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

SPINTECH

MINISTERUL EDUCAȚIEI, CULTURII ȘI CERCETĂRII

SPINTECH

Hybrid Nanostructures for Spintronics and Qubits

Anatolie Sidorenko

SPINTECH-project :

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

University of Twente, the Netherlands, 11-13 November 2021

UNIVERSITY OF TWENTE.

Stockholm University

Goals of the project

- The overall aim of the SPINTECH project is to boost 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,

in tight collaboration with high-experienced partners: Stockholm University (Sweden) and University of Twente (The Netherlands).

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

Valdimir Krasnov
Stockholm, Sweden

Alexander Golubov,
Twente, NL

Mikhail Kupriyanov,
Moscow, Russia

Vasily Stolyarov,
MIPT, Dolgoprudny, Russia

Bernhard Keimer,
Stuttgart, Germany

Horst Hahn
Karlsruhe, Germany

Alexander Vakhrushev
Izhevsk, Russia

Lenar Tagirov
Kazan, Russia

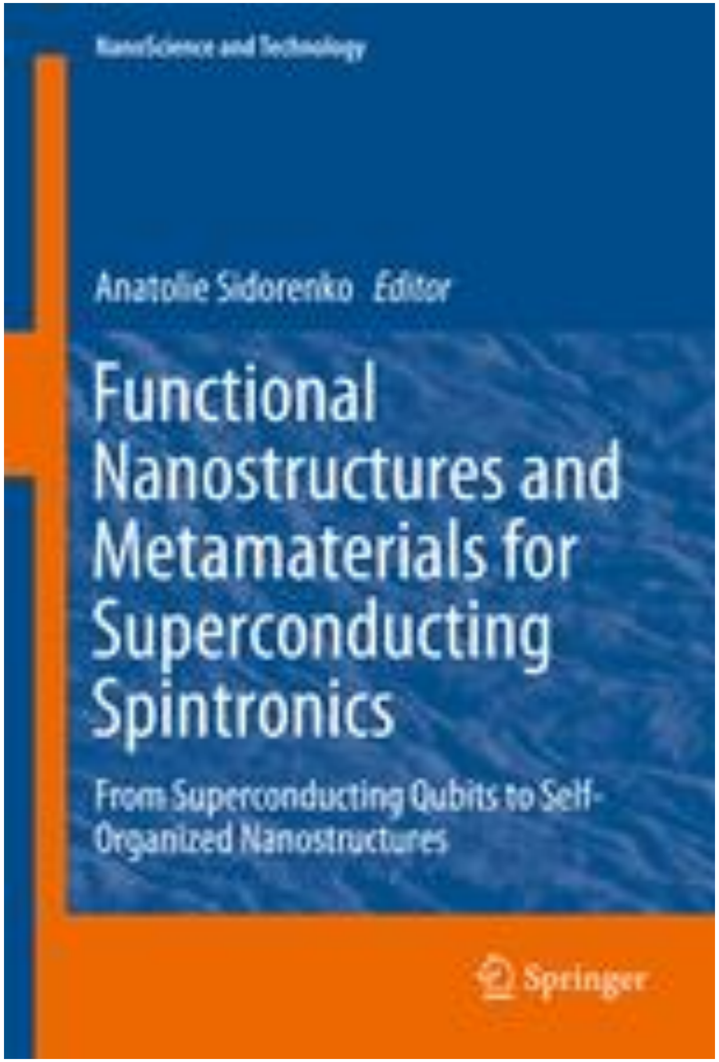
And with project MELON (Amienne, France) - Igor Lukyanchuk https://www.melon.ferroix.net/

State of the art

- As the base of the project served the book:

- are summarized results of theoretical and experimental investigation of nanostructures Superconductor/Feromagnet, novel technologies of their fabrication and characterization methods, publishd in: Functional Nanostructures and Metamaterials for Superconducting Spintronics. Ed. by A.Sidorenko,“Springer”, 2018, 270p.

:



Phenomena presented in the book – base for the project:

re-entrant superconductivity in SF hybrids – doctor thesis of Andrei Prepelitsa

На правах рукописи

УДК: 537.312.62

Препелицэ Андрей Анатольевич

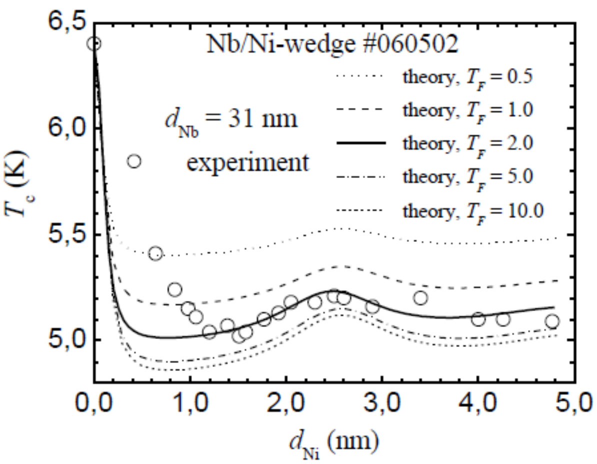
Сверхпроводящие свойства наноструктур сверхпроводник-ферромагнетик

01.04.07 – физика конденсированного состояния

Диссертацияна соискание ученой степени доктора физико-математических наук

Кишинев 2006

Неоднор **)FF-состояние**



- Обнаружены отчетливые осцилляции температуры сверхпроводящего перехода образцов с фиксированной толщиной слоев ниобия и переменной толщиной никеля. Это наблюдение является экспериментальным подтверждением квазиодномерного неоднородного сверхпроводящего состояния LOFF в слое ферромагнитного никеля.

Multi-periodic re-entrant superconductivity in SF hybrids – doctor thesis of Roman Morari

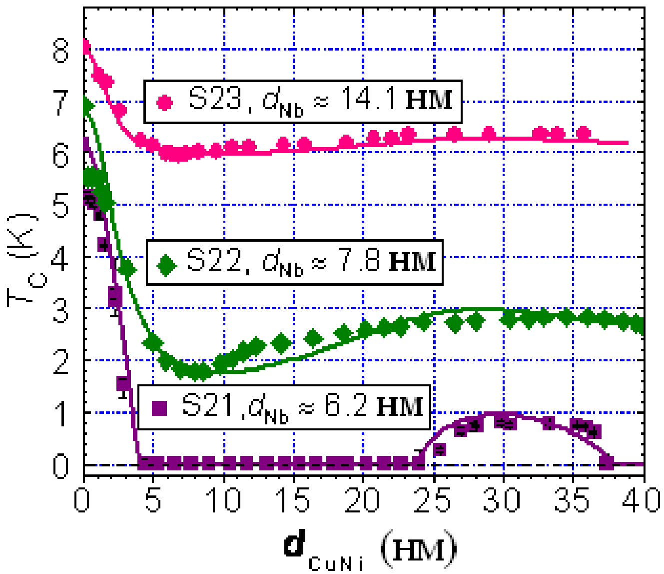
На правах рукописи
УДК: 537.312.62

МОРАРЬ Роман Андреевич

ВОЗВРАТНАЯ СВЕРХПРОВОДИМОСТЬ В СВЕРХПРОВОДЯЩИХ НАНОСТРУКТУРАХ НА ОСНОВЕ НИОБИЯ И СПЛАВА МЕДЬ-НИКЕЛЬ.

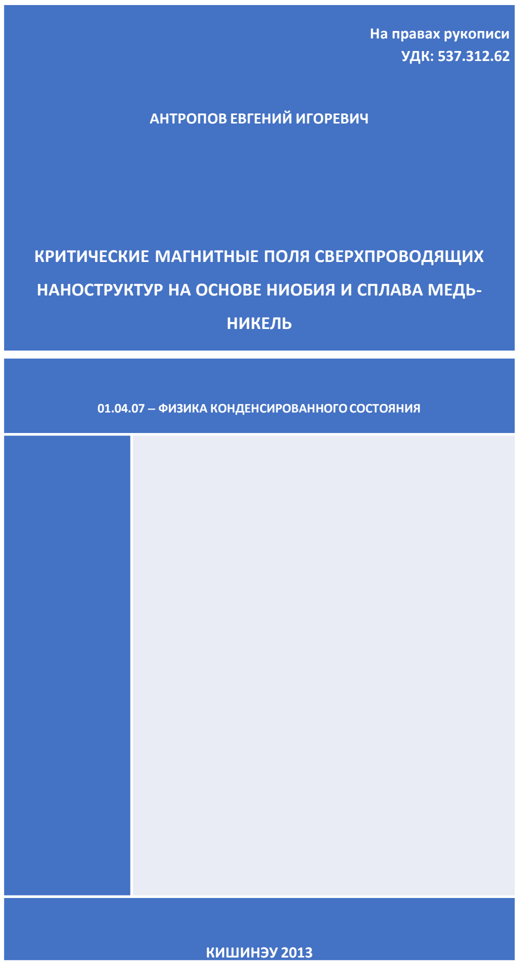
01.04.07 – Физика конденсированного состояния

Кишинеэу 2011



Обнаружены все возможные типы поведения Тс, предсказанные теорией неоднородного LOFF -состояния, а именно: от простого немонотонного поведения Тс для серии образцов с толстым слоем ниобия, превышающим значение длины когерентности сверхпроводника, к осциллирующему для серии с толщиной слоя ниобия близкой по величине длине когерентности и к поведению типа «возвратная сверхпроводимость» для серии структур с толщиной слоя ниобия, меньшей длины когерентности, как убедительное доказательство возникновения в исследованных образцах предсказанного теорией неоднородного квазиодномерного сверхпроводящего состояния Ларкина-Овчинникова-Фулде-Феррелла

Anizotropy of critical magnetic fields and triplet superconductivity in SF hybrids – doctor thesis of Evgheni Antropov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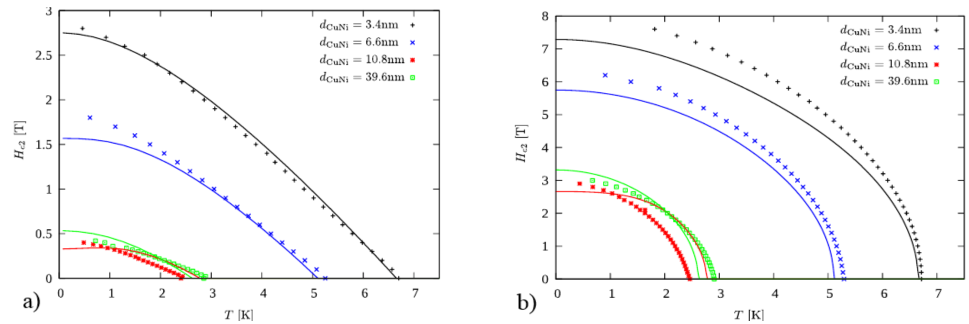
УДК: 537.312.62

