Спинтроника на сверхпроводящих системах

(*Сверхпроводящие наноструктуры для электроники будущего*)

Наталия Григорьевна Пугач

Доцент МИЭМ НИУ ВШЭ

Старший научный сотрудник НИИЯФ МГУ им. М.В. Ломоносова


Сверхпроводящие наноструктуры
Криогенная электроника (RSFQ),
Джозефсоника
Квантовая логика
Сверхпроводящая спинтроника

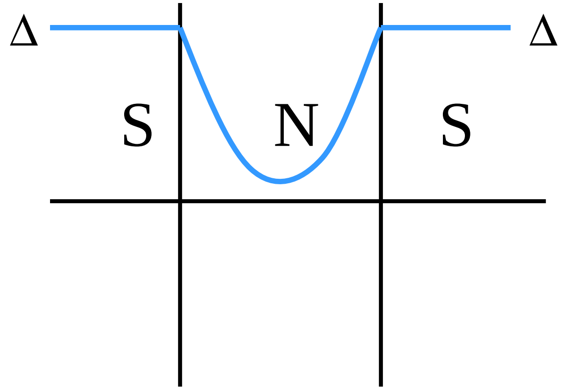
Эффект Джозефсона

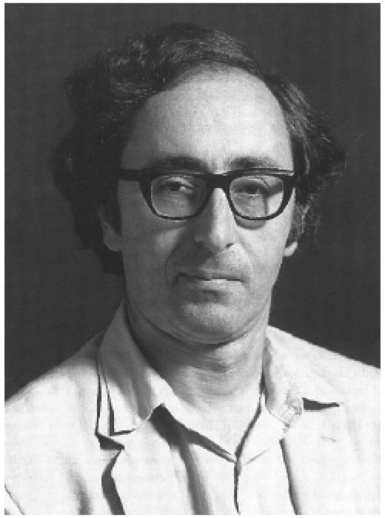
Джозефсоновский переход

сверхпроводник

туннельный барьер

сверхпроводник





Брайан Джозефсон
(Brian Josephson)
1962 г.

Уравнения Джозефсона

$$\begin{cases} I_S = I_C \sin\varphi \\ V = \dfrac{\Phi_0}{2\pi}\dfrac{d\varphi}{dt} \end{cases}$$

