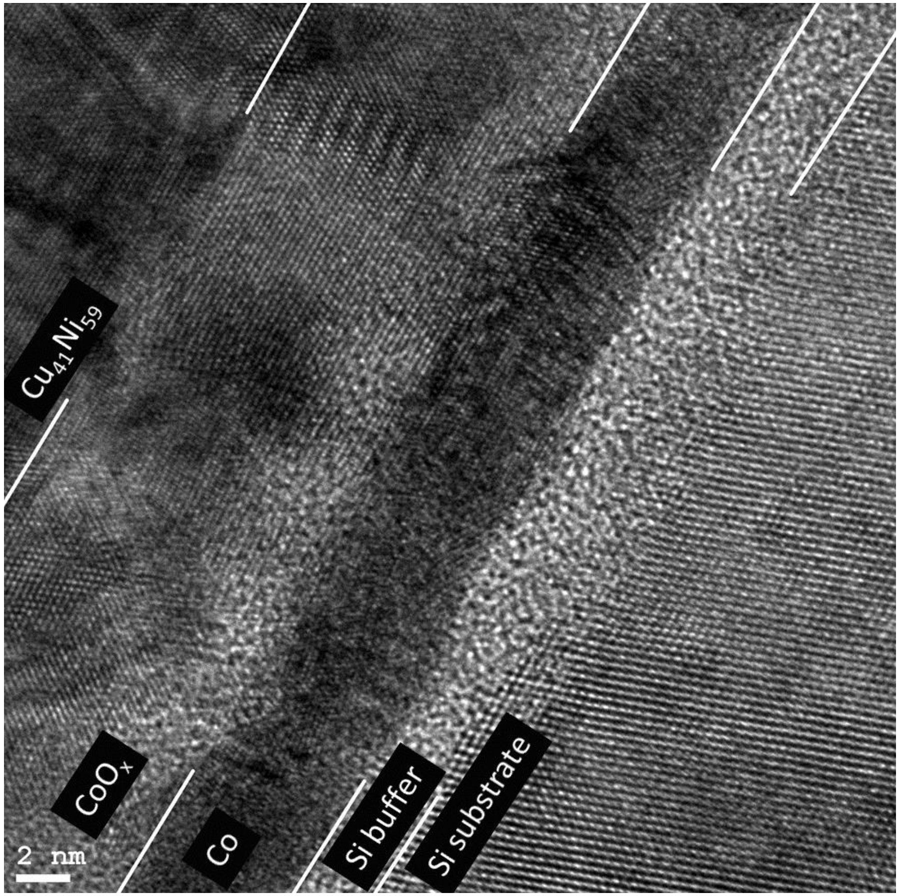
TEM cross-section



V.I. Zdravkov, A.S.Sidorenko *et al.*, APL/2013

Results of TEM and HRTEM

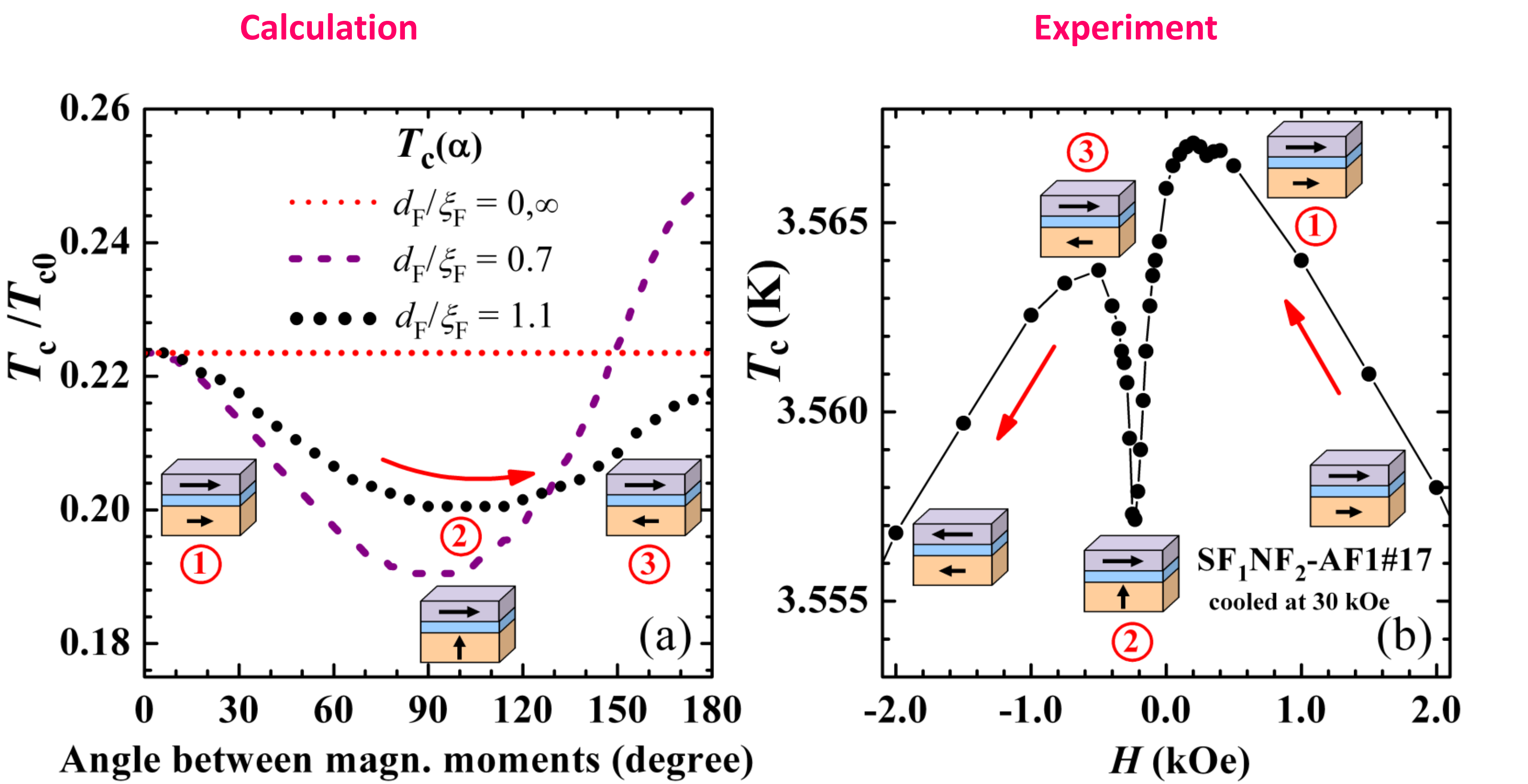




a) Sketch of the samples.