АНТРОПОВ ЕВГЕНИЙ ИГОРЕВИЧ

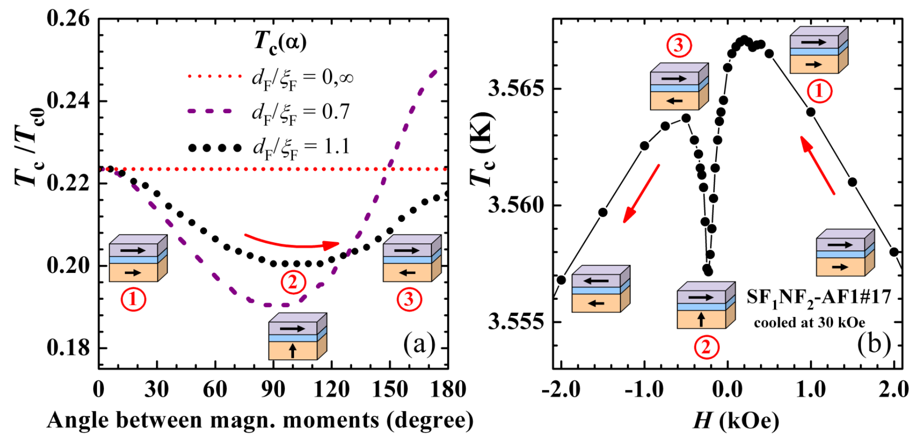
КРИТИЧЕСКИЕ МАГНИТНЫЕ ПОЛЯ СВЕРХПРОВОДЯЩИХ НАНОСТРУКТУР НА ОСНОВЕ НИОБИЯ И СПЛАВА МЕДЬ-НИКЕЛЬ

01.04.07 – ФИЗИКА КОНДЕНСИРОВАННОГО СОСТОЯНИЯ

КИШИНЭУ 2013



- Анизотропия критических магнитных полей у исследованных трехслойных F/S/F структур существенно сильнее, чем у ранее изученных структур S/F/S, при этом резко отличается поведение температурных зависимостей перпендикулярных критических магнитных полей, которые существенно нелинейные для случая F/S/F и практически линейные для случаев S/F/S структур и базовой теории Буздина-Радовича для многослойных S/F структур.

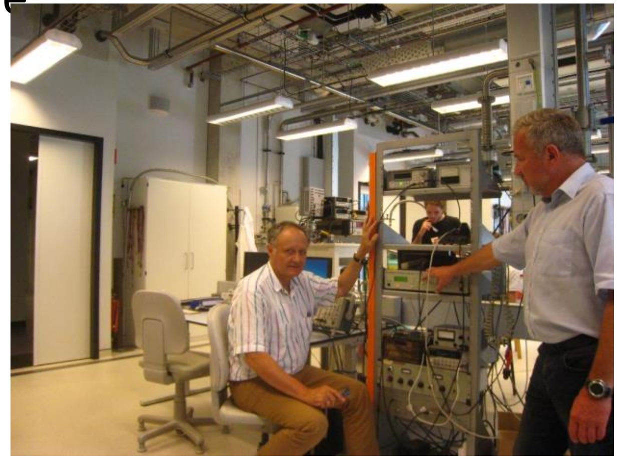


Project implementation in: Cryogenic laboratory of IEEN, Chisinau, Moldova

- The project is carried out by the **Cryogenic laboratory of IEEN**, which accumulated long – term experience in:
- - Development of different vacuum technologies for fabrication of superconducting compounds, and superconductor/ferromagnet nanostructures, using MBE, DC and RF magnetron sputtering.
- - Experimental research and detection of new phenomena: re-entrant and multiband superconductivity, triplet pairing and triplet spin-valve effect in layered nanostructures;
- - Development of electronic devices – superconducting spin valve for spintronics, based on new detected phenomena.

and by partners of the SPINTECH project:

- at University of Twente , Enschede, The Netherlands,



- theoretical prediction and calculation of new phenomena in superconductors, SQUID-microscopy and XRD characterization (A. Golubov, UTWENTE):

- and at Stockholm University, Sweden - they are highly experienced in:

- nanolithography and characterization of nanostructures , experimental investigation of superconducting properties and elaboration of superconducting devices (V. Krasnov, SU):

To achieve the aims of the project during the 3 years of its realization, the partners implement a research and innovation strategy with the following objectives:

- **Objective 1**: Strengthen IEEN's research excellence in spintronics
- **Objective 2**: Enhance the research and innovation capacity of IEEN and the Twinning partners
- **Objective 3**: Raise the research profile of IEEN and the Twinning Partners
- **Objective 4**: Contribute to the research and innovation priorities of Moldova
- **Objective 5**: Support research and innovation on a European level .

Work packages of the project

In order to achieve these objectives, the consortium partners put into practice a comprehensive set of **measures** via the project's work packages, which include :

(i) short term staff exchanges (WP1);

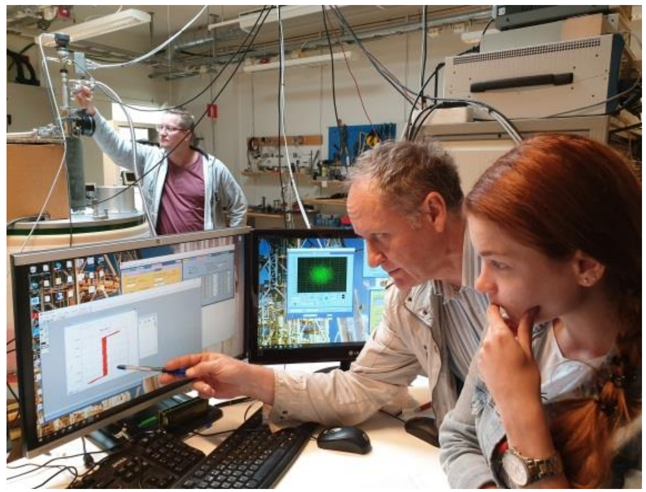
(ii) **training workshops, conferences and summer schools** (WP2);

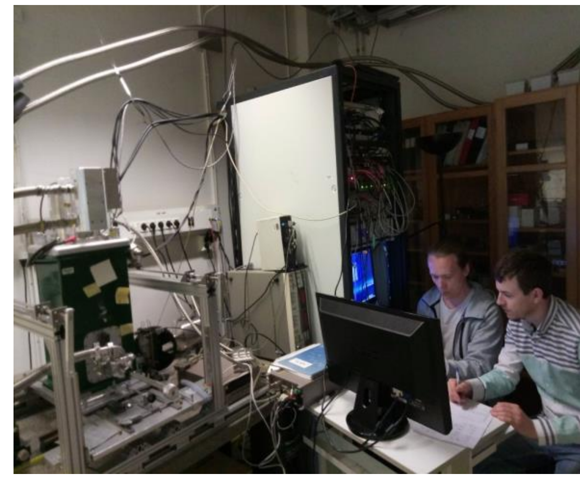
(iii) **dissemination and outreach activities** (WP3).

Short term staff exchanges (WP1) – 16 researchers participated in working visits:

4 from SU, 3 from U-Twente, 11 from IIEN "D.GHITU"

- In Stockholm Uni:





- In Uni-Twente:

Training workshops, conferences and summer schools

- 5 planned training workshops in Chisinau, Twente and Stockholm and 2 international conferences were organized in Chisinau:

< In September 2019

And

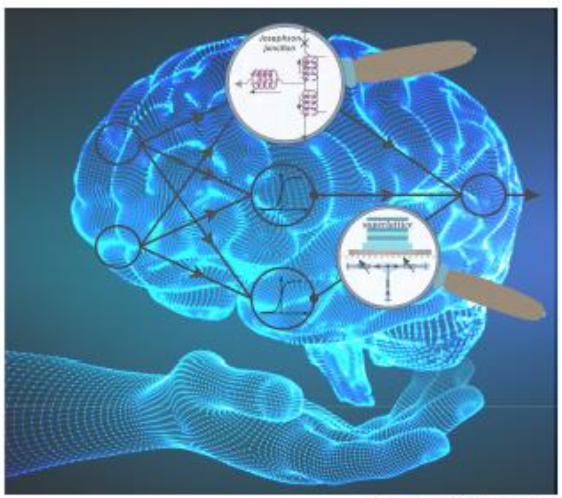
In September 2021 >

Publication of planned book after the conferences:

BEILSTEIN JOURNAL OF NANOTECHNOLOGY

Functional nanostructures for electronics, spintronics and sensors

Edited by Anatolie S. Sidorenko



Generated on 30 November 2020, 17:02

- published 30 November 2020

BEILSTEIN JOURNAL OF NANOTECHNOLOGY

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

- Will be published in May 2022

Three summer schools were organised:

Chisinau, september 2019

European Commission

"SPINTECH-Conference
+ Humboldt Kolleg

SPINTECH

SPINTECH Summer school "S/F Hybrid Structures for Spintronics",

27-30 September 2019 *Chisinau, Moldova*

This event is supported by the European Union H2020-WIDESPREAD-05-2017-Twinning project "SPINTECH" under grant agreement Nr. 810144.

Twente, august 2020

European Commission

SPINTECH

MESA+
INSTITUTE FOR NANOTECHNOLOGY

Hybrid Structures for Spintronics and Qubits

SPINTECH summer school-2020,

University of Twente, the Netherlands, 01-03 October 2020

This event is supported by the European Union H2020-WIDESPREAD-05-2017-Twinning project "SPINTECH" under grant agreement Nr. 810144.

Stockholm,
June 2020

IIEN

SPINTECH

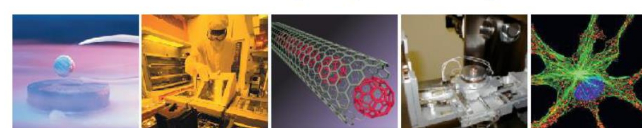
Fysikum

Brain-like Artificial Neural Network: Superconducting Spintronic's Alternative

SPINTECH Summer School,
27-28 Mai 2021, Stockholm, Sweden

This event is supported by the European Union H2020-WIDESPREAD-05-2017-Twinning project "SPINTECH", grant agreement Nr. 810144:

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



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

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

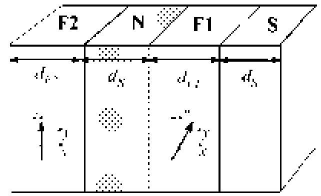
Even triplet WF with zero projection (*E*ex +AP mag.)