$$\Phi_0 = \frac{h}{2e} \approx 2.07\times10^{-15}\,\mathrm{V}\cdot\mathrm{s}$$

квант магнитного потока

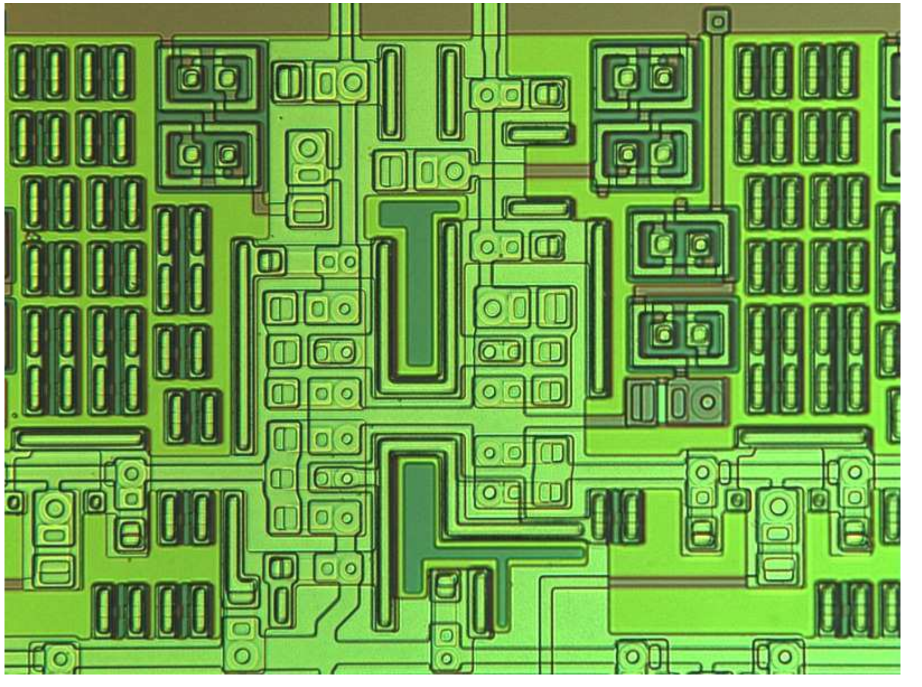
Компьютеры на сверхпроводниках

К. К. Лихарев

В. К. Семенов

K. K. Likharev and V. K. Semenov,
IEEE Trans. Appl. Supercon. **1**, 3 (1991)

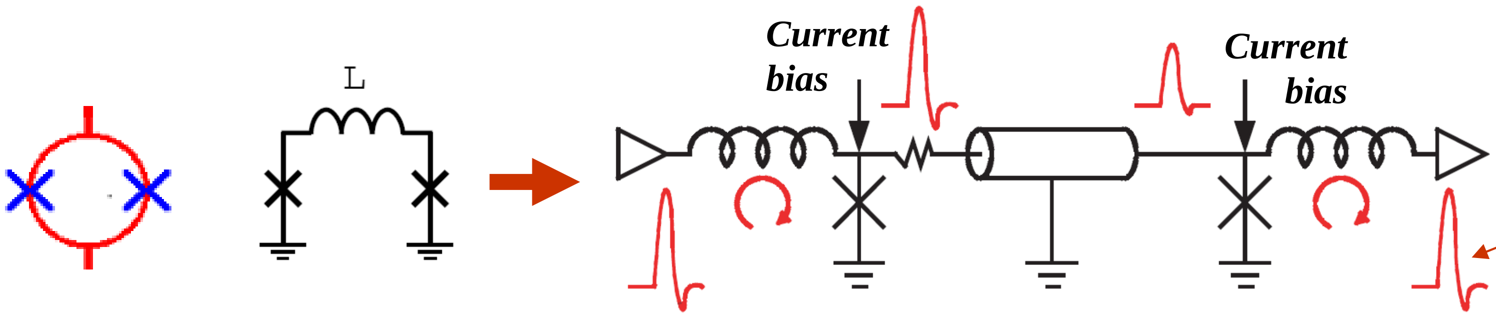
сверхпроводящая цифровая логика



придумано в России

Rapid **S**ingle **F**lux **Q**uantum logic = **RSFQ** logic

RSFQ-logic principles

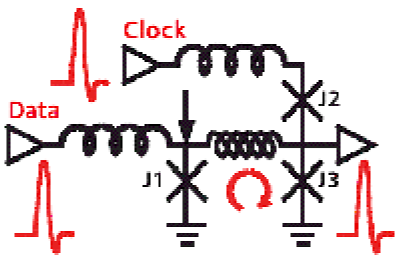


$\int V dt = \Phi_0$

$LI_c > \Phi_0$

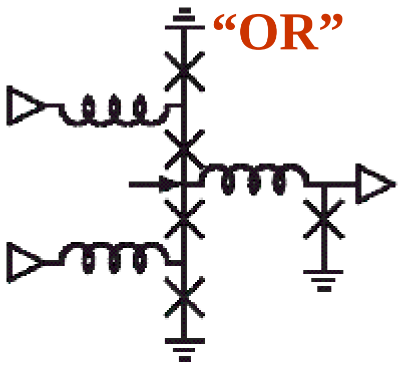
$j_c \sim 1$ кА/см^2

Passive Josephson transmission line for picosecond SFQ-pulses

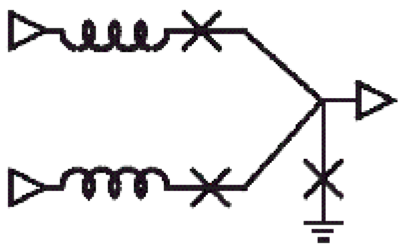


data register

“OR”