b) Cross-sectional TEM of Sample I

High-resolution TEM image of Sample I at the exchange bias region of the system.

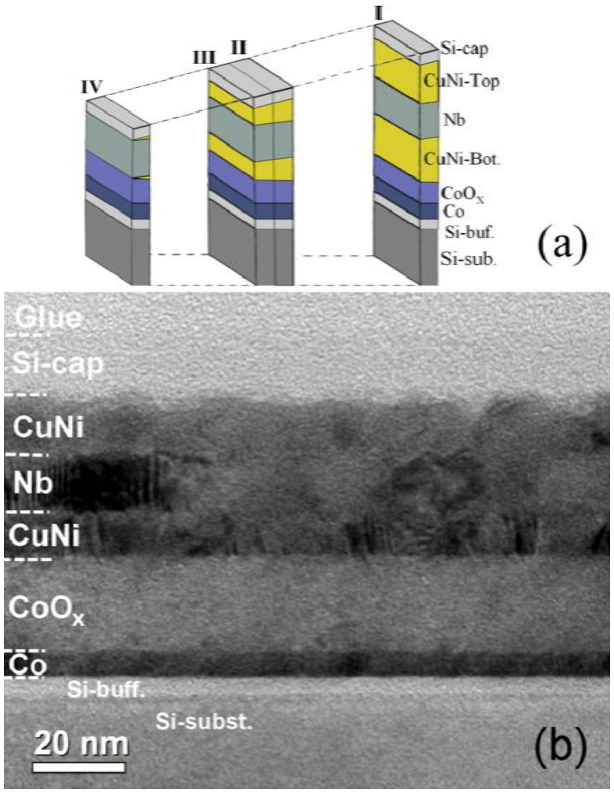
Dependence of the superconducting transition temperature on magnetic field

