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EDUCAȚIEI, CULTURII
ȘI CERCETĂRII



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

"Boosting the scientific excellence and innovation capacity in spintronics of the D. GHITU Institute of Electronic Engineering and Nanotechnologies of Moldova

SPINTECH

Summer School:

Brain-like Artificial Neural Network: Superconducting Spintronic's Alternative
27-28 Mai 2021, Stockholm, Sweden

Advanced Methods of Nanostructures Fabrication for Spintronics

Anatolie Sidorenko



UNIVERSITY
OF TWENTE.



Goals of the HORIZON-2020 project

- The overall aim of the “SPINTECH” project is:
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

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,
MIPT, Dolgoprudny, Russia

Alexander Vakhrushev
Izhevsk, Russia

Lenar Tagirov
Kazan, Russia

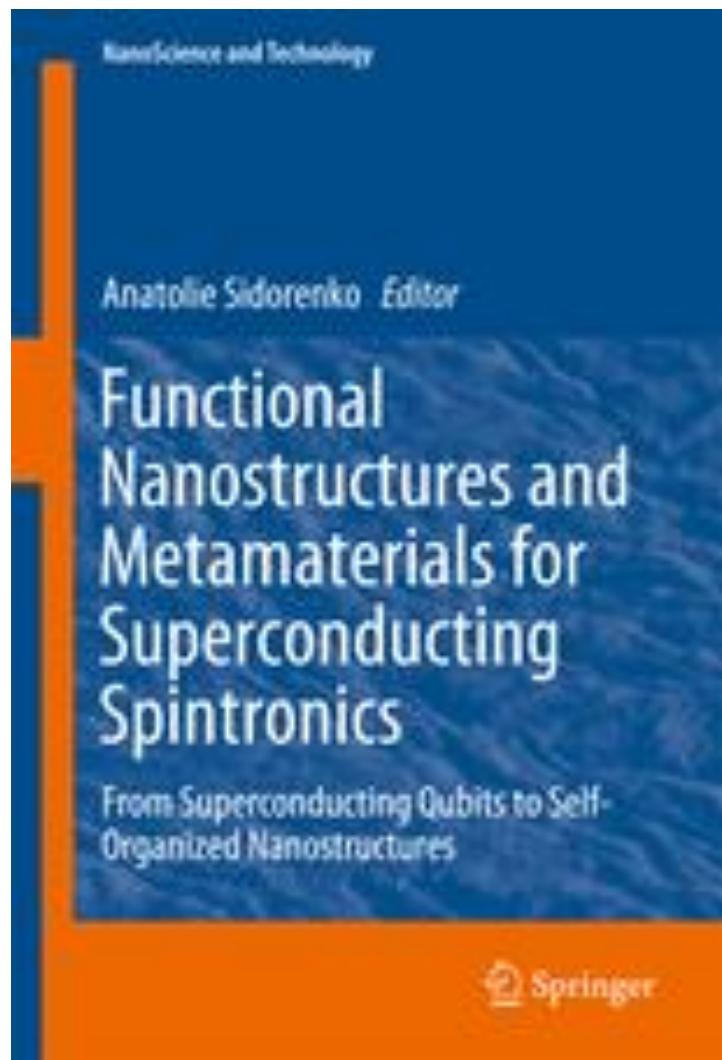
Bernhard Keimer
Yuri Khadukov,
Stuttgart, Germany

Horst Hahn
Karlsruhe, Germany



State of the art

- As the base of the project serves the book:
 - are summarised results of theoretical and experimental investigation of nanostructures Superconductor/Ferromagnet, novel technologies of their fabrication and characterization methods,
- in: Functional Nanostructures and Metamaterials for Superconducting Spintronics. Ed. by A.Sidorenko, "Springer", 2018, 270p.



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 <small>*estimated</small>

Supercomputers: K-Computer (Japan)



www.top500.org



Courtesy of S. Holmes

Data Centers:

- Cloud computing
- Banking
- Shopping
- Social Networks
- Search Engines....

Luleå 
data center:
120 MW
(max power)



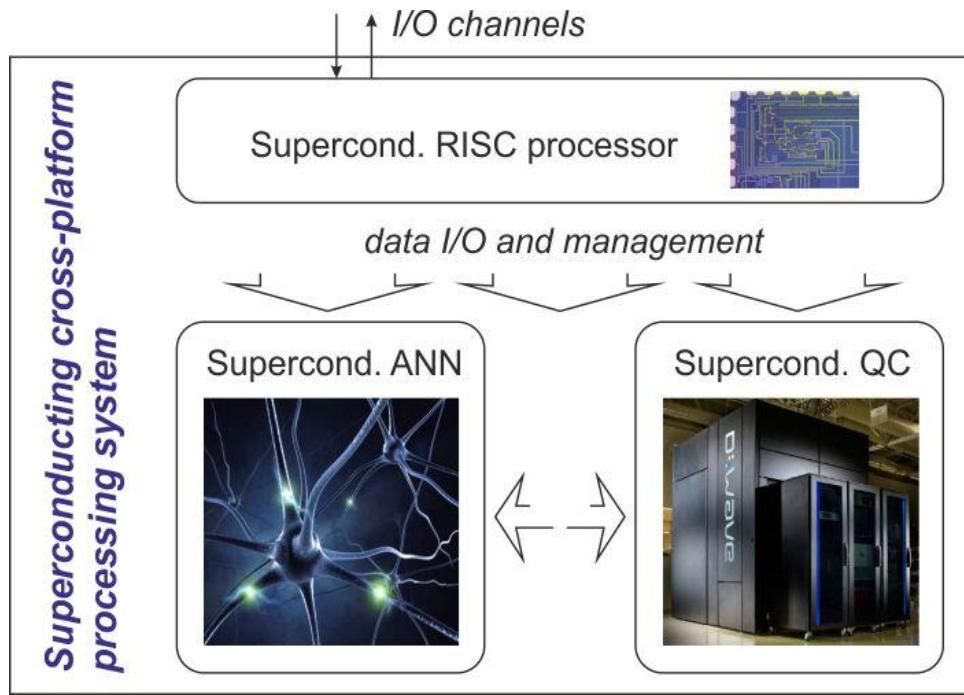
**Top500 No. 4 supercomputer: K-computer (Japan):
10.51 petaflop/s, 12.7 MW**

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

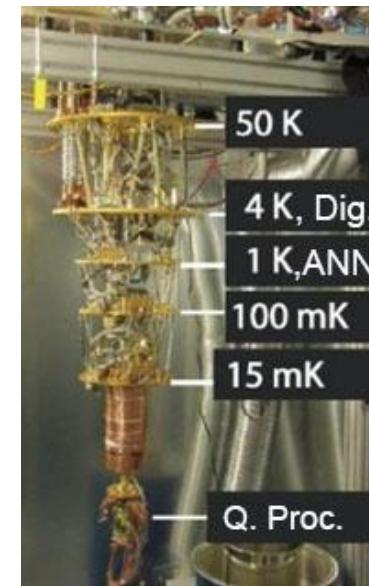
rating updated in June 2014

Superconducting solution -

Rapid and energy-efficient platform for neural network and quantum computer
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

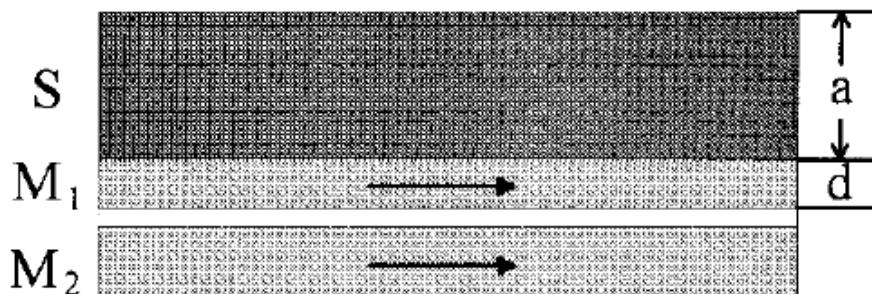
*Department of Physics, Korea Advanced Institute of Science and Technology, Kusung-Dong, Yusung-Gu,
Taejon 305-701, Korea*

M. R. Beasley^{a)}

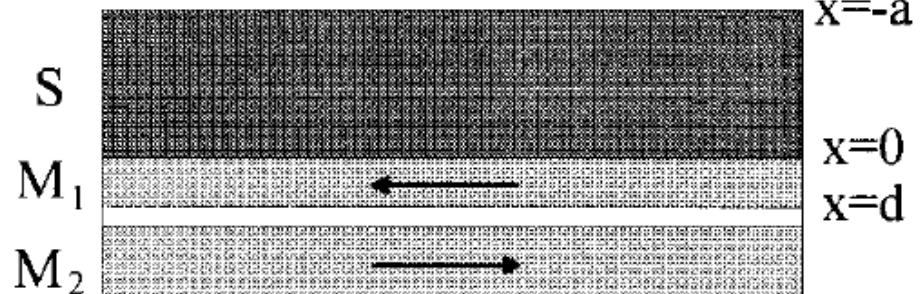
Department of Applied Physics, Stanford University, Via Palou, Stanford, California 94305-4085

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

(a)



(b)



Beasley's Superconducting Memory Element (BSME)

[Applied Physics Letters 71, 2376 (1997)]