“AND

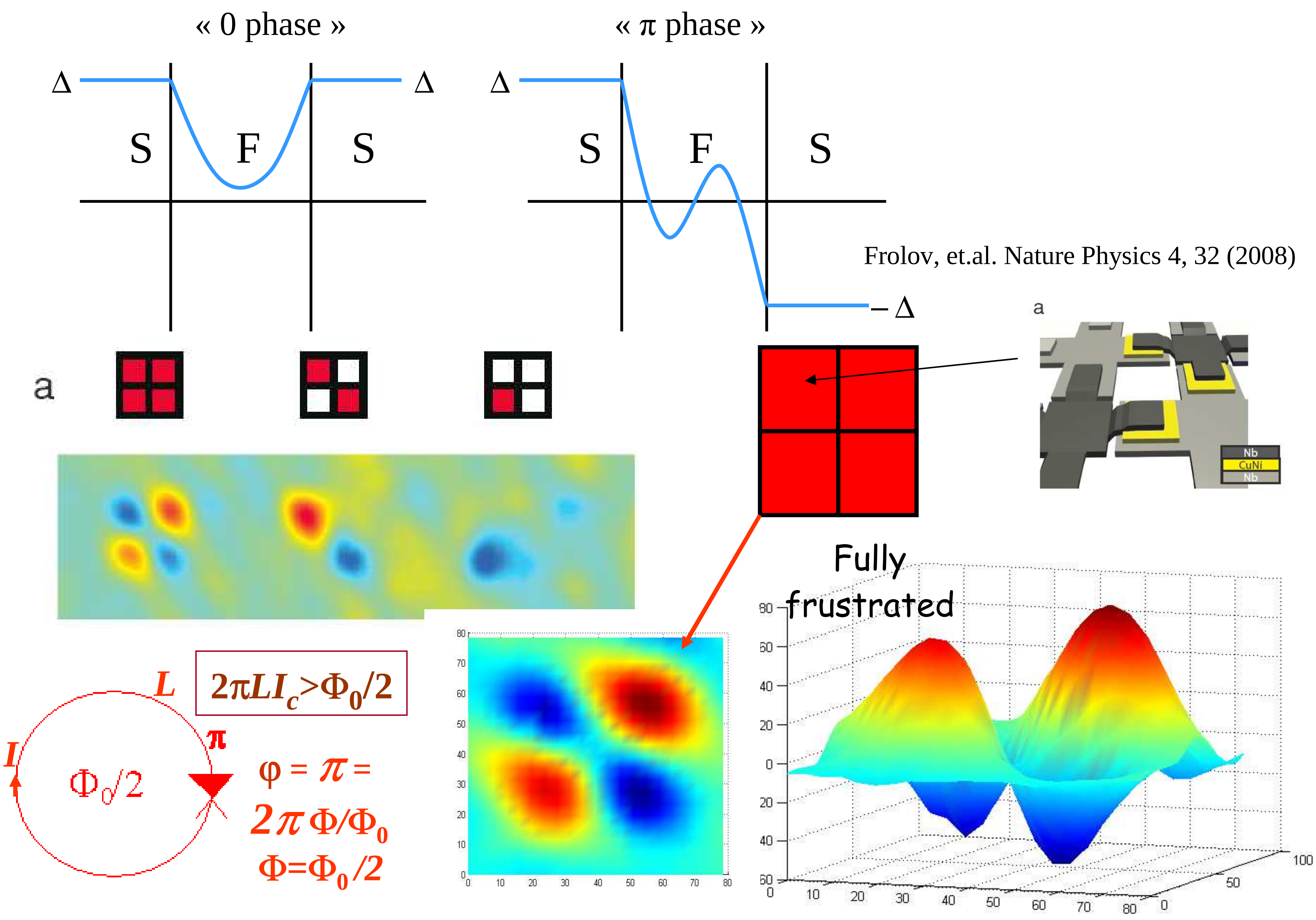


K.K. Likharev, O.A. Mukhanov, and V.K. Semenov, SQUID’85, pp.1103, Germany (1985);

K.K. Likharev and V.K. Semenov, IEEE Trans. Appl. Supercond. 1, 3 (1991);

V.P. Koshelets, K.K. Likharev et al., IEEE Trans. Magn. 23, 755 (1987)

Пи – контакт (с ферромагнитной связью)