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

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

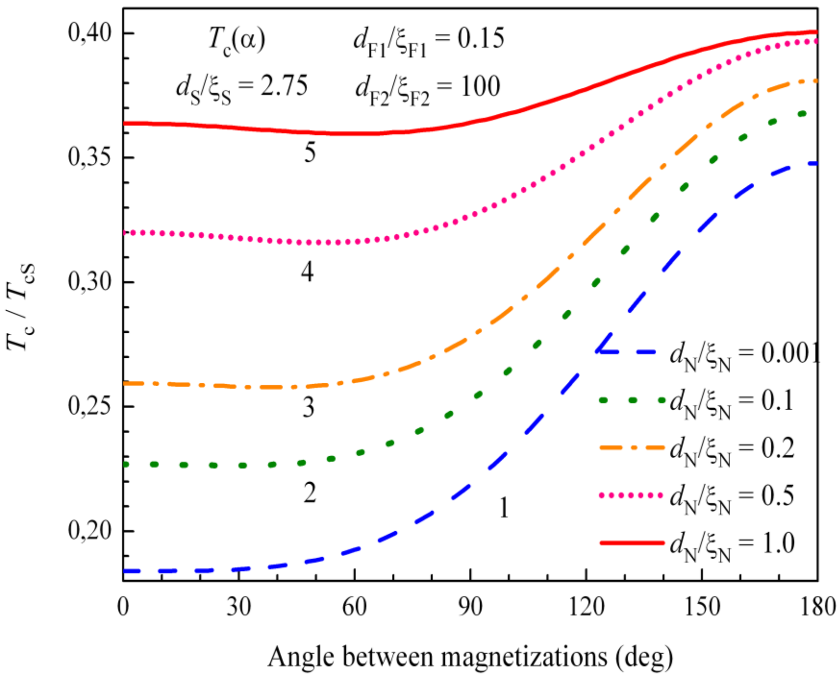
F.S. Bergeret, A.F. Volkov and K.B. Efetov, PRL **86**, 4096 (2001);
A.F. Volkov, F.S. Bergeret and K.B. Efetov, PRL **90**, 117006 (2003);
Alexader Golubov, Mikhail Kupriyanov et al. / JETPL (2003);

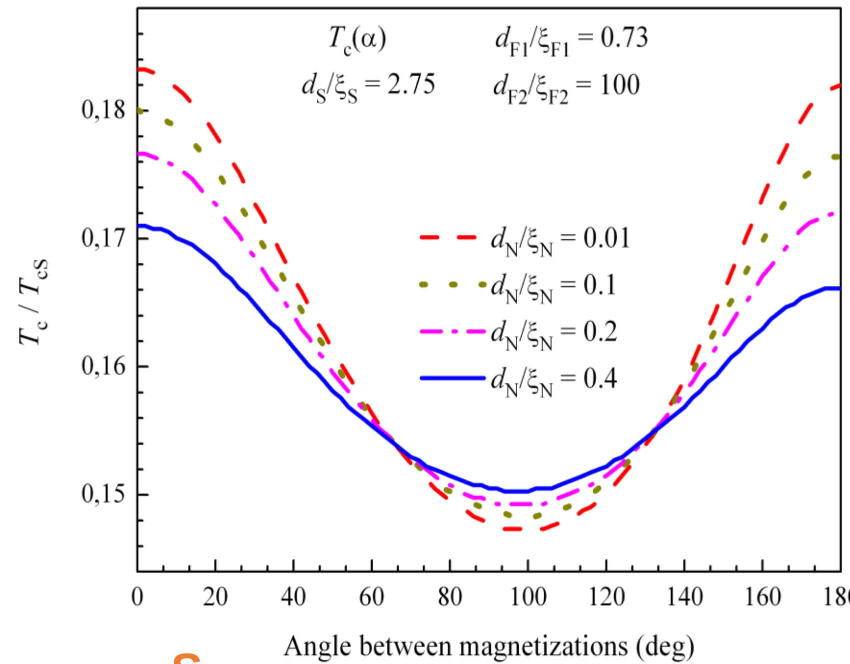
General model – influence of the norm. metal spacer (N)

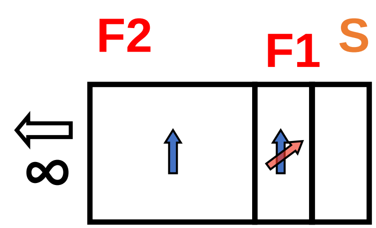


«Direct» switching

«Triplet » switching





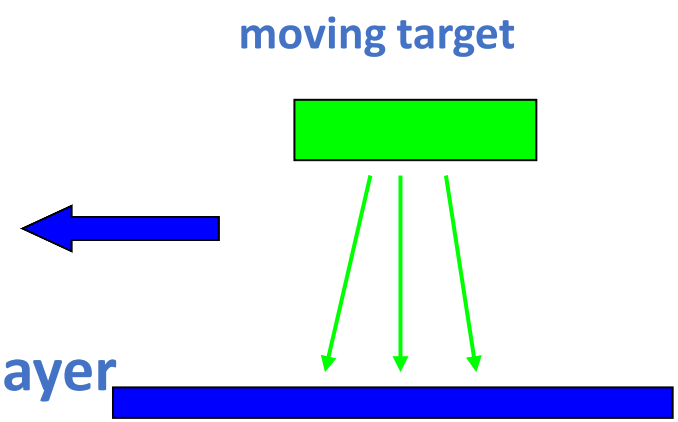


Golubov-Karminskaya-Kupriyanov-Deminov-Tagirov, JETPL 91, 308 (2010)

Sample preparation- Novel Technology :

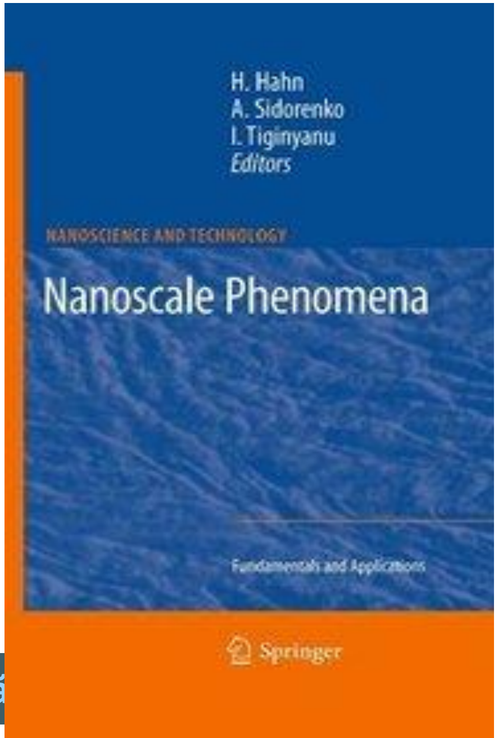
- **DC magnetron sputtering with:**

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



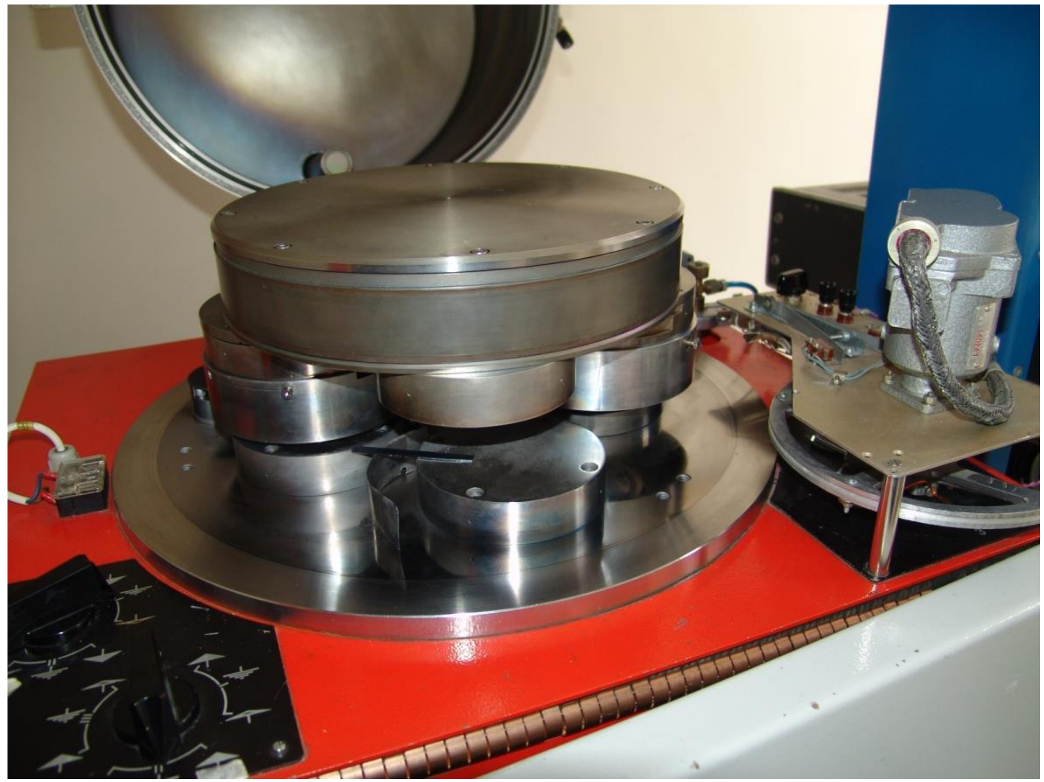
Detailes of the technology are descriebed in:

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



SF- samples

magnetron sputtering



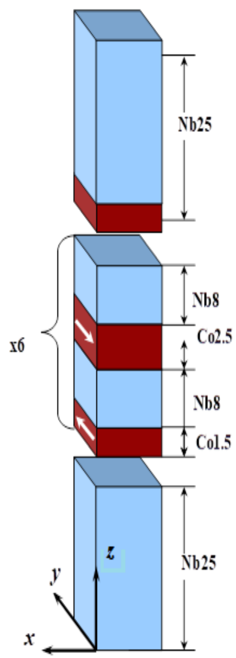
Technology patented: Patent of RM №3135 from 31.08 2006.
Sidorenko A.S., Zdravkov V.I.,
“Device for thin films preparation”

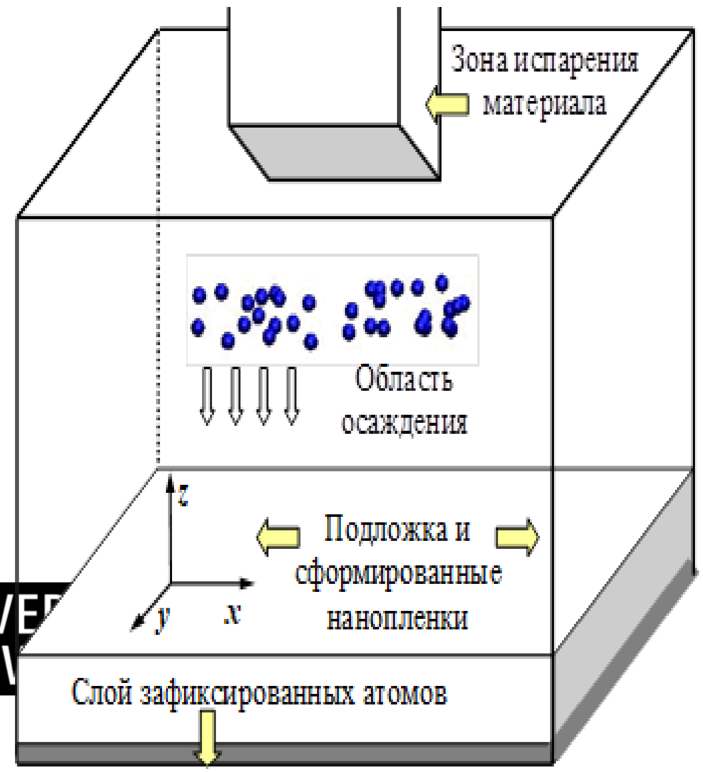
European Commission

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

SPINTECH

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)