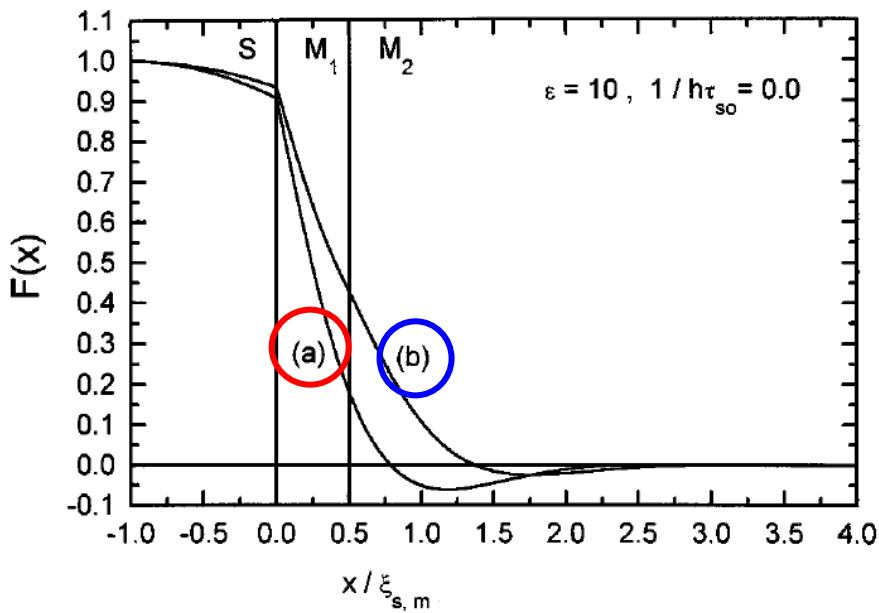
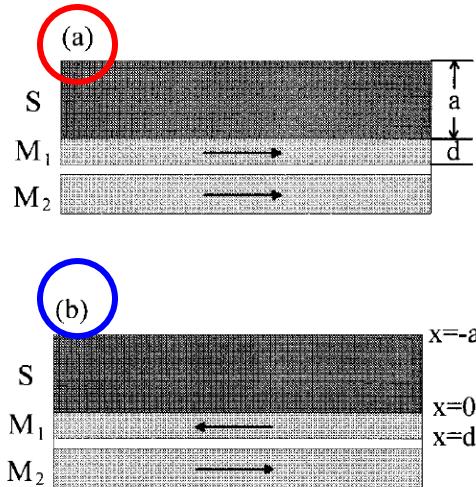


FIG. 2. Normalized pair wave functions, $F(x) = \sum_{\omega} [f_{-}(\omega, x) + f_{+}(\omega, x)]$,

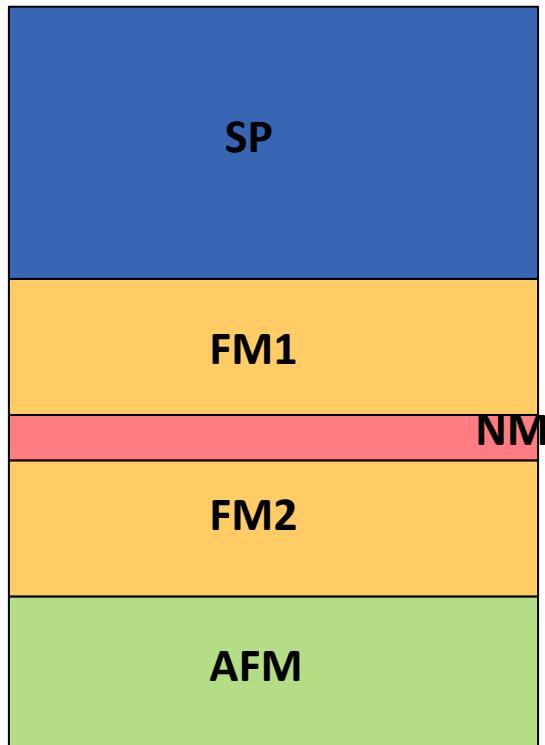


Coined as “Standard”, or “Direct” switching

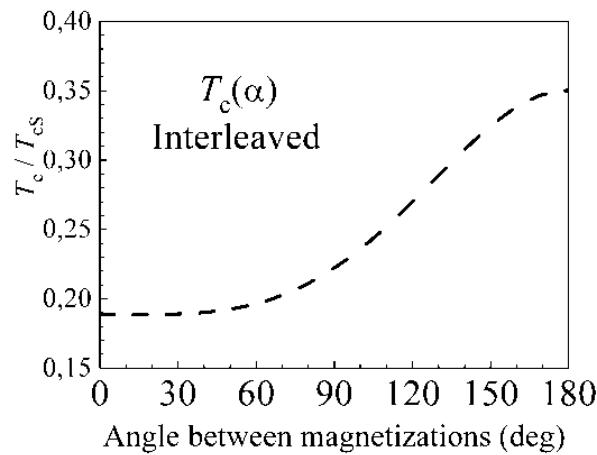
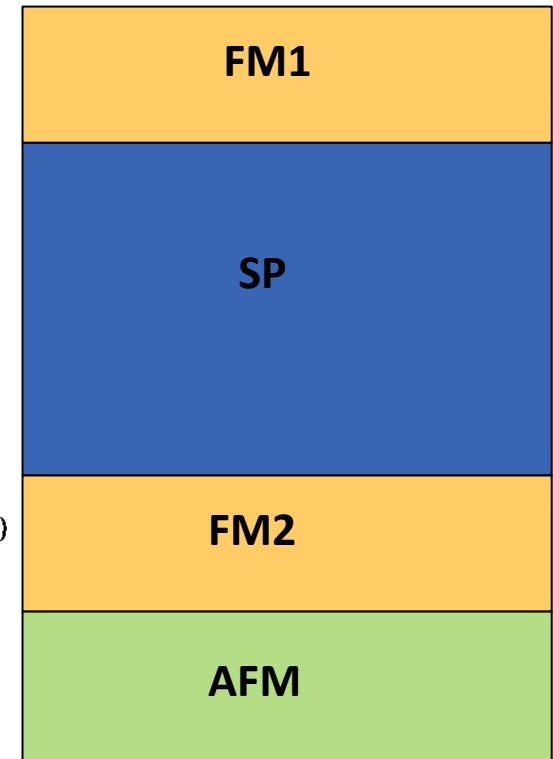
Augsburg-2002

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

Adjacent



Interleaved



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

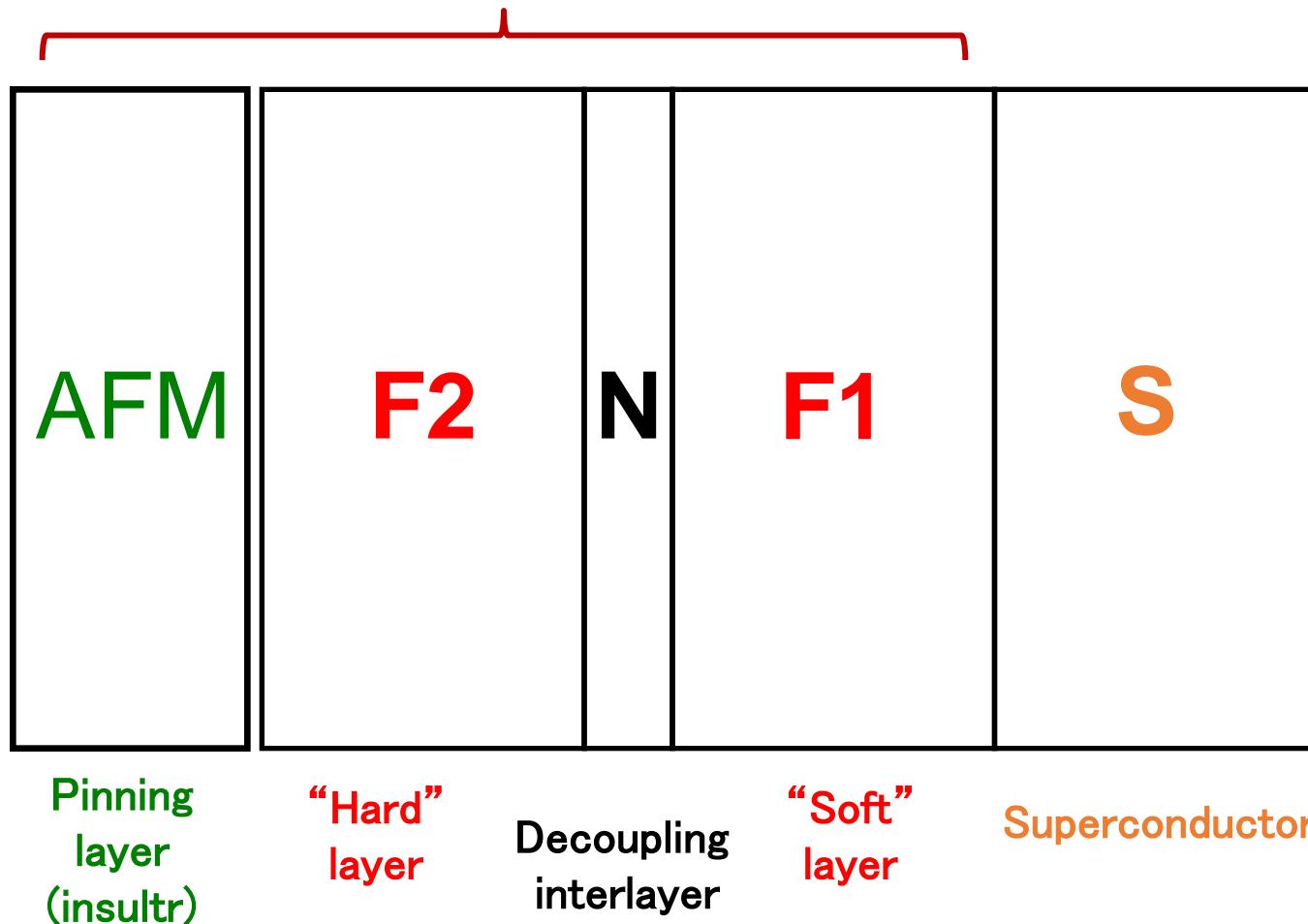
Oh, Youm, Beasley/1997

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 (Eex +AP mag.)