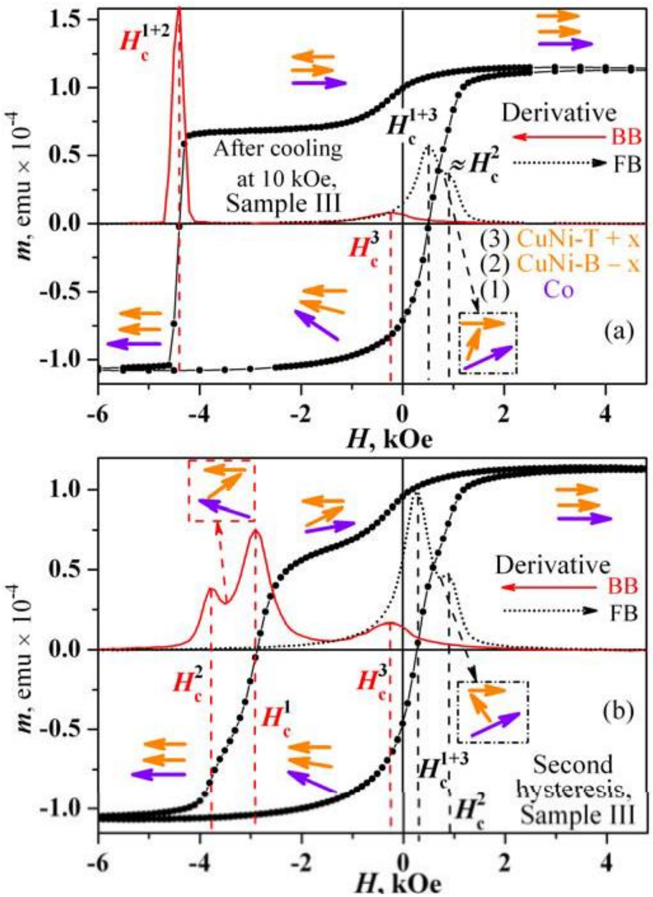


Phys.Rev.B87, 144507 (2013)

Experimental Observation of the Triplet Spin-Valve Effect in a Superconductor-Ferromagnet Heterostructure. V.I. Zdravkov, A.S.Sidorenko, L.R.Tagirov et al.

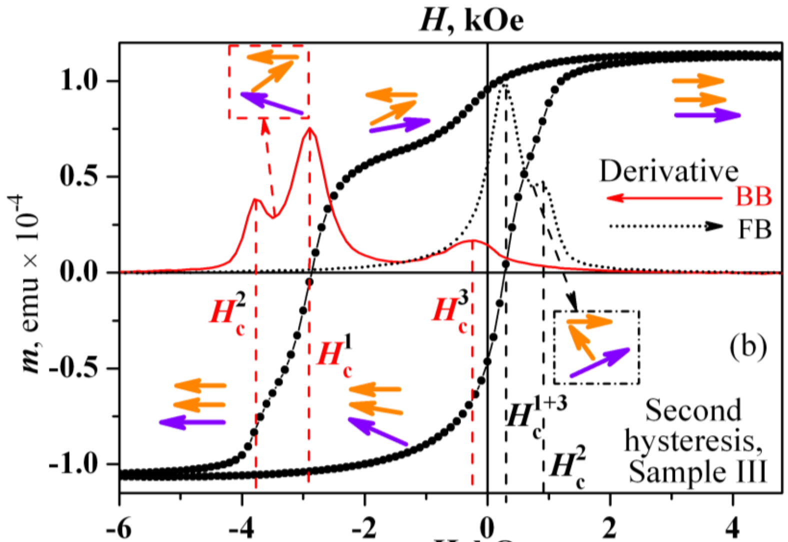
Memory effect in the superconducting $Co/CoO_x/Cu_{41}Ni_{59}/Nb/Cu_{41}Ni_{59}$ - layered heterostructure