European Commission

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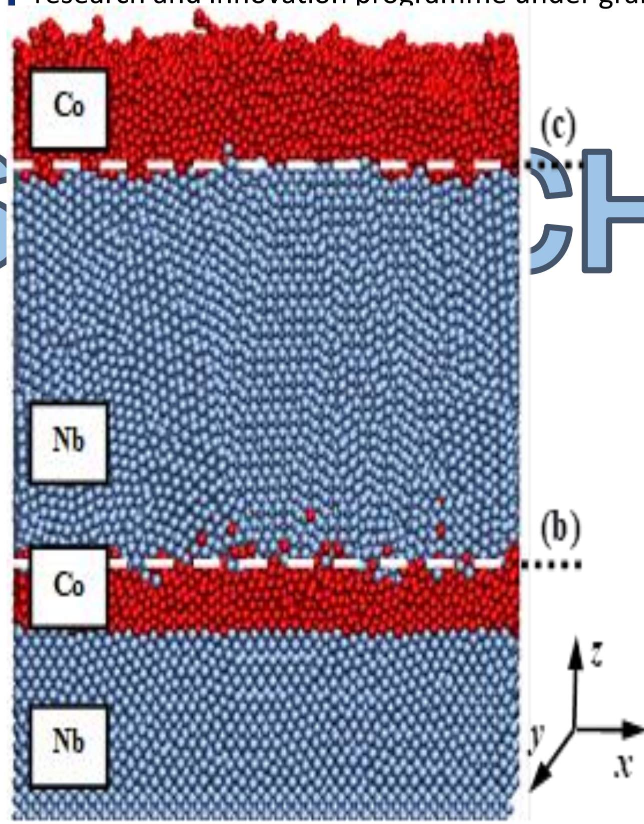

UNIVERSITY OF TWENTE.

Stockholm University

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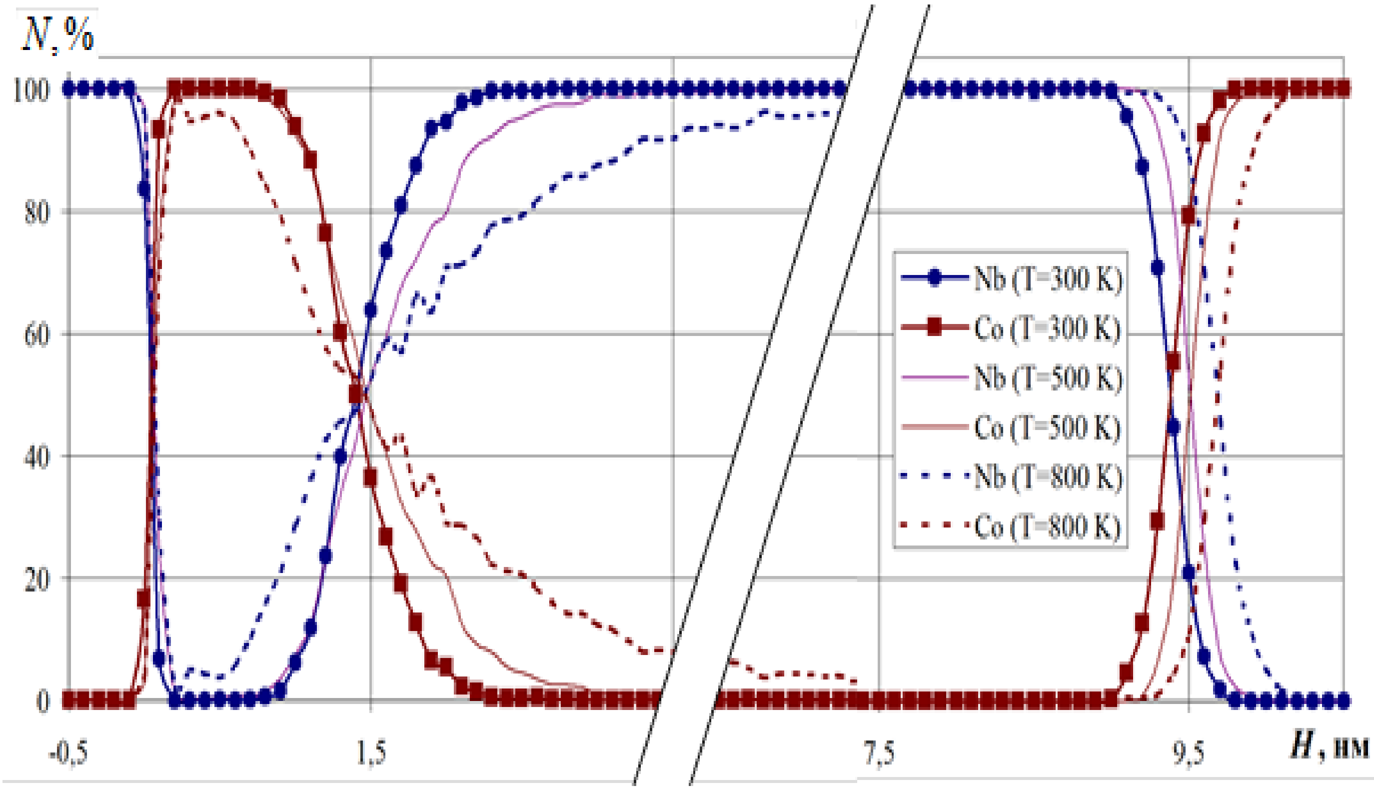
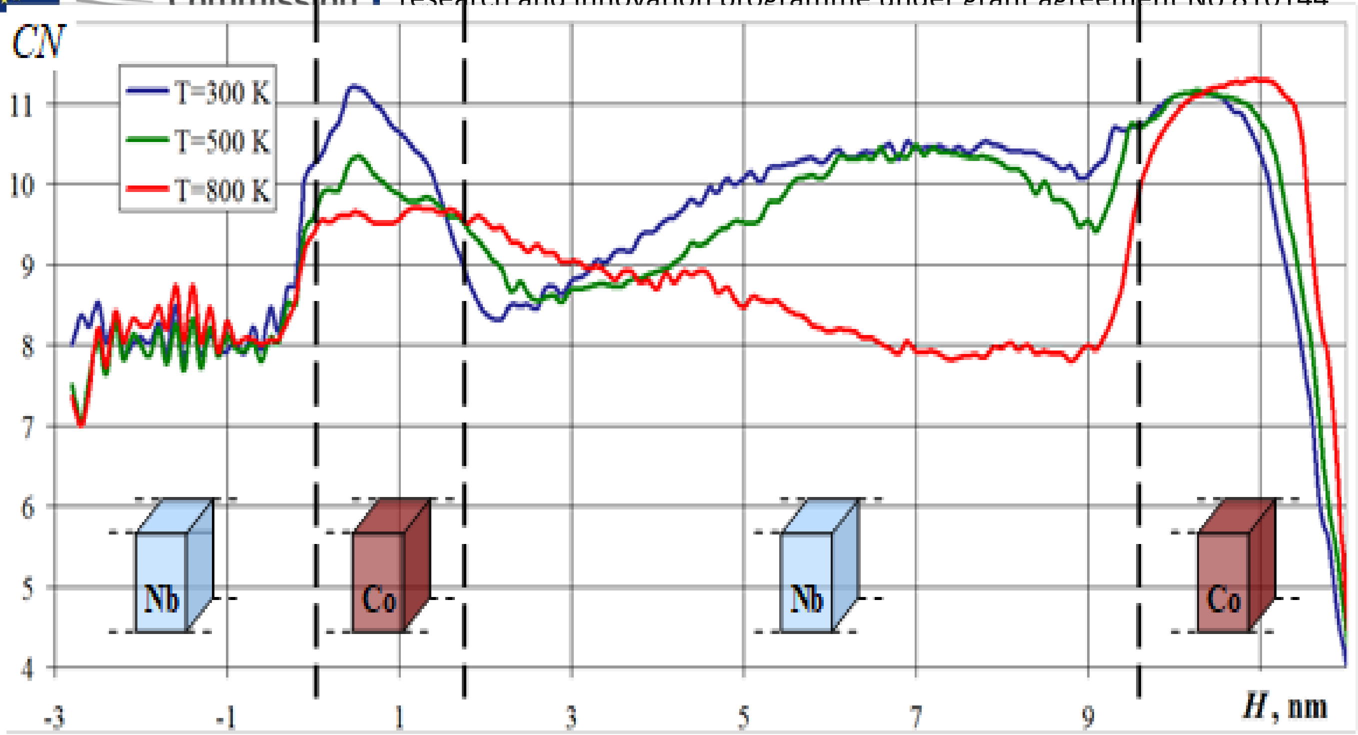


Composition of the layers Nb and Co depending on substrate temperature (model calculations)

IIEN
UNIVERSITY OF TWENTE.
Stockholm University

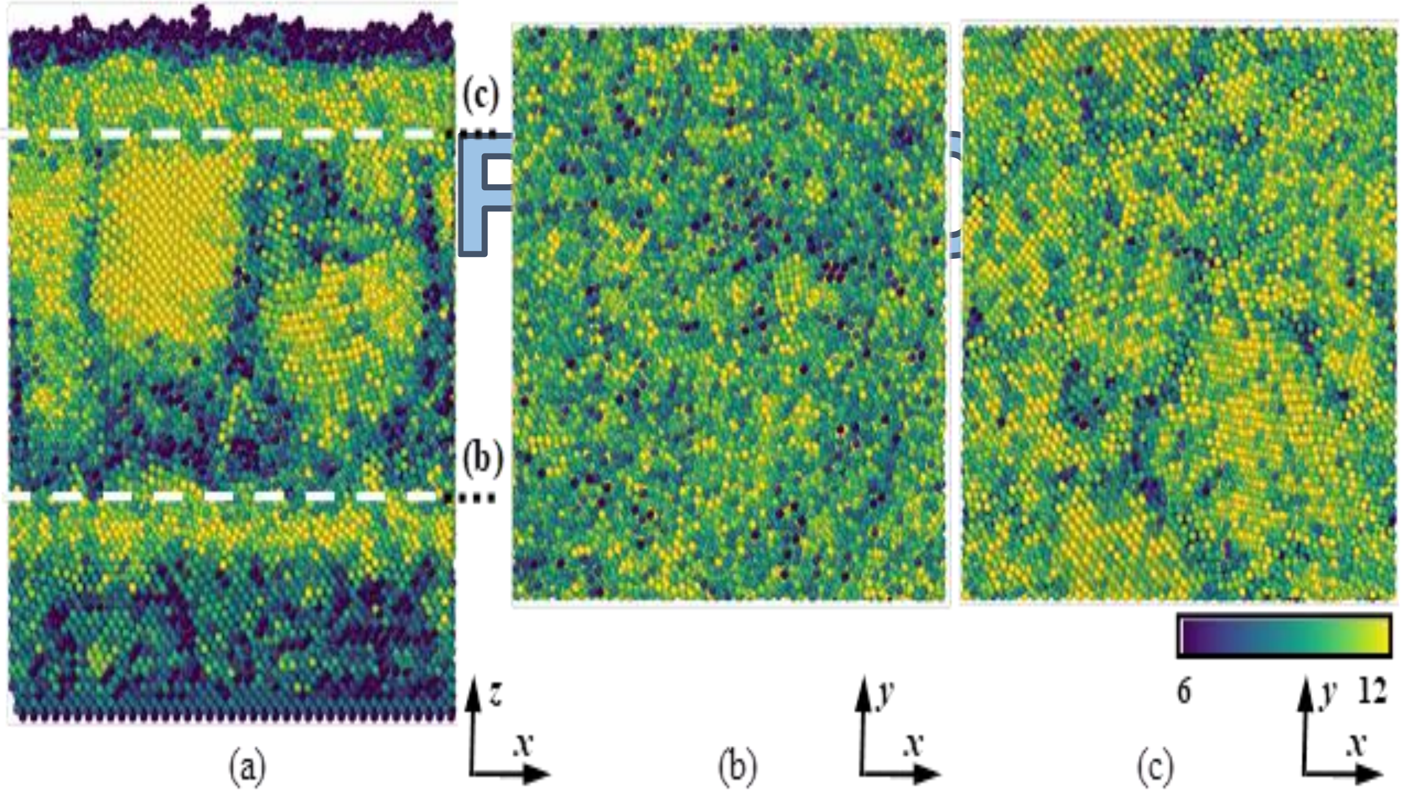
European Commission

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



Changes of the coordination number of Nb and Co in multilayer depending on substrate temperature (model calculations)