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

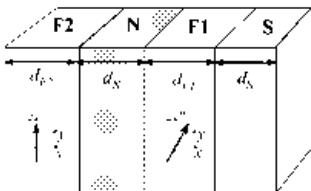
Odd triplet WF with ± 1 projection (Long-Range, Eex +non-coll. mag.)

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);

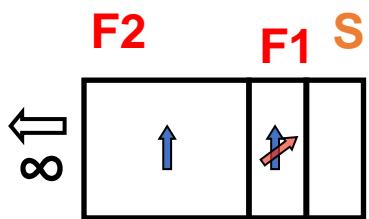
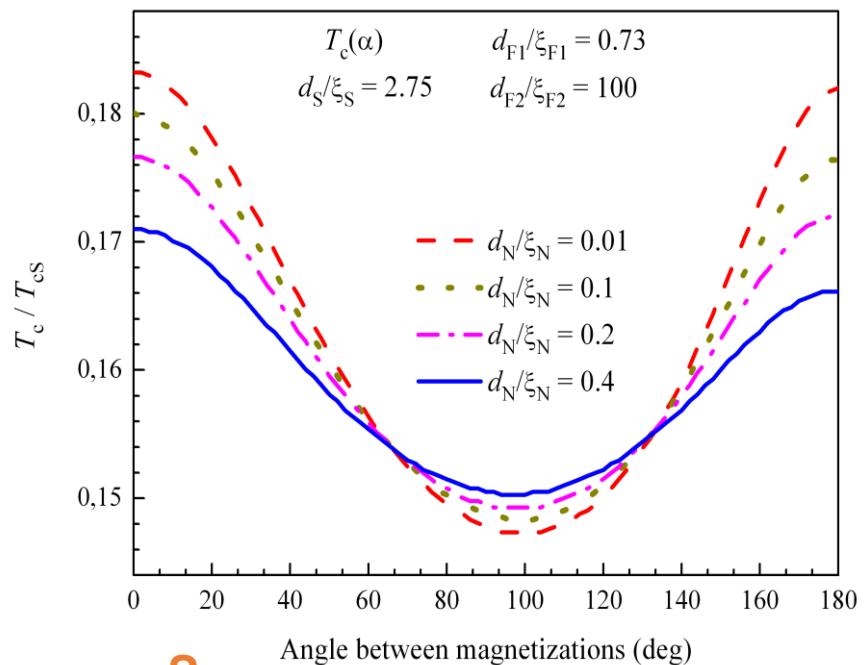
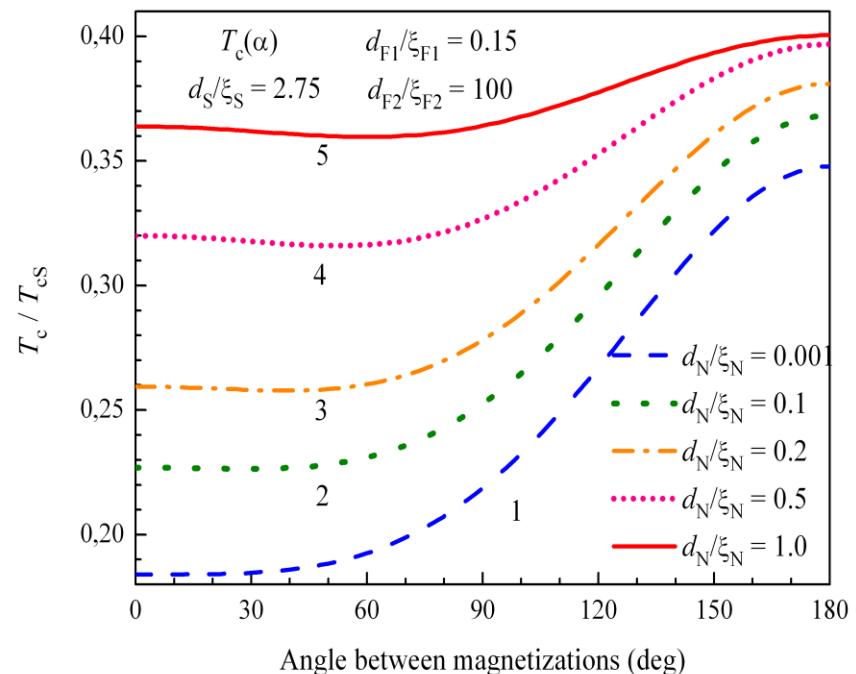
Alexander Golubov, Mikhail Kupriyanov et al. / JETPL (2003);

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



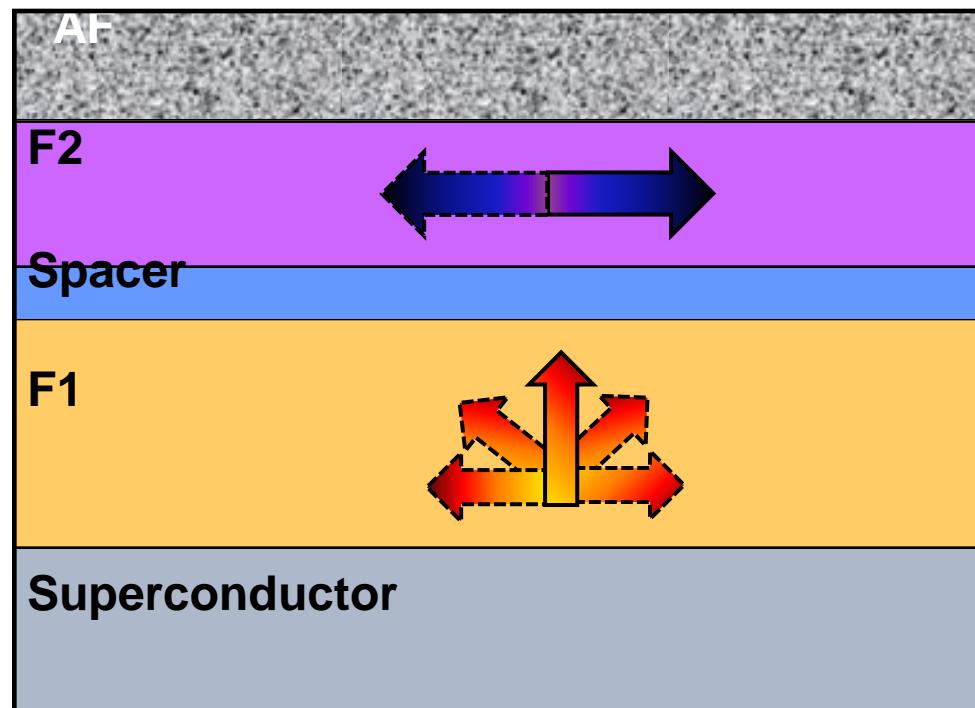
«Direct» switching

«Triplet » switching



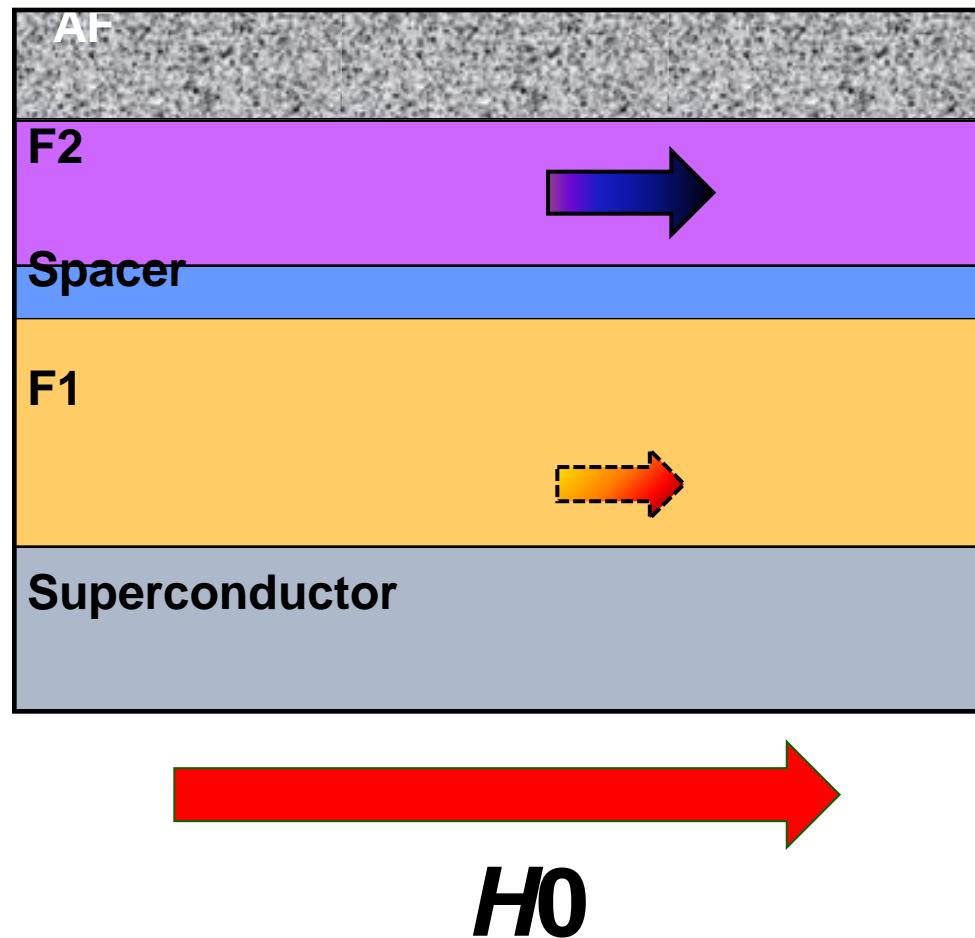
The experiment idea and the sample design