Superconducting digital electronics

Started in Russia in 1985:

RSFQ –logic (Rapid Single Flux Quantum logic)

Based on storage of the magnetic flux quanta $\Phi_0 = h/(2e) = 2.07\times10{-}15$ Wb

- **Josephson magnetic memory based on the SFS junction (MJJ)**
- **Complementary classical π-SFQ-cell and π-SFQ- Toggle Flip-Flop**
- **RSFQ-logic operations**
- **Superconducting data lines**

Advantages:

High frequencies: 20 - 700 GHz

Ultra-low power, can be used for reversible computing

All these achievements may present a base for the development of the new type of advanced electronics – cryogenic nanoelectronics

IARPA Cryogenic Computing Complexity (C3) Program

(IARPA – Intelligence Advanced Research Project Activity)

USA

C3 is a five-year, two-phase program.

Phase one (first three years): to develop the technologies that are required to demonstrate a small superconducting processor.

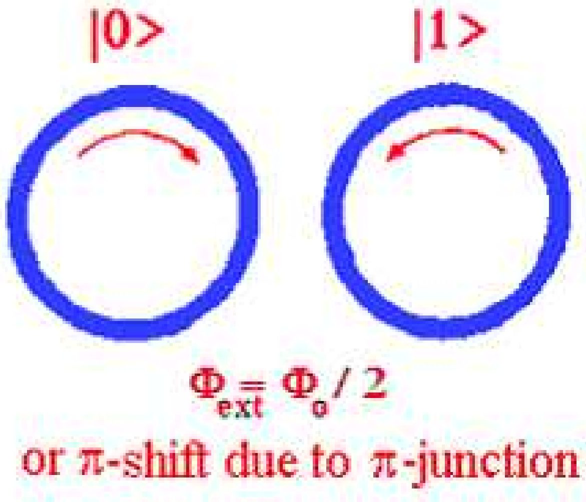
Phase two: to integrate those new technologies into small-scale working model of a superconducting computer.

C3 Program thrust will include:

1.Cryogenic memory: New approaches to enable high performance computing systems with greatly improved memory capacity and energy efficiency.

2.Logic, communications and systems: Development of advanced superconducting circuits and integration with memory and other components for demonstration of a limited superconducting computer system on which to measure performance metrics.

Сверхпроводящий кубит (тихий)



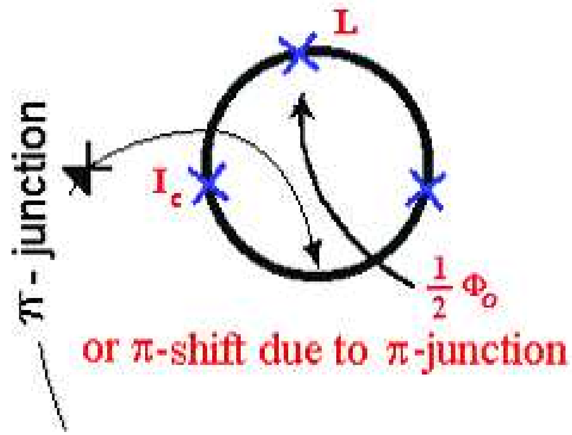
классический бит (бит)

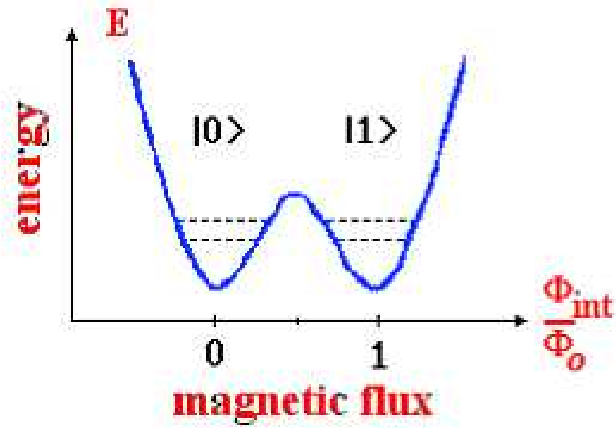
$$|\Psi\rangle = |0\rangle, \quad |\Psi\rangle = |1\rangle$$