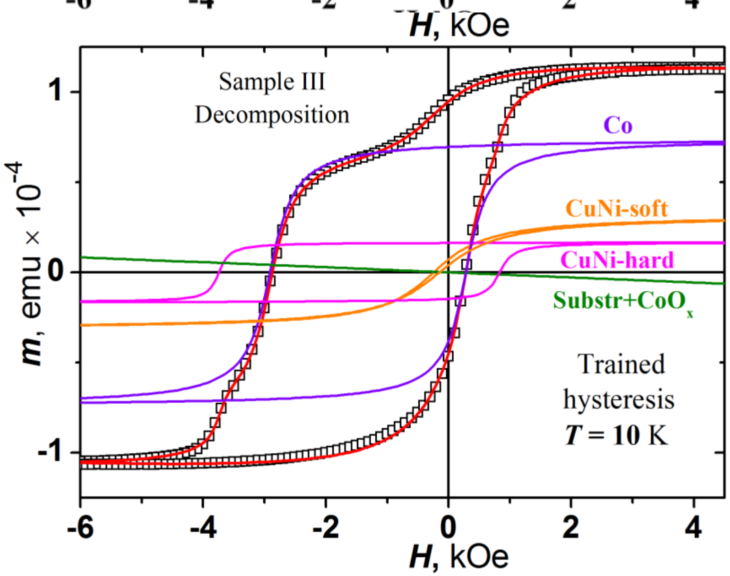




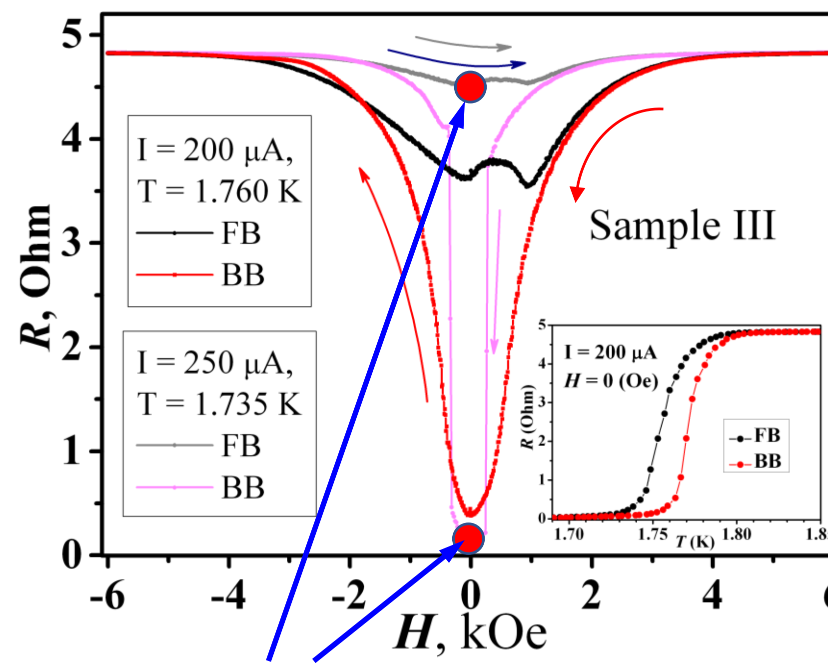
Strong exchange bias (H_{EB} ≈ -2 kOe), as well as the training effect - decrease of the hysteresis loop asymmetry, coercivity and squareness by further magnetic field cyclings.

Memory effect in the superconducting Co/CoOx/Cu41Ni59/Nb/Cu41Ni59 - layered heterostructure