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



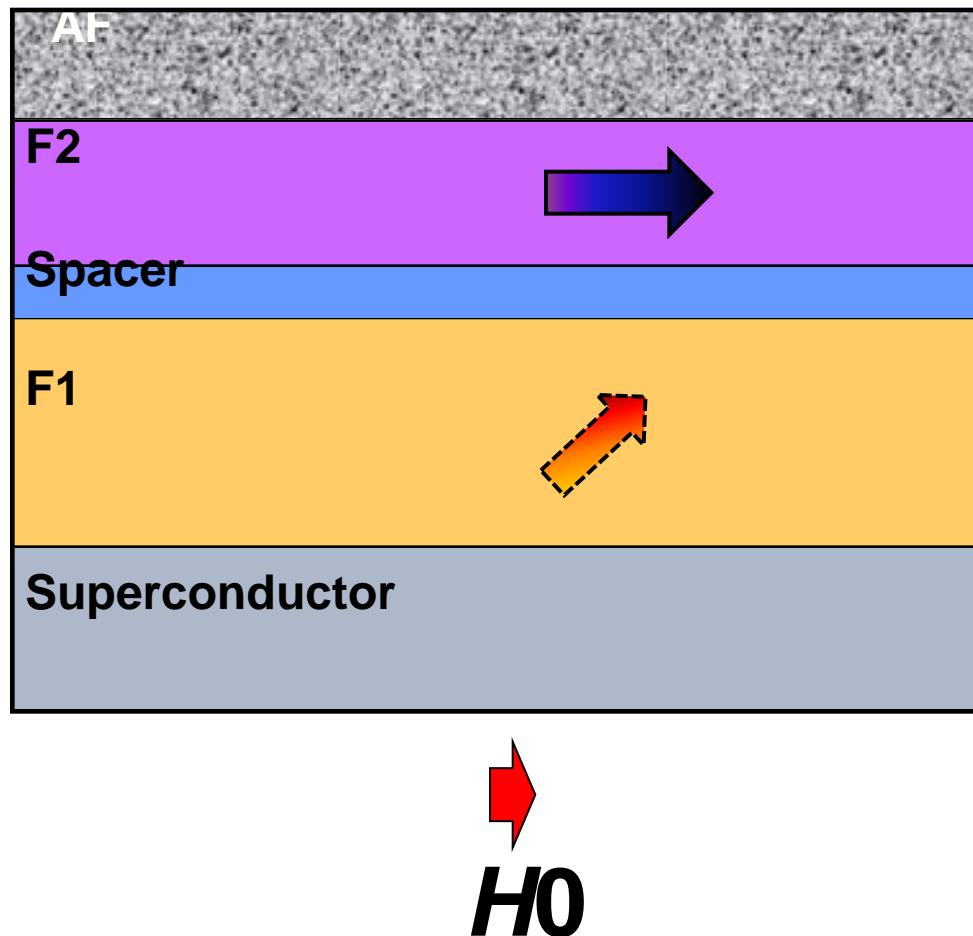
The experiment idea and the sample design

Strong rightward directed (RWD) field



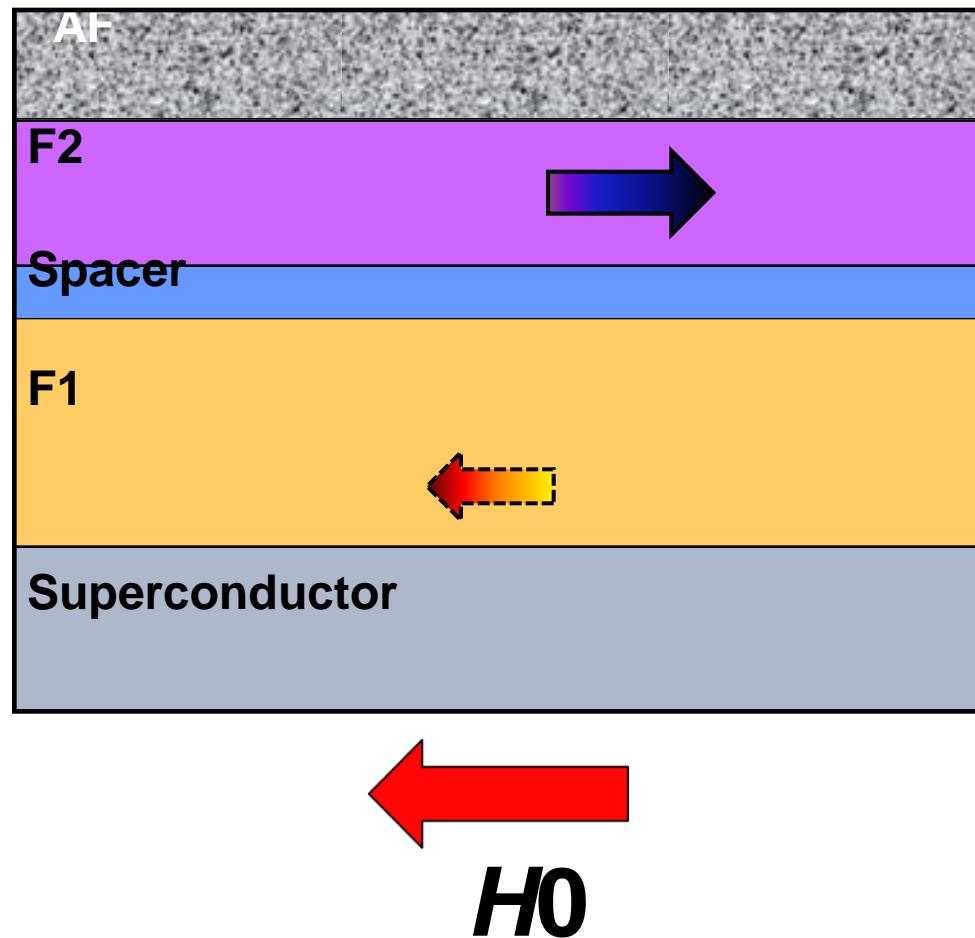
The experiment idea and the sample design

Small RWD or zero field



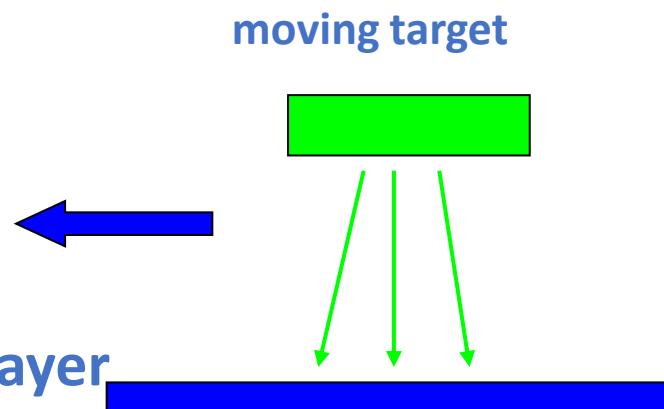
The experiment idea and the sample design

Antiparallel alignment



Sample preparation- Novel Technology :

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

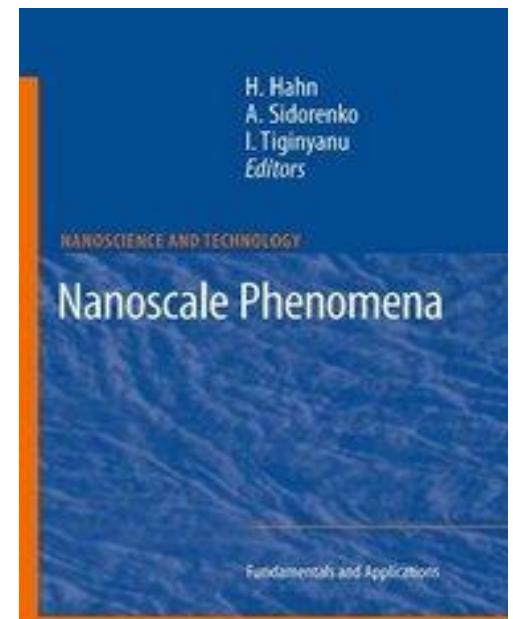


Details of the advanced technology are described in:

Nanoscale Phenomena – Fundamentals and Applications.

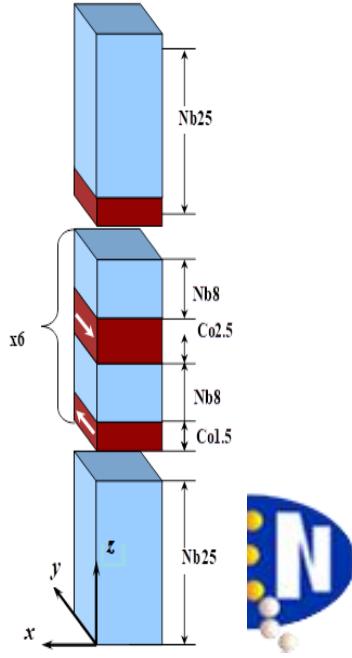
H.Hahn, A.Sidorenko, I.Tiginyanu,

Springer, 2009, 237p.