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

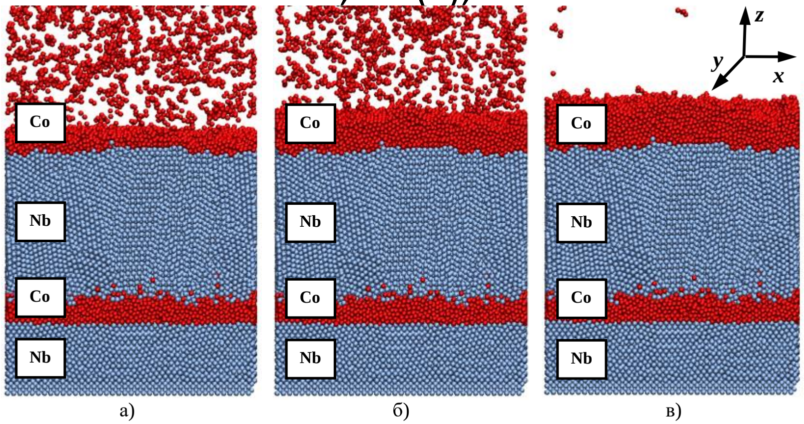


Space distribution (in planes "c" and "b") of the coordination number of Nb and Co layers in the Nb/Co multilayer , substrate temperature Ts=300 K (model calculations)

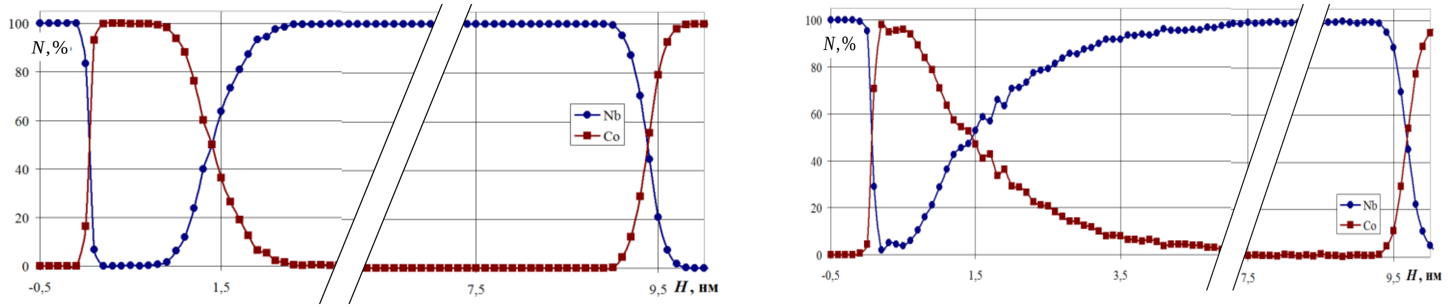
Model calculations are published in:

Моделирование процессов формирования сверхпроводящего спинового вентиля на основе многослойной наноструктуры "сверхпроводник/ ферромагнетик".

ВАХРУШЕВ А.В., ФЕДОТОВ А.Ю., САВВА Ю.Б., СИДОРЕНКО А.С. *Химическая физика и мезоскопия*. 2019, **21** (3), 362-374.

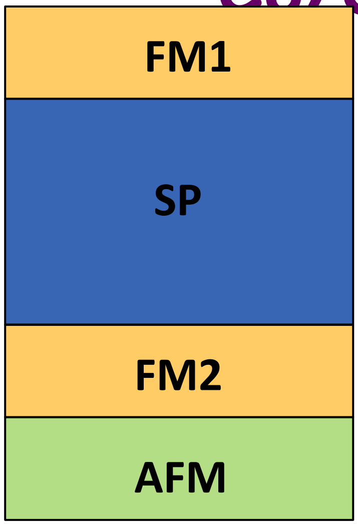


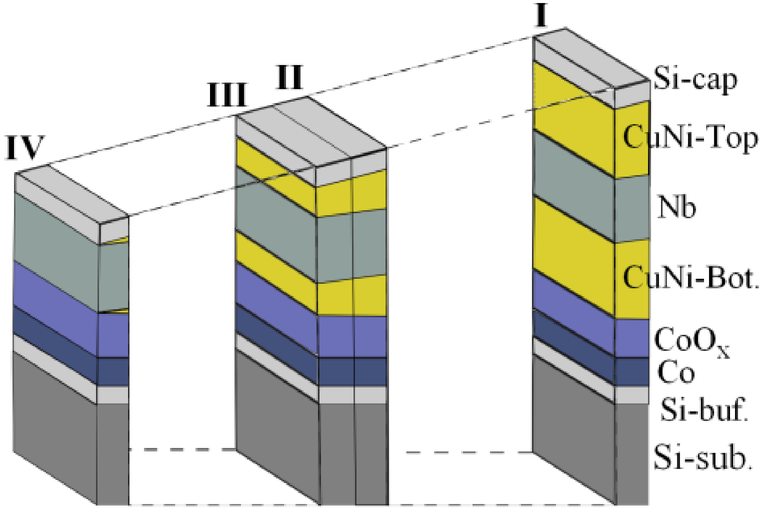
Condensation of nanolayers Co and Nb at different deposition time:
а) 0,1 нс, б) 0,2 нс и в) 0,4 нс. Substrate temperature is fixed at 300 K
(model calculations)



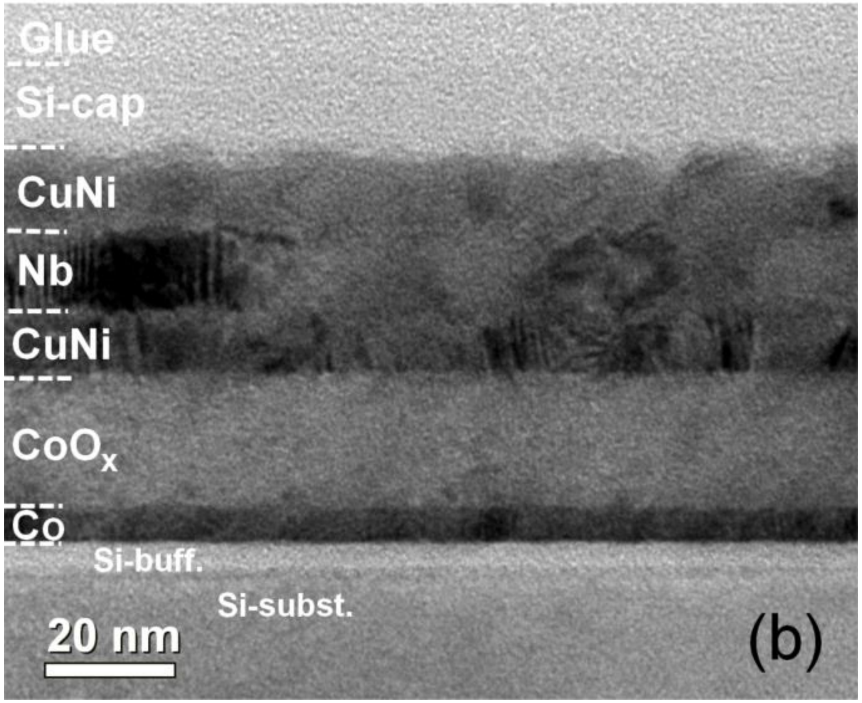
Composition of the layers Nb and Co, at two different substrate temperatures - 300 K (left) and 800 K (right)
(model calculations)

Spin-valve sample design
cell core with additional Co layer
$Co/CoO_x/Cu_{41}Ni_{59}/Nb/Cu_{41}Ni_{59}$