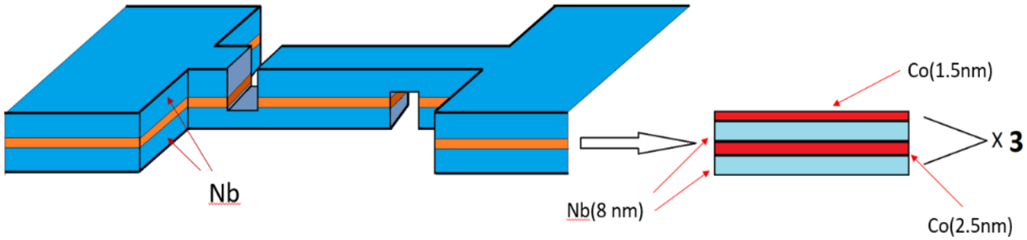


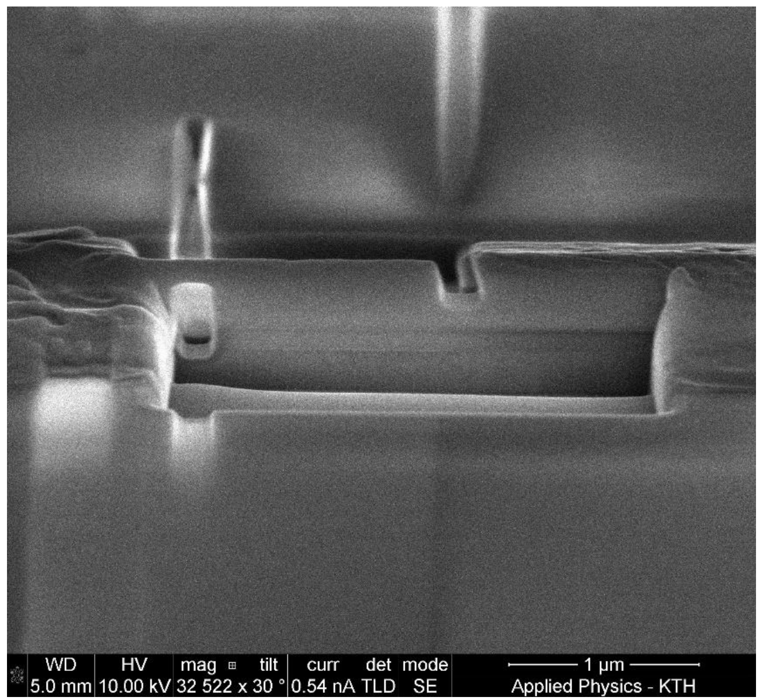
The resistivity of nanolayered superconductor-ferromagnet spin-valve structure depends on the preceding magnetic field polarity.



The difference of high and low resistance states (corresponding to logic "one" and "zero") at zero magnetic field .

Fabrication of the artificial neurons - Josephson-spin valve, using Focused Ion Beam (FIB)-technology (knowledge transfer from Stockholm SU to IEEN)





Artificial synapse -Josephson contact with multilayered magnetic weak link

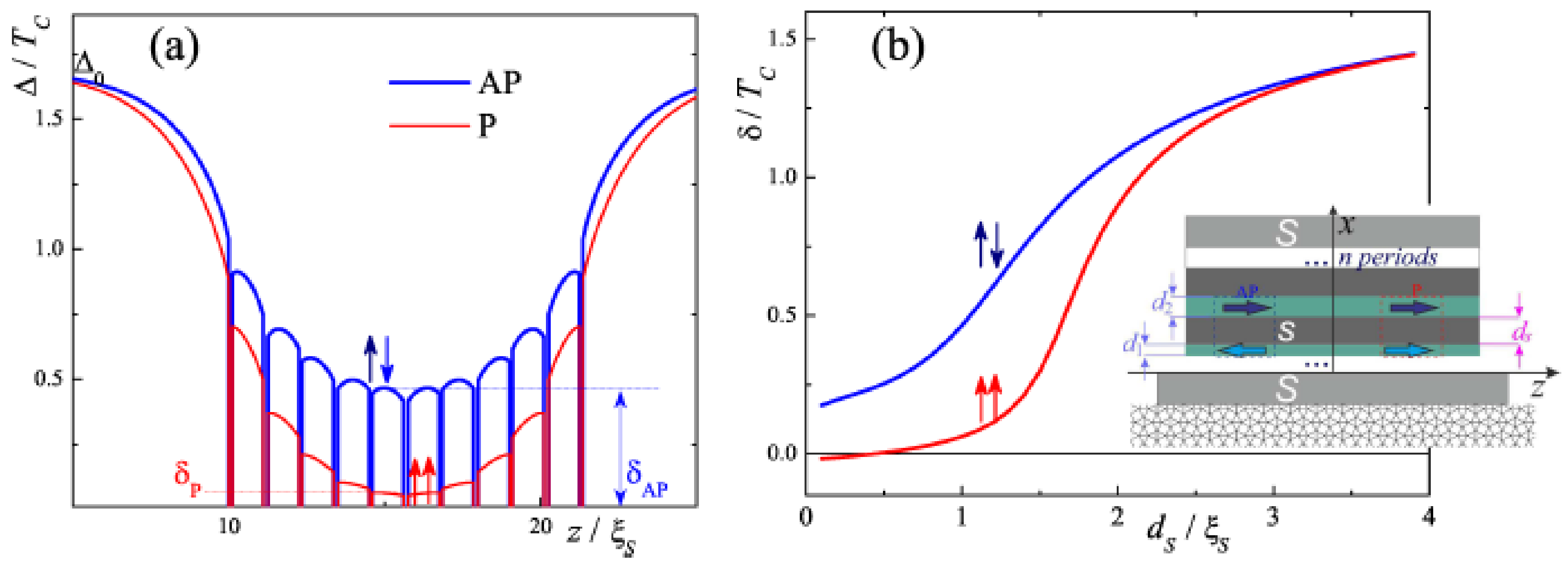
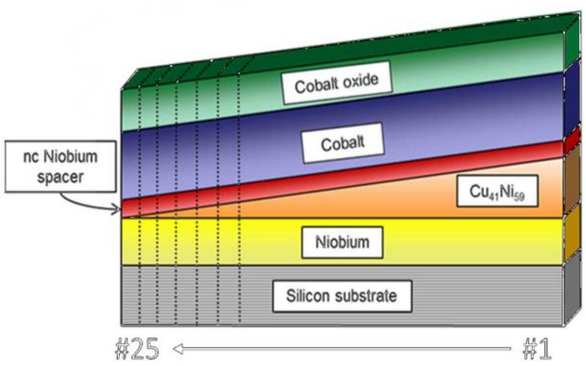