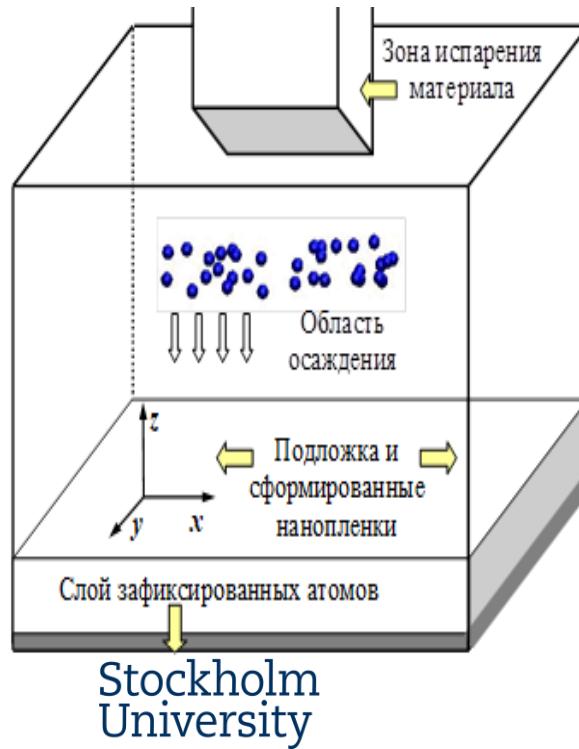


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Modelling of the deposition process for optimization of deposition technology of layers Nb and Co depending on substrate temperature, deposition rate et cet.
(model calculations – for optimization of technology)



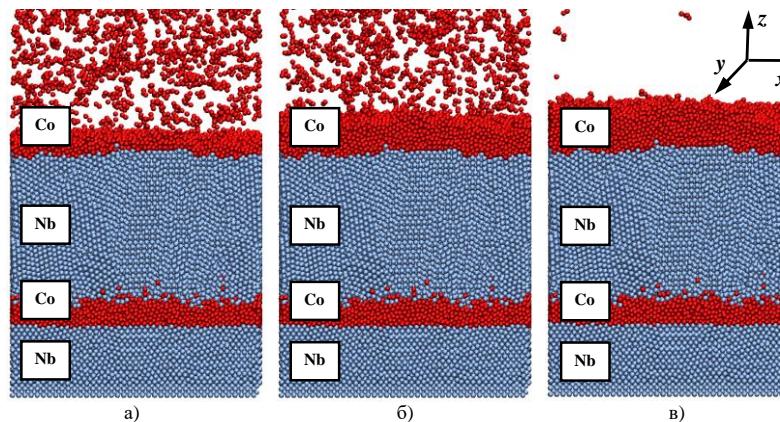
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OF TWENTE.



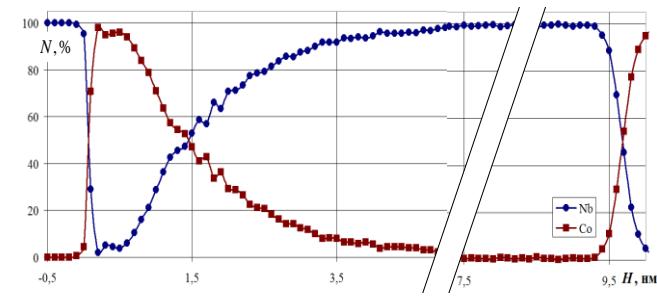
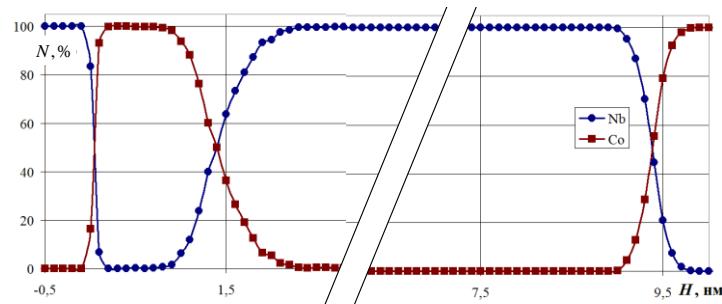
Stockholm
University

Model calculations of Nb/Co nanostructures:

Alexander Vakhrushev, Aleksey Fedotov, Vladimir Boian, Roman Morari, and Anatolie Sidorenko.
Molecular dynamics modeling of the influence forming process parameters on the structure and morphology of a superconducting spin valve. Beilstein J. Nanotechnol. 2020, 11, 1776–1788.



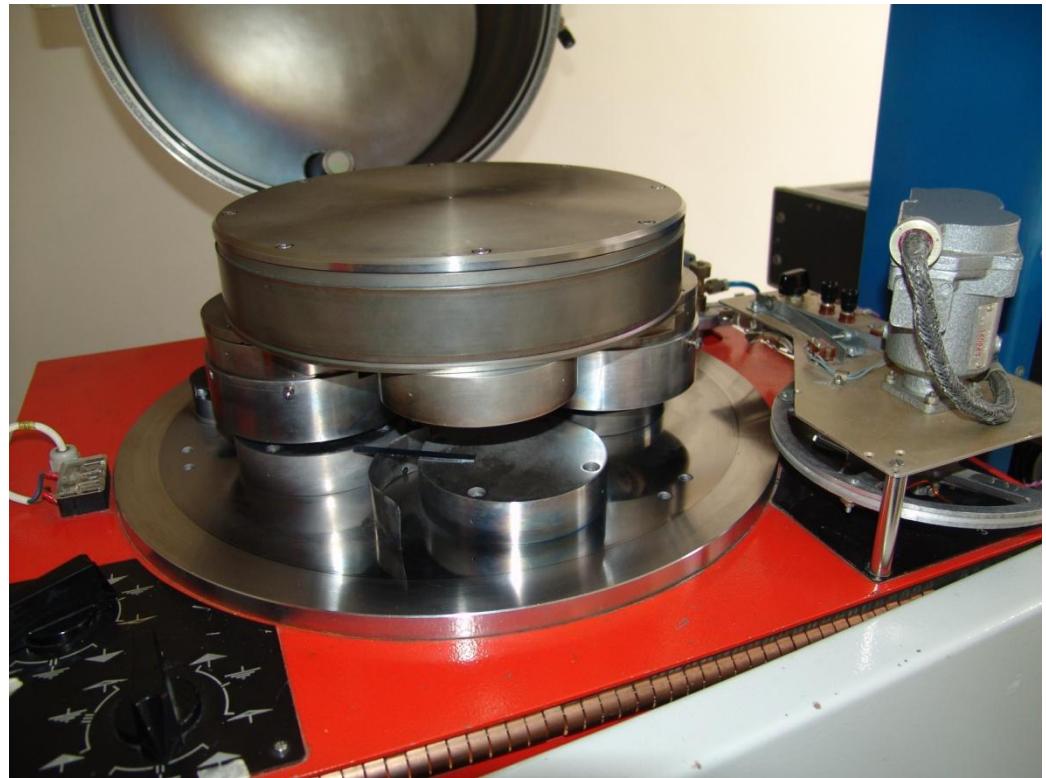
Condensation of nanolayers Co and Nb at different deposition time:
a) 0,1 нс, б) 0,2 нс и в) 0,4 нс. Substrate temperature is fixed at 300 K
(model calculations)