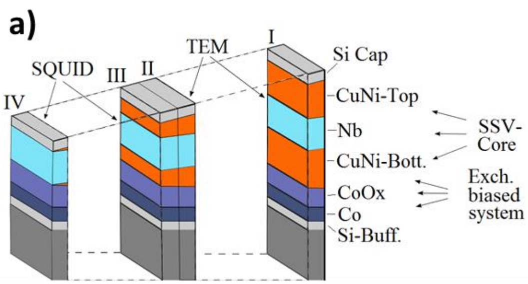


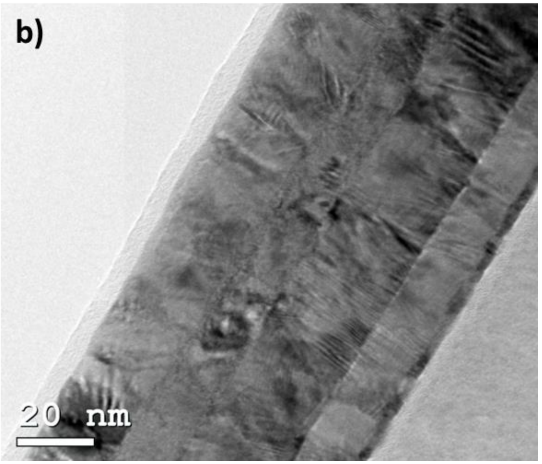
TEM cross-section

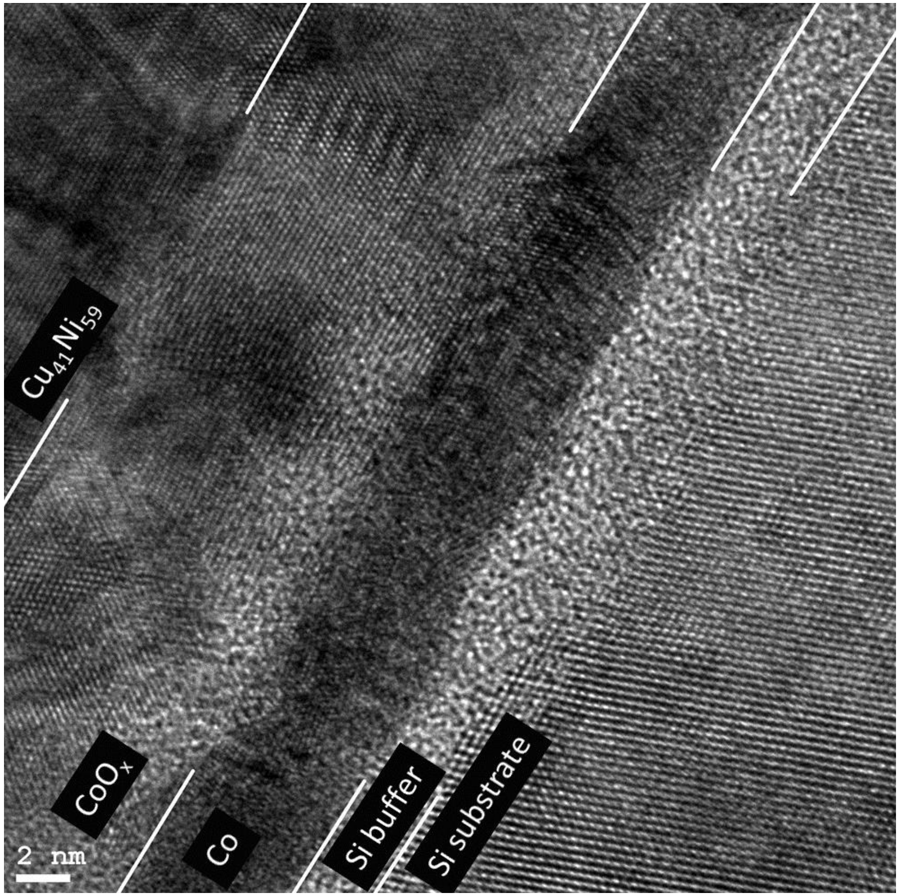


V.I. Zdravkov *et al.*, APL/2013

Results of TEM and HRTEM





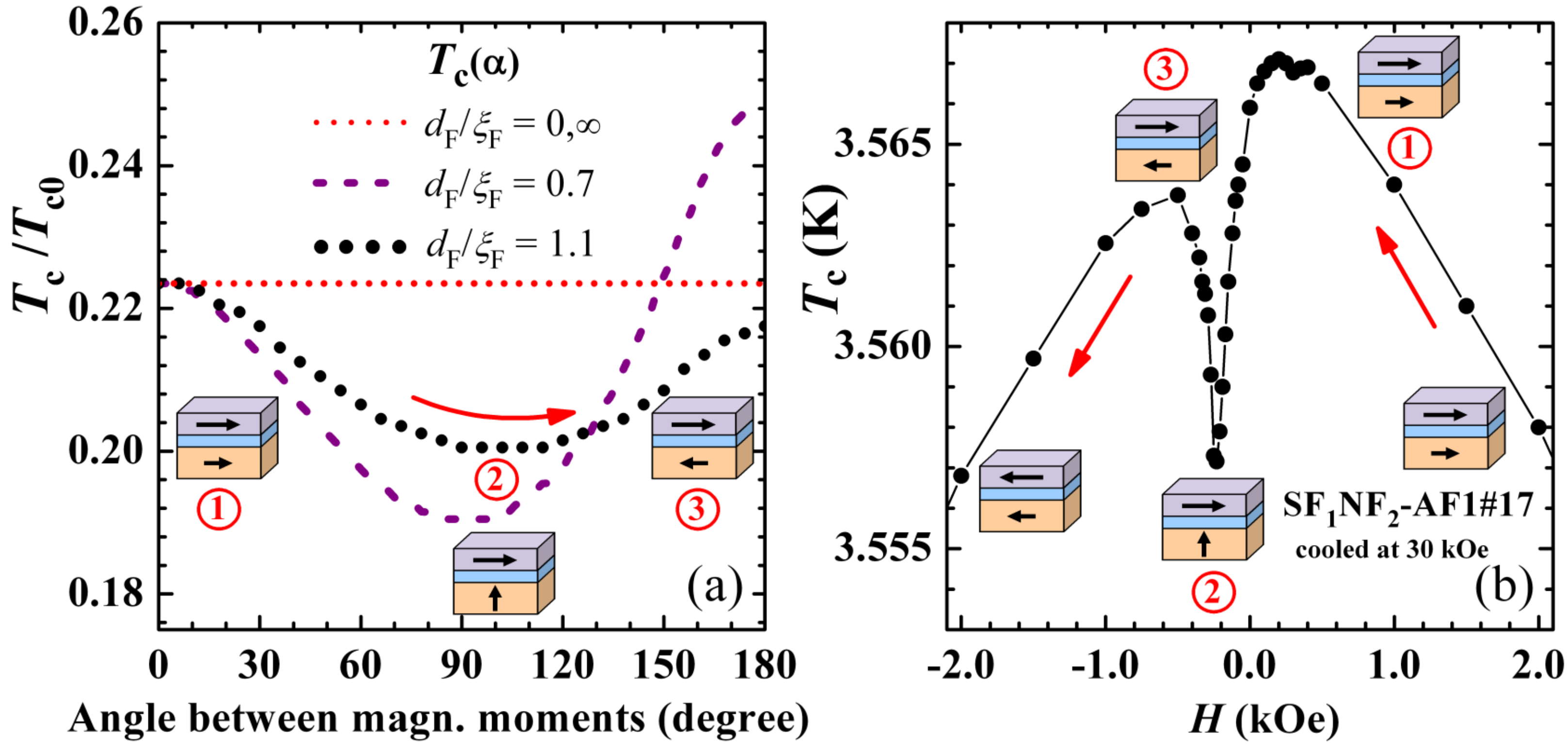


a) Sketch of the samples. b) Cross-sectional TEM of Sample I

Cross-sectional high-resolution TEM image of Sample I at the exchange bias region of the system.

Dependence of the superconducting transition temperature on mag. field

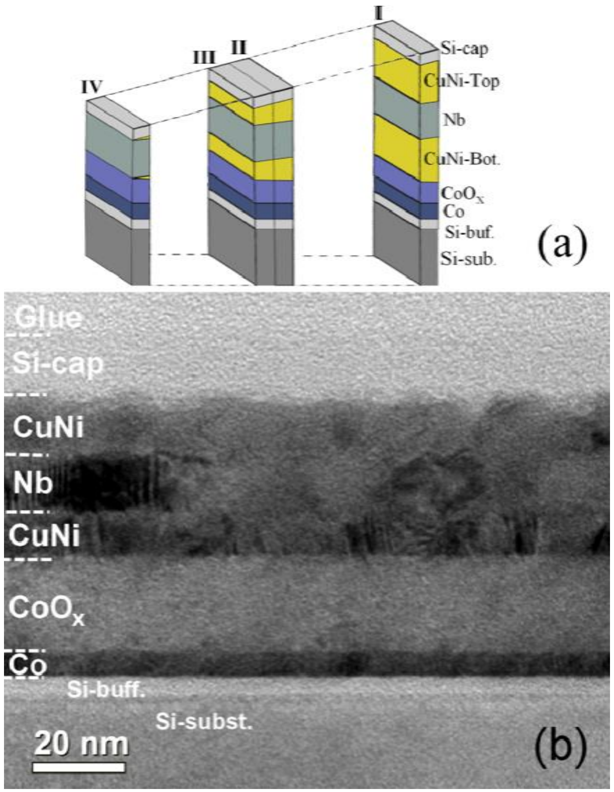
Calculation   Experiment

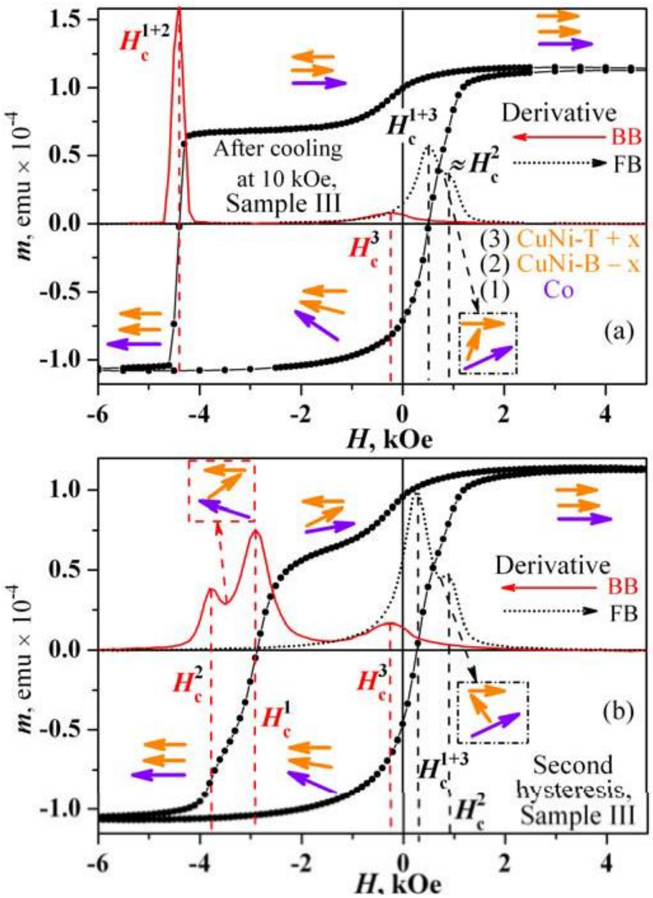


Phys.Rev.B87, 144507 (2013)

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

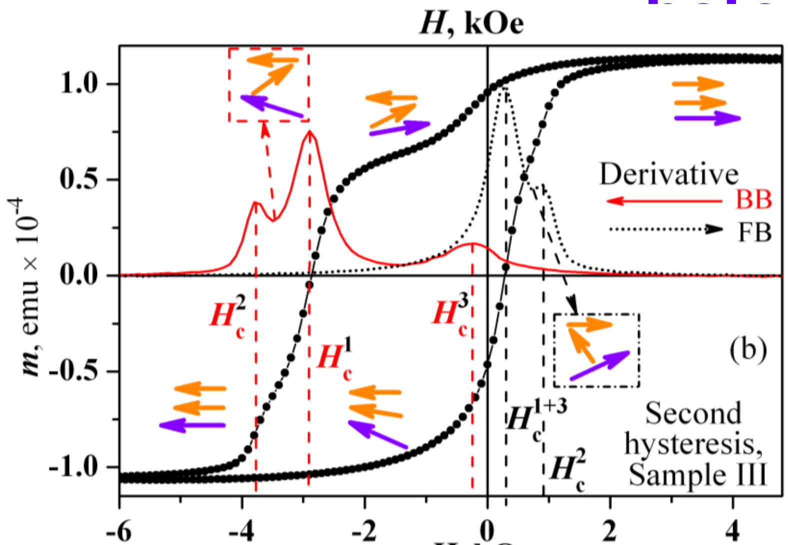
Memory effect in the superconducting $Co/CoO_x/Cu_{41}Ni_{59}/Nb/Cu_{41}Ni_{59}$ - layered heterostructure