волновая функция квантового бита

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

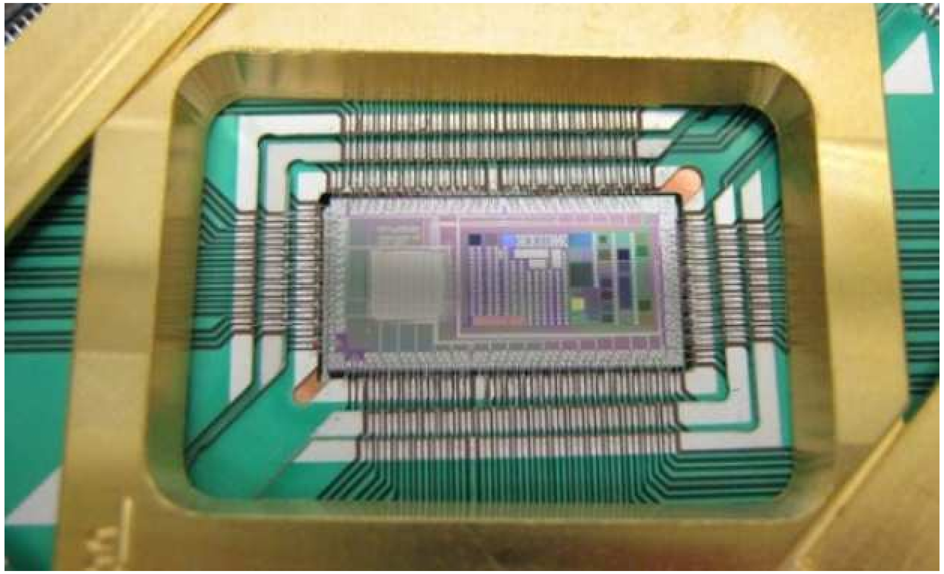
суперпозиция состояний -> параллелизм





Пока единственная реализация квантового компьютера (D-wave)