SF- samples



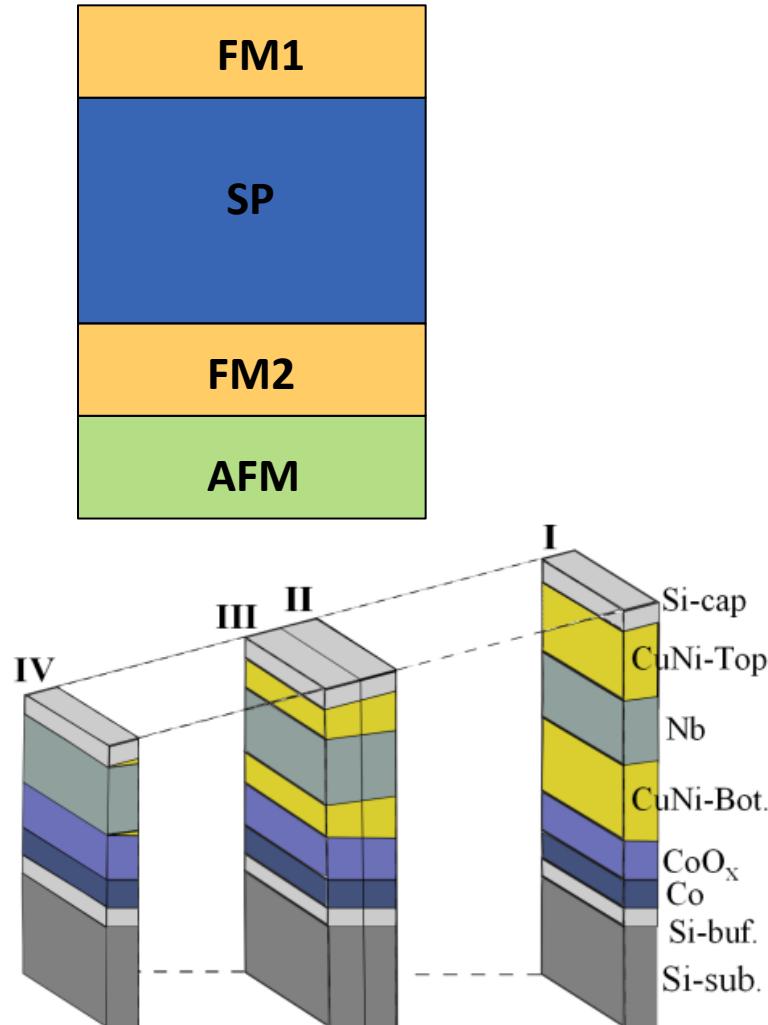
Leybold Z400 magnetron sputtering



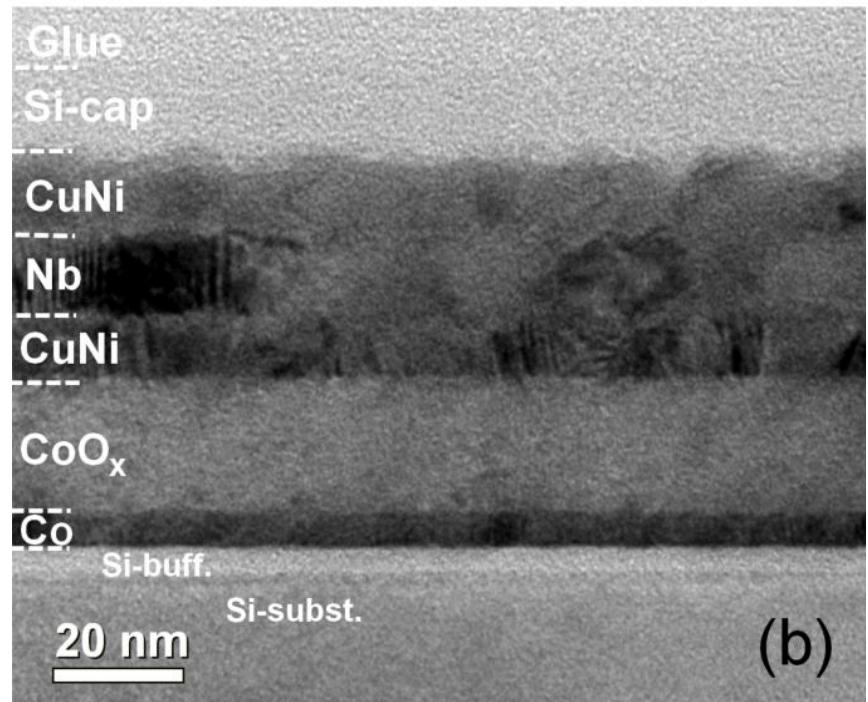
Technology patented: Patent of RM №3135 from 31.08 2006.
Sidorenko A.S., Zdravkov V.I., "Device for thin films preparation"

Spin-valve sample design

$\text{Co}/\text{CoO}_x/\text{Cu}_{41}\text{Ni}_{59}/\text{Nb}/\text{Cu}_{41}\text{Ni}_{59}$

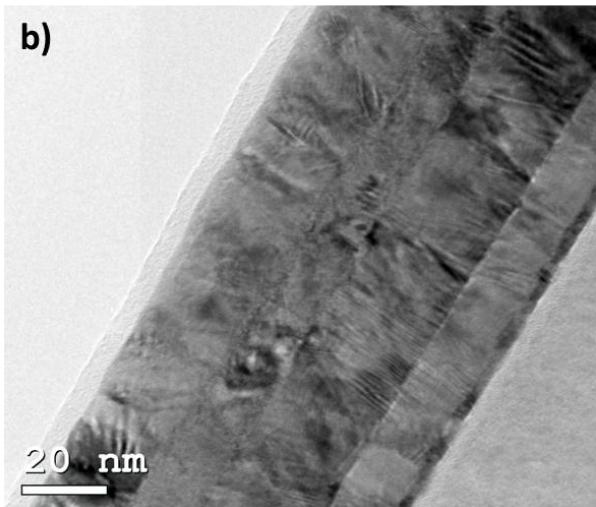
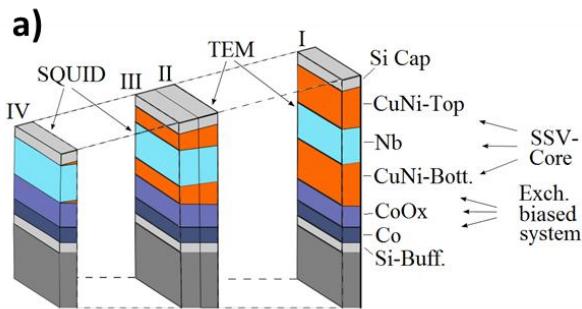