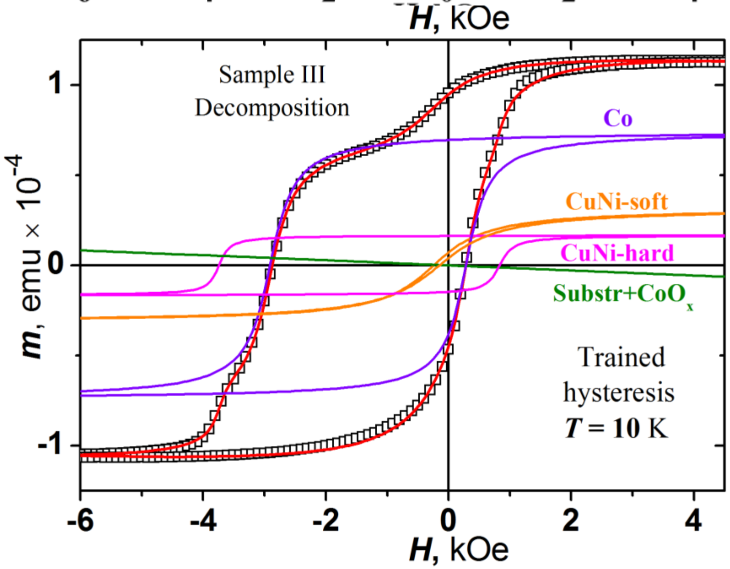




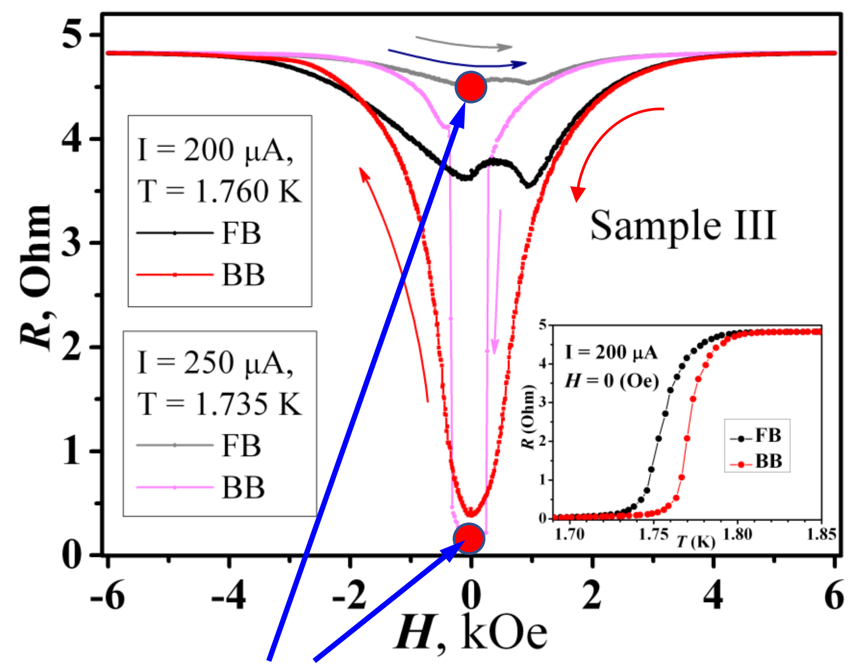
Strong exchange bias ($H_{EB} \approx$ -2 kOe), as well as the training effect - decrease of the hysteresis loop asymmetry, coercivity and squareness by further magnetic field cyclings.

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 .

Full Switching FSF-type Superconducting Spin-Triplet MRAM-Element

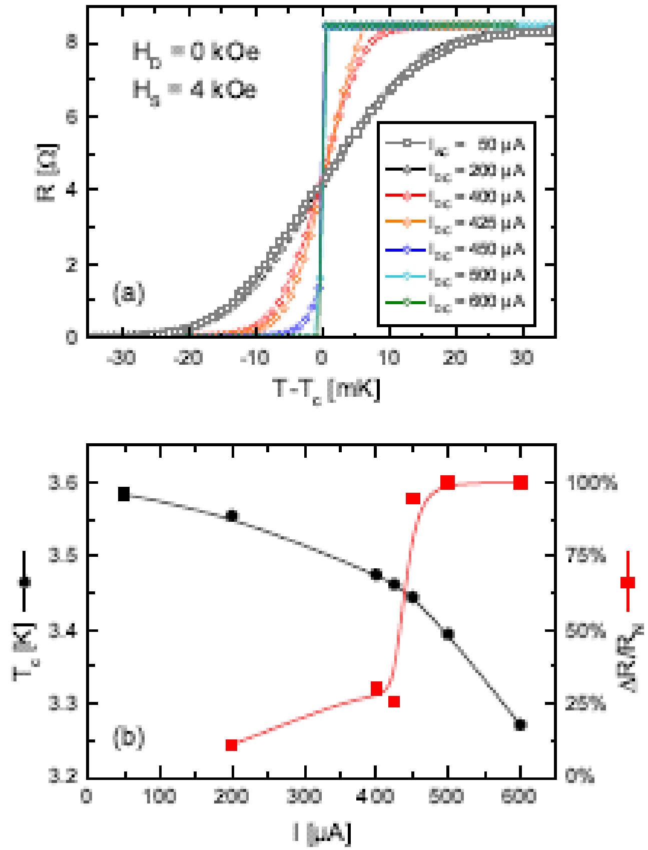


FIG. 5. (a) Superconducting transitions for zero detection field, H_D, and H_S = 4 kOe and various transport currents, I, plotted as a function of the temperature relative to the transition temperature, T_c. All transitions plotted have been recorded after increasing the applied field from $-H_S$ to H_D. There is an obvious sharpening of the transi-

Full Switching FSF-type Superconducting Spin-Triplet MRAM-Element

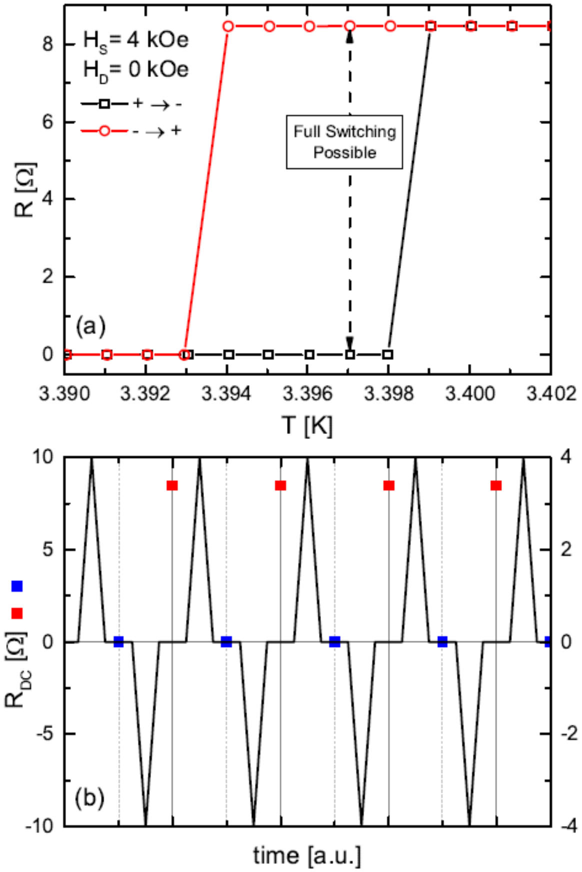


FIG. 8. (a) Superconducting $R(T)$ transition curves measured at zero magnetic field for decreasing and increasing H_D (black and red, respectively). Full switching from the superconducting to the normalconducting state is possible, as indicated *e.g.* at $T = 3.397$ K. (b) Demonstration of the switching between the normal state (red) and the superconducting state (blue) for zero applied magnetic field at $T = 3.397K$. The solid curve illustrates the magnetic field applied for the switching.

A.Sidorenko, V. Zdravkov, D. Lenk, R. Morari, et al. Full Switching FSF-type Superconducting Spin-Triplet MRAM-Element.

Phys. Rev. B **96**, 184521 (2017)

Giant spin-valve effect in Josephson contact with magnetic weak link

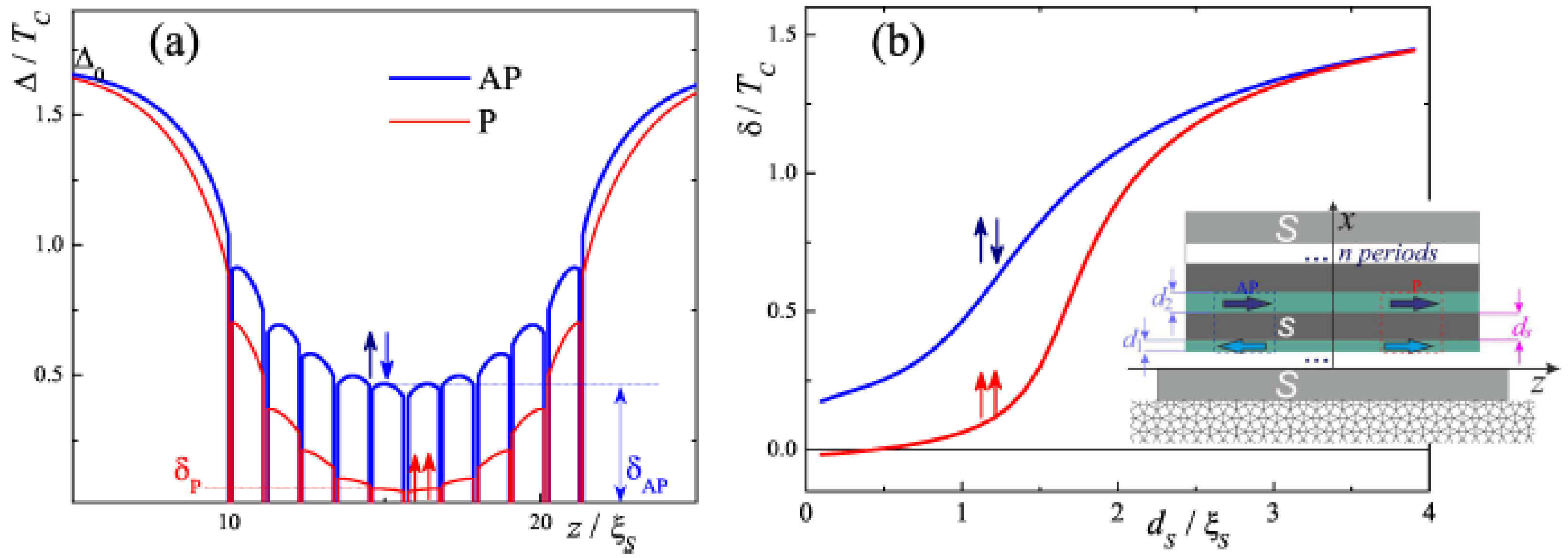
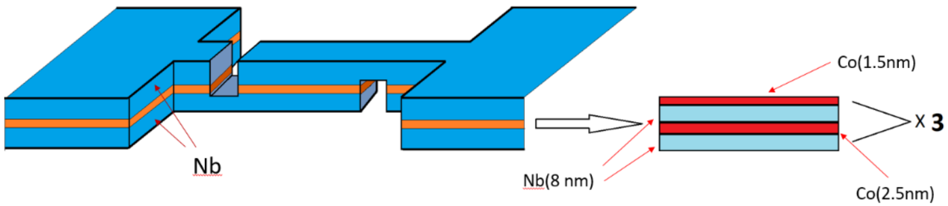
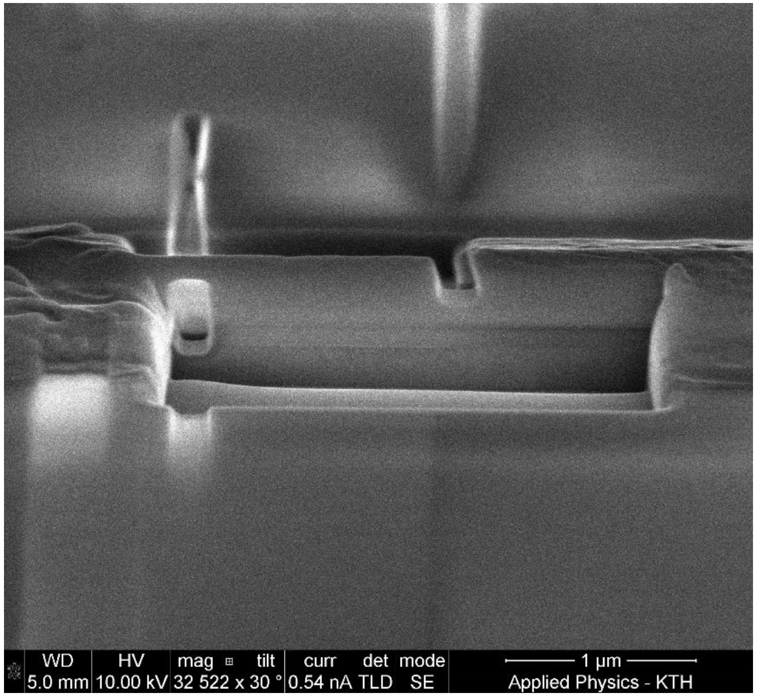