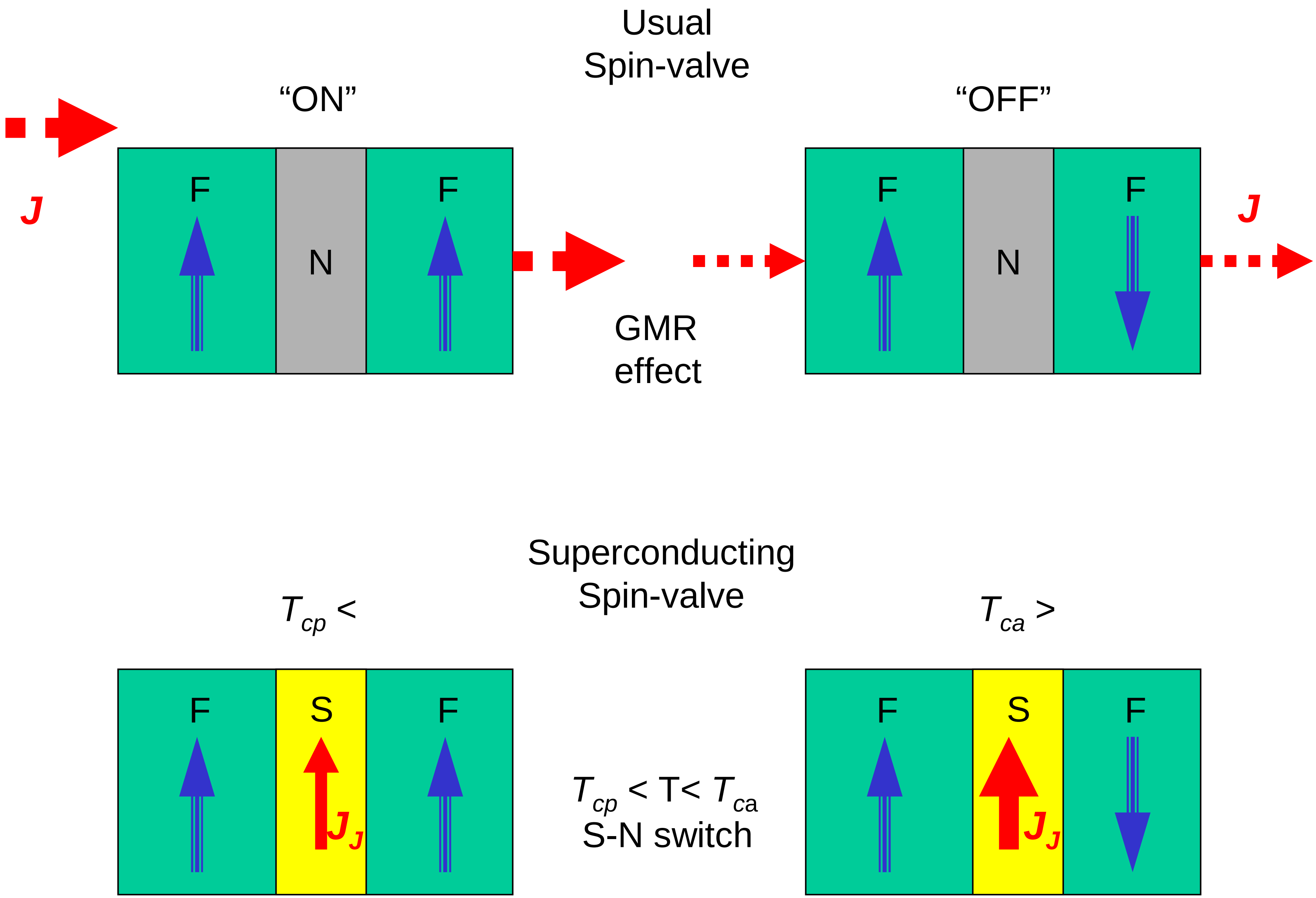
«Квантовый компьютер» компании D-Wave



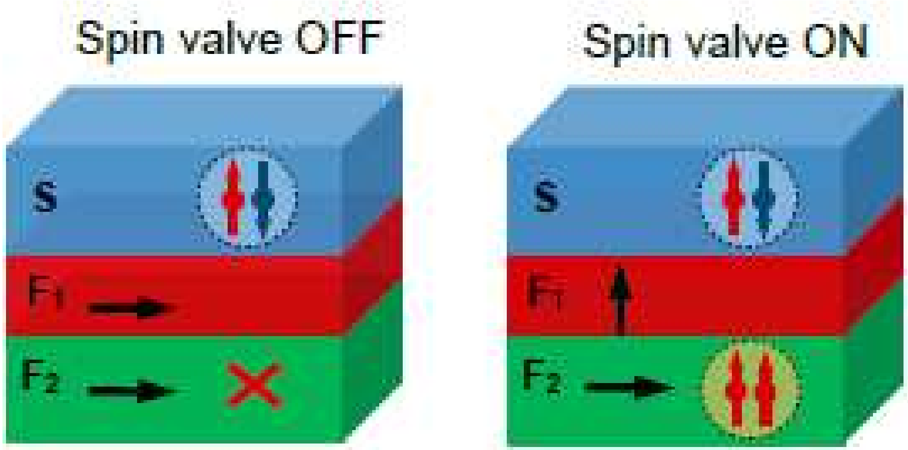
adiabatic quantum annealer

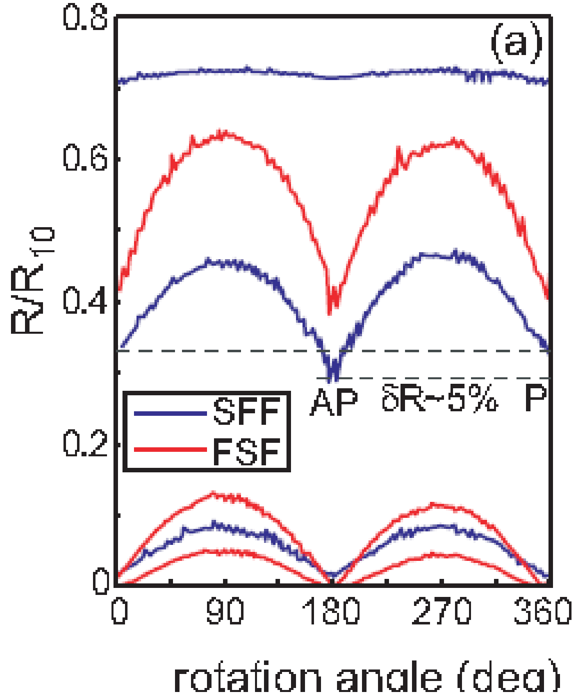
«Квантовый компьютер» D-Wave купили Lockheed Martin, NASA, Google, и др.