TEM cross-section

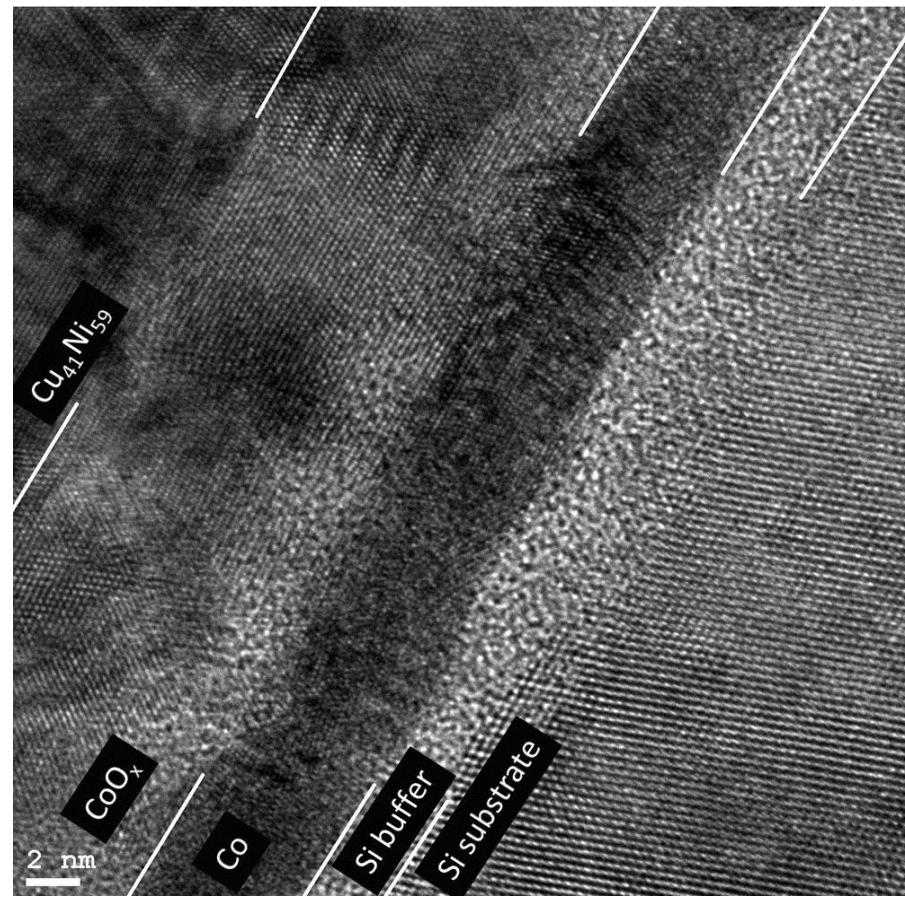


V.I. Zdravkov, A.S. Sidorenko *et al.*,
APL/2013

Results of TEM and HRTEM

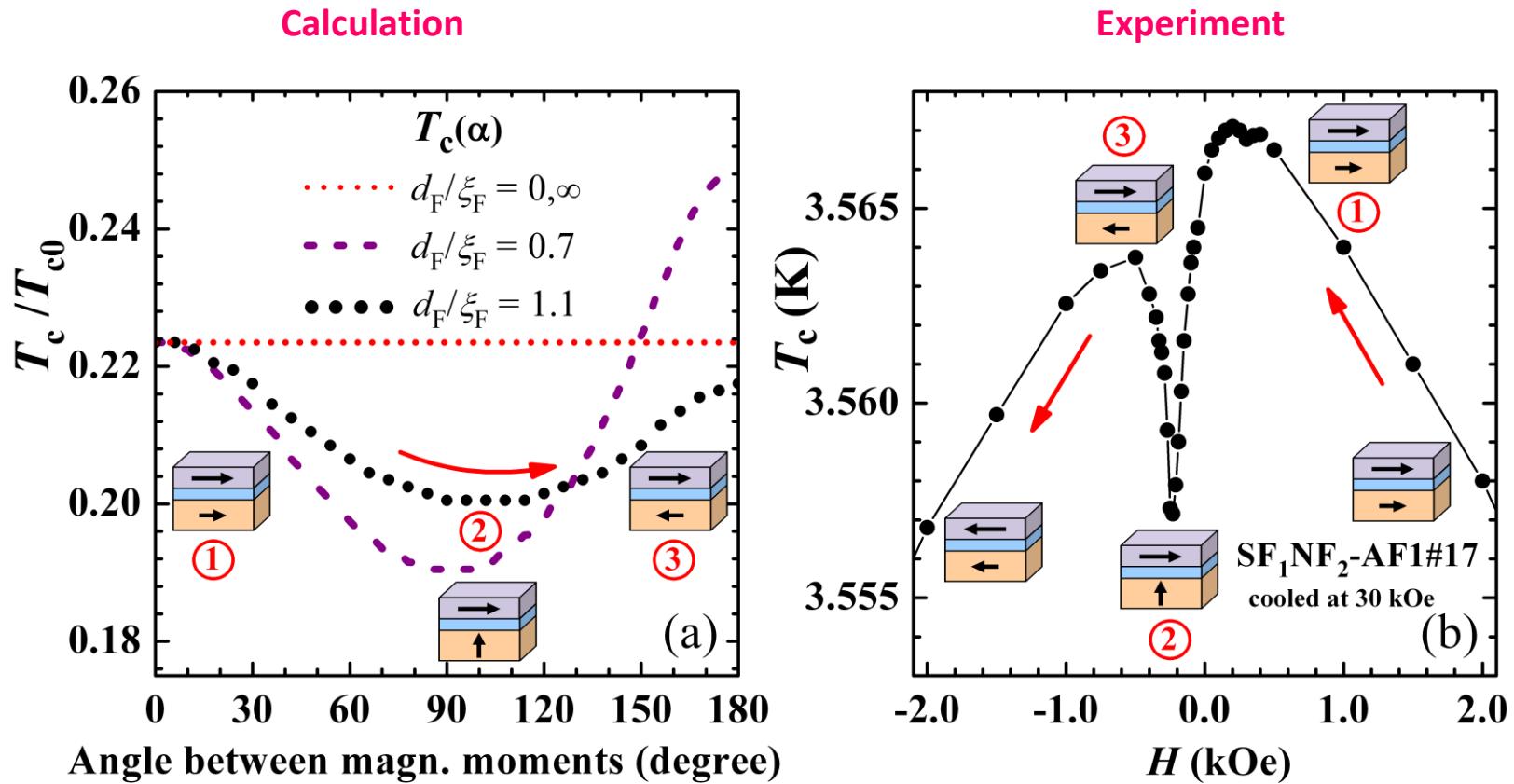


- a) Sketch of the samples.
- b) Cross-sectional TEM of Sample I



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

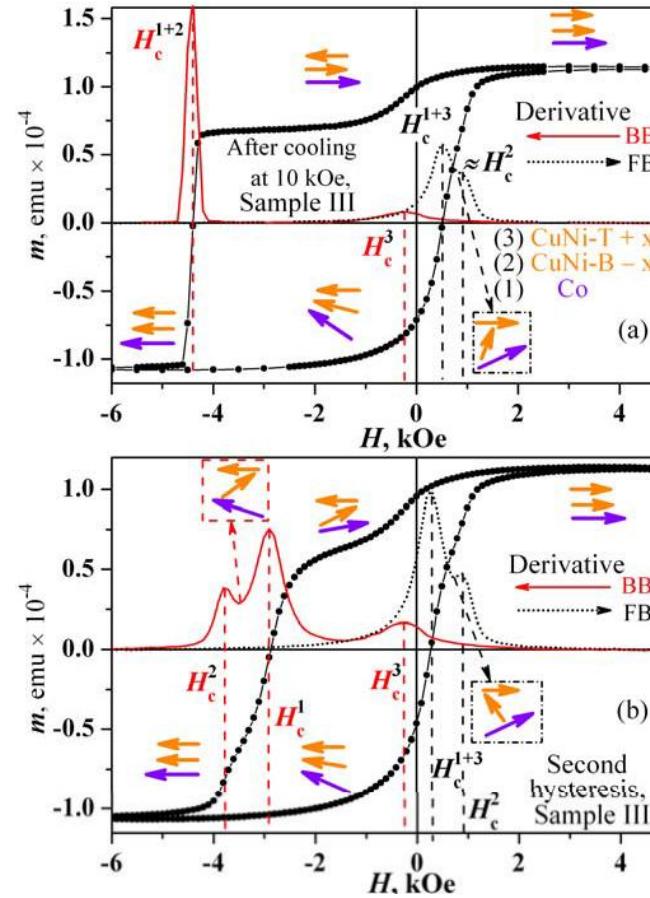
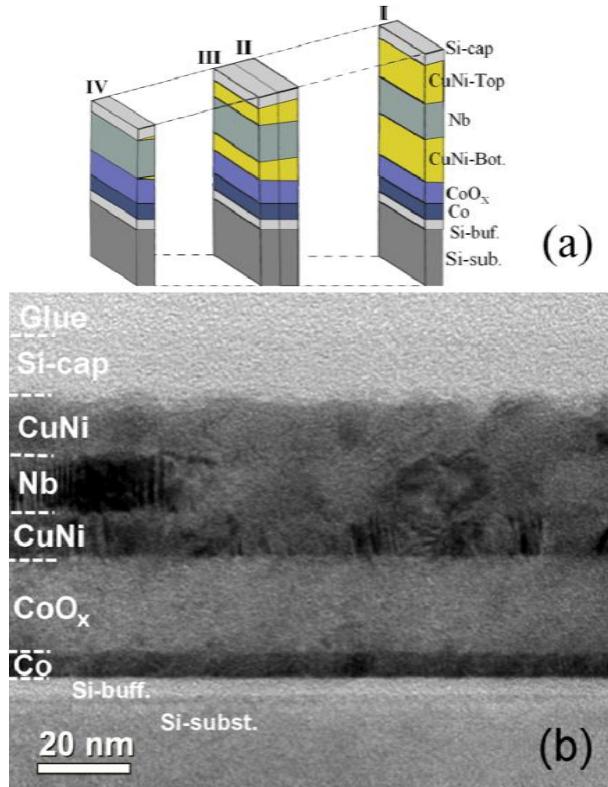
Dependence of the superconducting transition temperature on magnetic field



Phys. Rev. B87, 144507 (2013)

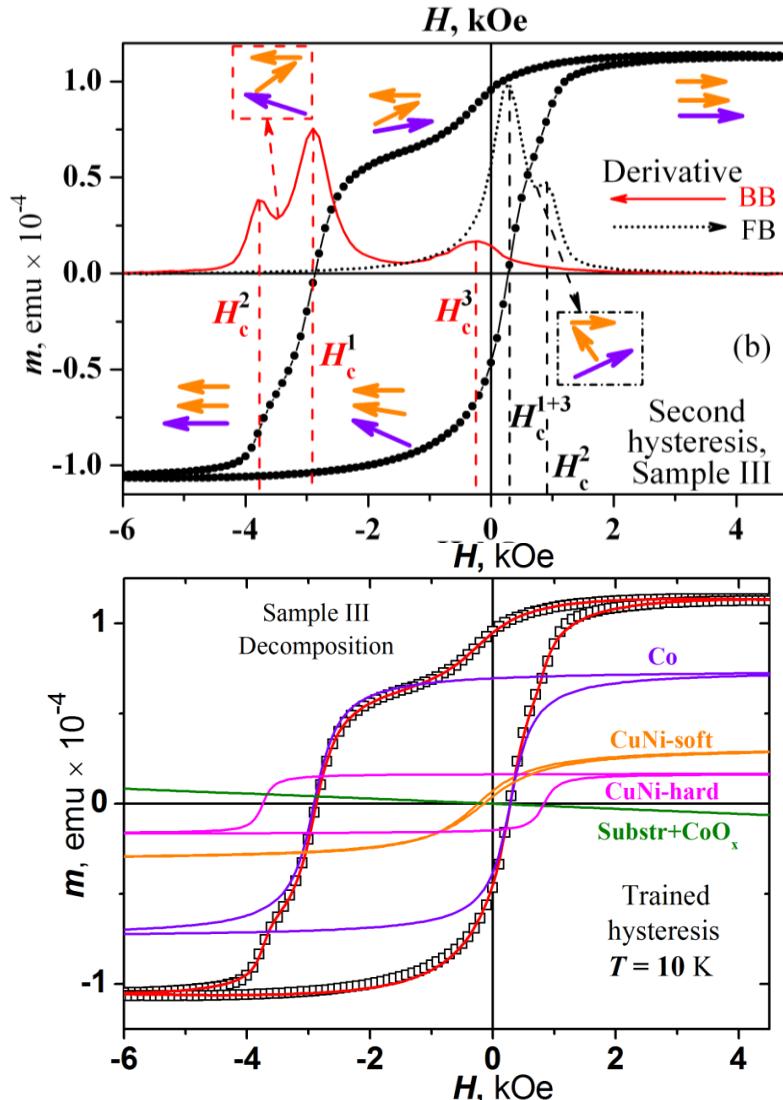
Experimental Observation of the Triplet Spin-Valve Effect in a Superconductor-Ferromagnet Heterostructure. V.I. Zdravkov, A.S. Sidorenko, L.R. Tagirov et al.

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

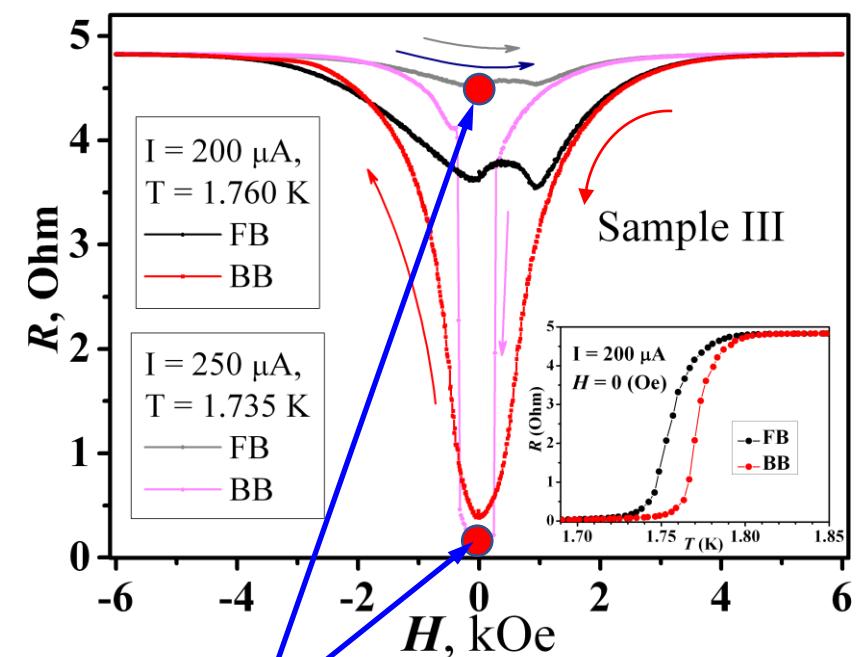


Strong exchange bias ($H_{EB} \approx -2$ kOe), as well as the training effect - decrease of the hysteresis loop asymmetry, coercivity and squareness by further magnetic field cyclings.