Figure 2: (a) The depth profile of the superconducting pair potential amplitude of the $S/[F_1/s/F_2/s]_5/F_1/S$ structure in the P and AP cases. (b) The amplitudes of the superconducting pair potential in the middle of the weak link for the same situations. Inset – schematic representation of the considered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

Fabrication of the Josephson-spin valve using Focused Ion Beam (FIB)-technology





Josephson spin valve - reflectometry with polarized neutrons

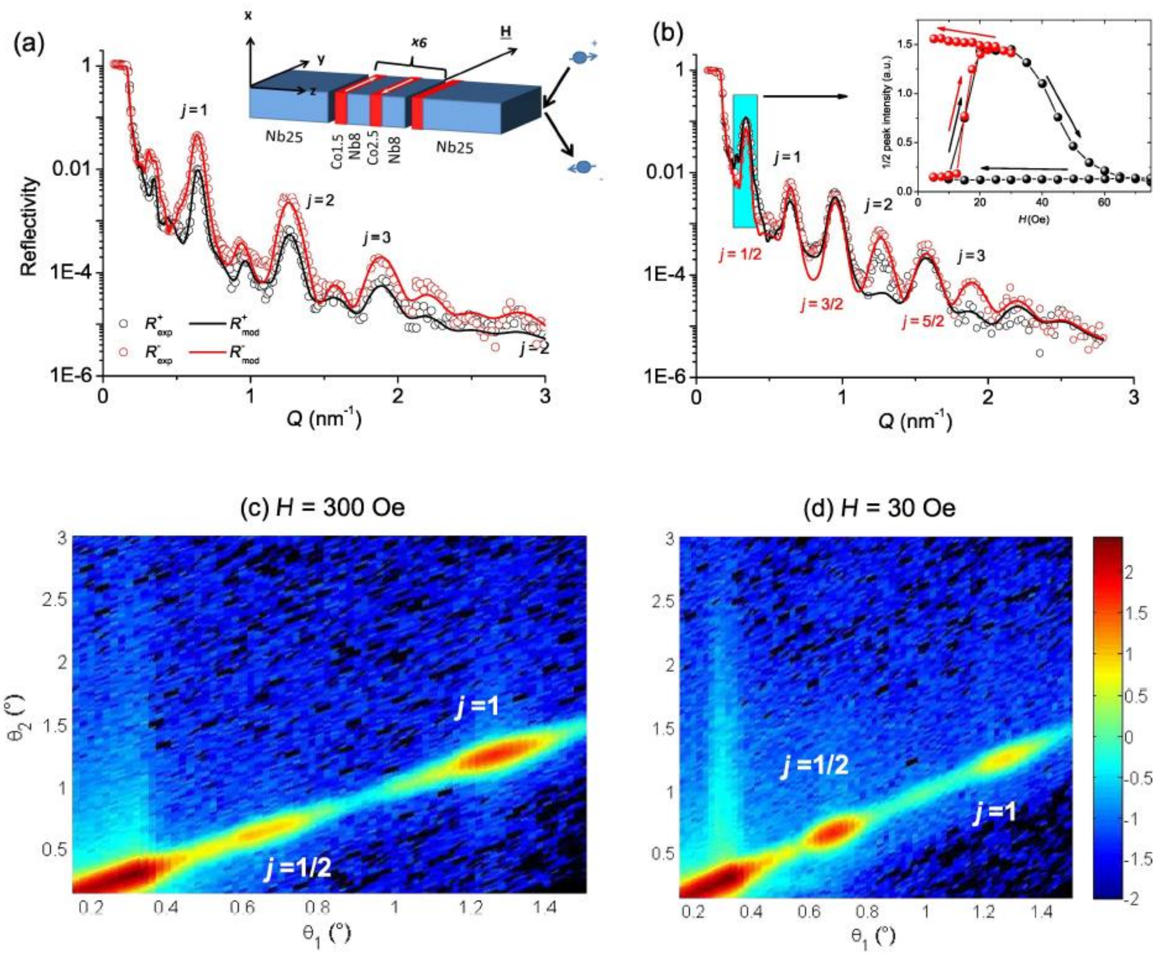


Figure 3: Experimental (dots) specular neutron reflectivity measured at T = 13 K in magnetic fields H = 300 Oe (a) and H = 30 Oe (b). Solid lines show the model curves for the magnetization depth profiles depicted in Figure 4a. The inset in (a) shows the sketch of the sample and experimental setup. The numbers above show the corresponding order of Bragg reflection from the effective [Co(2 nm)/Nb(8 nm)] × 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 Oe and H = 30 Oe is shown in (c) and (d).

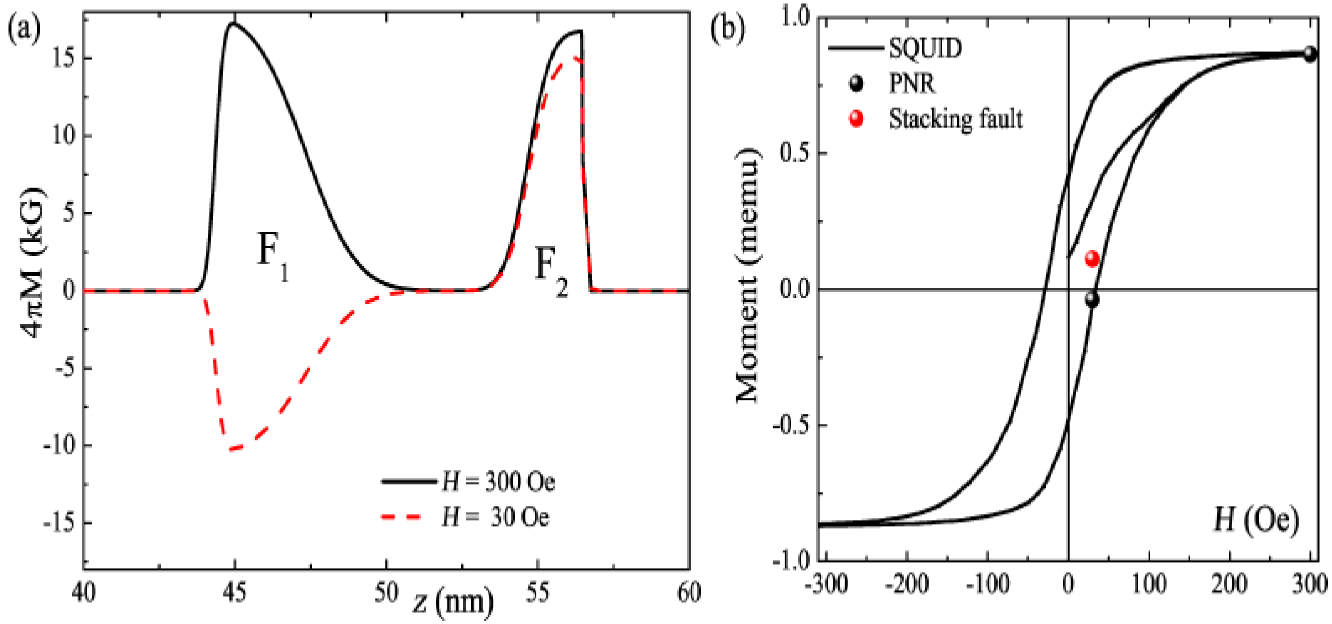


Figure 4: (a) Magnetic depth profiles of one unit cell for the P (black) and AP (red) alignment. Corresponding neutron curves are shown by solid lines in Figure 3a. (b) Hysteresis loop measured by SQUID magnetometry (solid line). The black dot indicates the magnetic moment of the sample which is obtained by the integration of the depth profiles depicted in (a). The red dot shows the magnetic moment at H = 30 Oe expected if one P segment were present in the AP aligned structure.

C O N C L U S I O N

1) Elaborated smart technology for S/F hybrid nanostructures fabrication,

2) Detected and investigated new phenomena ("memory effect", triplet spin-valve effect, crossover of the SFS Josephson contacts) serve as the base for development of superconducting spintronics and elaboration of non-von Neumann superconducting computer.

3) New experience and increased professional level of the IIEN personal as the result of staff-exchange visits of 11 researchers from IIEN to SU and UTWENTE

4) Obtained new fundamental results, their publication in two books and in high level Q1 journals (IF > 3), reporting at a number of conferences and workshops,

5) Increased visibility of the IIEN in scientific space due to permanent placement of all new information on the SPINTECH web page and IIEN web page .

6) IIEN gained in 2020 project of the State Program RM "Functional nanostructures and nanomaterials for industry and agriculture" 2020-2023.

- all that together led to clear boosting of excellence of IIEN in spintronics: Hirsh Index increased twice!