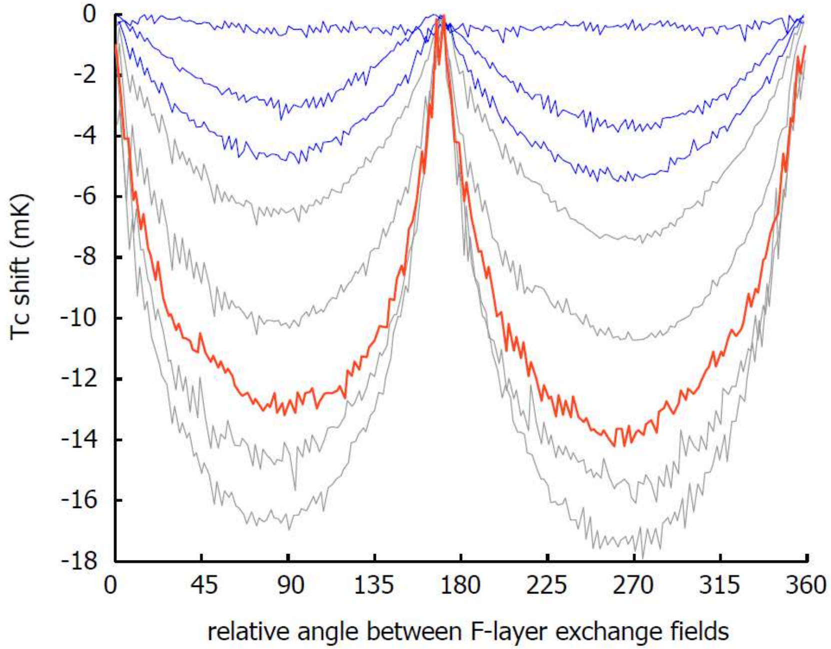
Сверхпроводниковая спинтроника



SFF Spin-valves





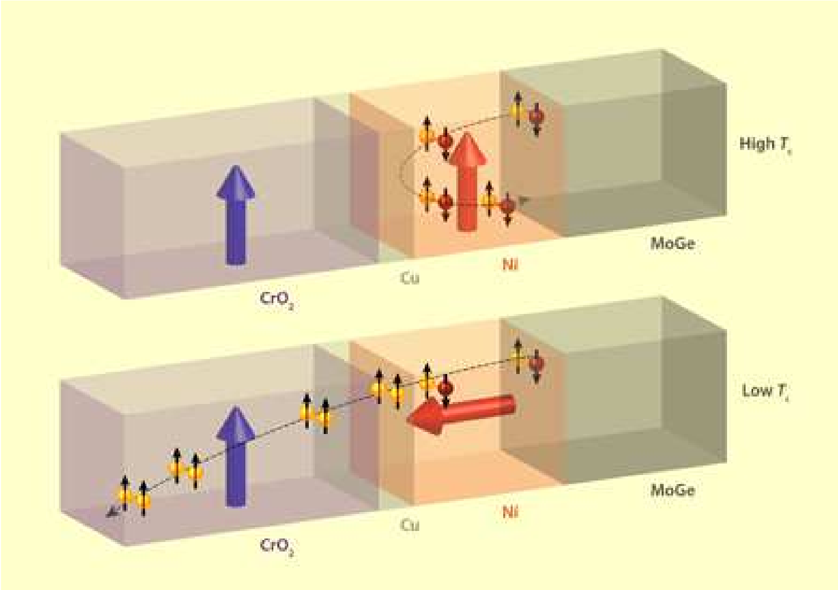


M. G. Flokstra, T. C. Cunningham, J. Kim N. Satchell, G. Burnell, P. J. Curran, S. J. Bending, C. J. Kinane, J. F. K. Cooper, S. Langridge, A. Isidori, **N. Pugach**, M. Eschrig, and S. L. Lee.