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

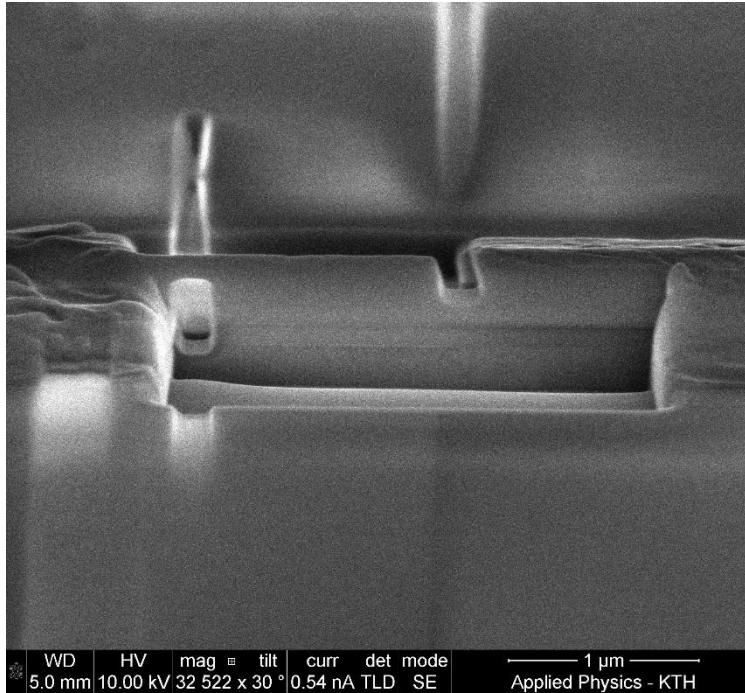
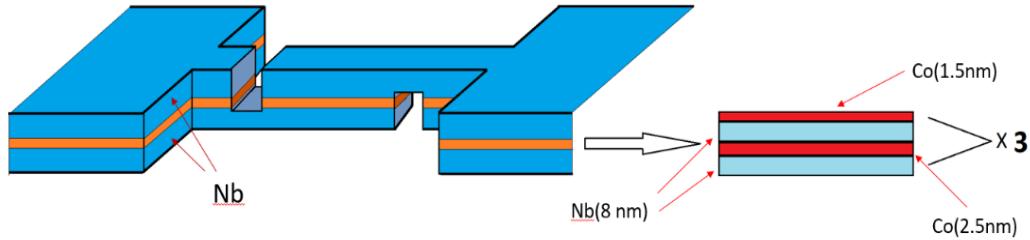


The resistivity of nanolayered superconductor-ferromagnet spin-valve structure depends on the preceding magnetic field polarity.



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

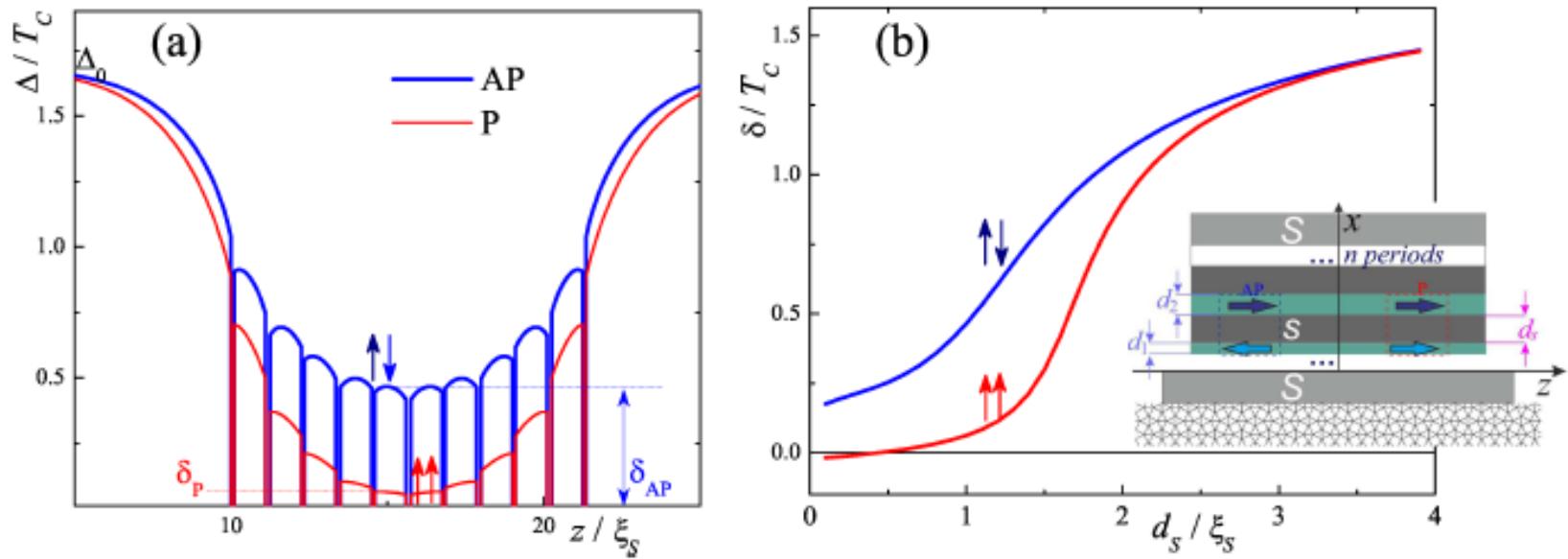


Figure 2: (a) The depth profile of the superconducting pair potential amplitude of the $S/[F_1/s/F_2/s]_5/F_1/S$ structure in the P and AP cases. (b) The amplitudes of the superconducting pair potential in the middle of the weak link for the same situations. Inset – schematic representation of the considered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

Josephson spin valve: reflectometry of polarized neutrons

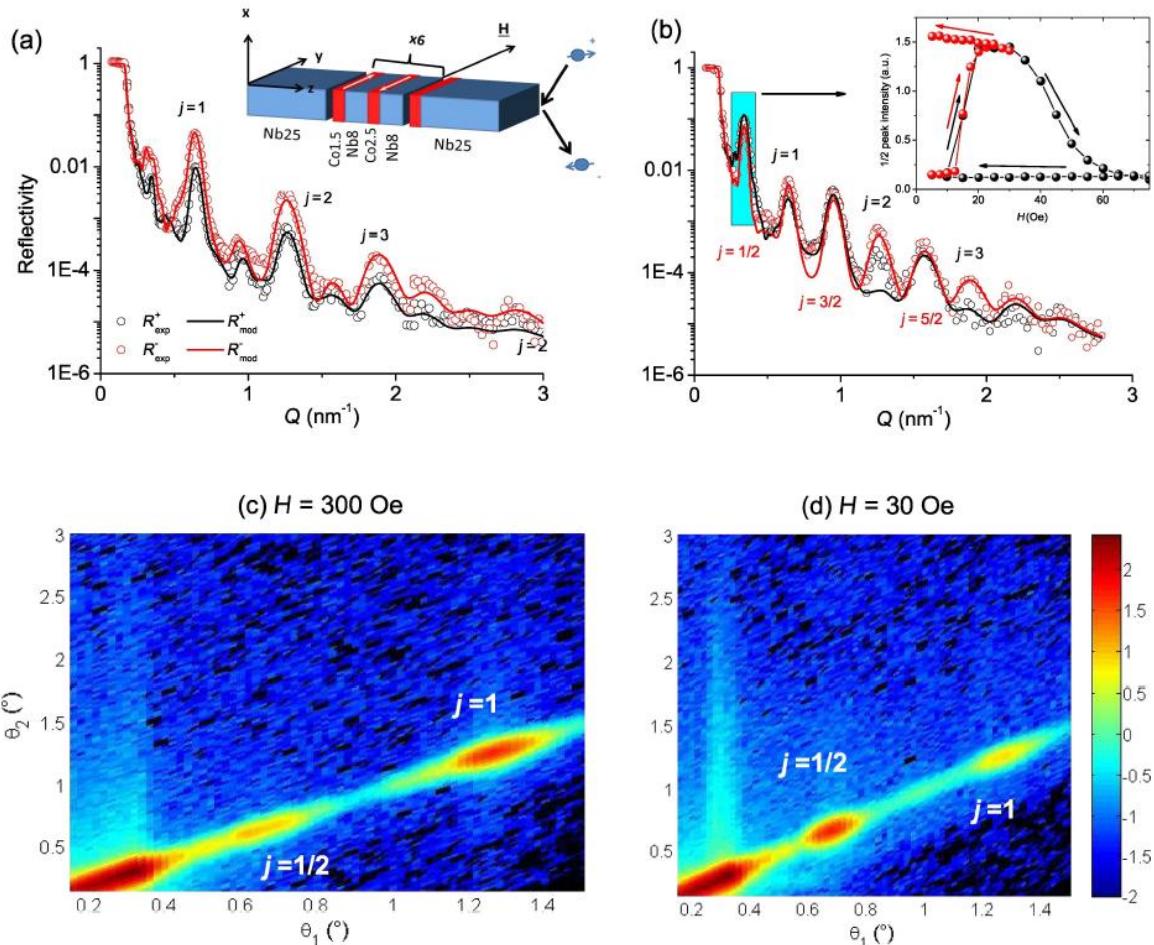


Figure 3: Experimental (dots) specular neutron reflectivity measured at $T = 13 \text{ K}$ in magnetic fields $H = 300 \text{ Oe}$ (a) and $H = 30 \text{ Oe}$ (b). Solid lines show the model curves for the magnetization depth profiles depicted in Figure 4a. The inset in (a) shows the sketch of the sample and experimental setup. The numbers above show the corresponding order of Bragg reflection from the effective $[\text{Co}(2 \text{ nm})/\text{Nb}(8 \text{ nm})] \times 12$ periodic structure. The inset in (b) shows the field dependence of the $j = 1/2$ peak shown by the blue rectangle in (b). The logarithm of intensity of spin-down scattered neutrons measured at $H = 300 \text{ Oe}$ and $H = 30 \text{ Oe}$ is shown in (c) and (d).

CONCLUSION

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.