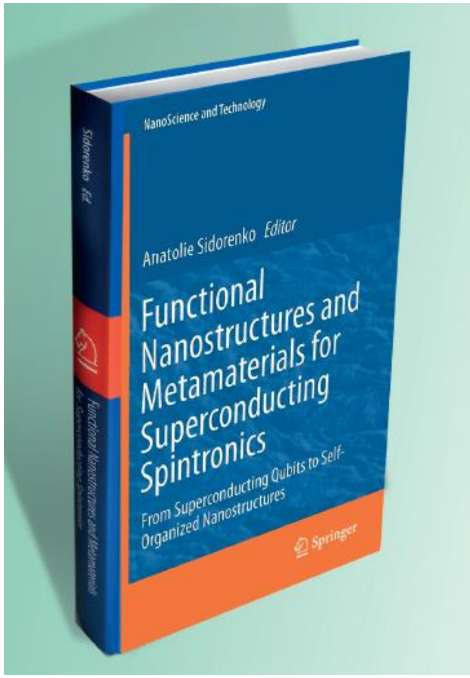
Figure 2: (a) The depth profile of the superconducting pair potential amplitude of the S/[F_1/s/F_2/s]$_5$/F_1/S structure in the P and AP cases. (b) The amplitudes of the superconducting pair potential in the middle of the weak link for the same situations. Inset – schematic representation of the considered stack structure.

N. Klenov, Y. Khaydukov, S. Bakurskiy, R. Morari, I. Soloviev, V. Boian, T. Keller, M. Kupriyanov, A. Sidorenko, B. Keimer, Periodic Co/Nb pseudo spin valve for cryogenic memory, Beilstein J. Nanotechnol. 10 (2019) 833–839. https://doi.org/10.3762/bjnano.10.83.

C O N C L U S I O N

Elaborated smart technology for S/F hybrid nanostructures fabrication, detected “memory effect” and triplet spin-valve effect, can serve as the base for development of superconducting spintronics and further for non-von Neumann computer design – artificial neural network.





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BEILSTEIN JOURNAL OF NANOTECHNOLOGY

(IF=3,65)

Thematic Issue:

Intrinsic Josephson effect

and prospects of superconducting spintronics

Editors:

Prof. Anatolie Sidorenko, Institute of Electronic Engineering and Nanotechnologies, Moldova

Prof. Vladimir Krasnov, University of Stockholm, Sweden

Prof. Horst Hahn, Institute of Nanotechnology, Karlsruhe Institute of Technology, Germany

Research contributions to this thematic issue may include but are not limited to the following topics:

- Physics and applications of the intrinsic Josephson effect
- Superconductor/ferromagnetic hybrid structures and prospects of superconducting spintronics
- High-frequency Josephson devices
- Modelling of functional nanostructures
- Unconventional and topological superconductivity
- Artificial neural networks, Qubits, and quantum computing

Submission Deadline: **December 31, 2021**

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