PRB 91, 060501(R) (2015)

Appl. Phys. Lett. 107, 262602 (2015)

Nature Phys. 12, 57 (2016).

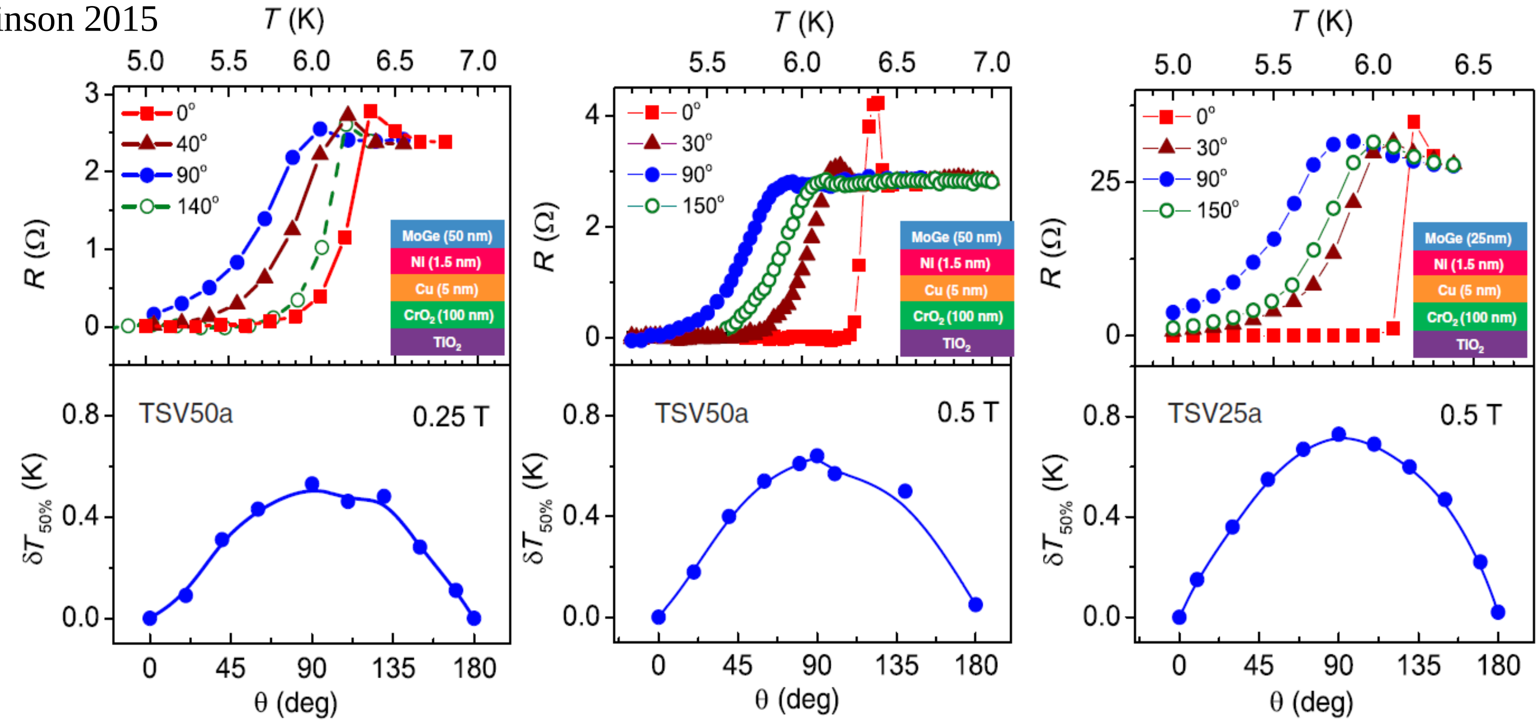


“Giant” spin-valve effect

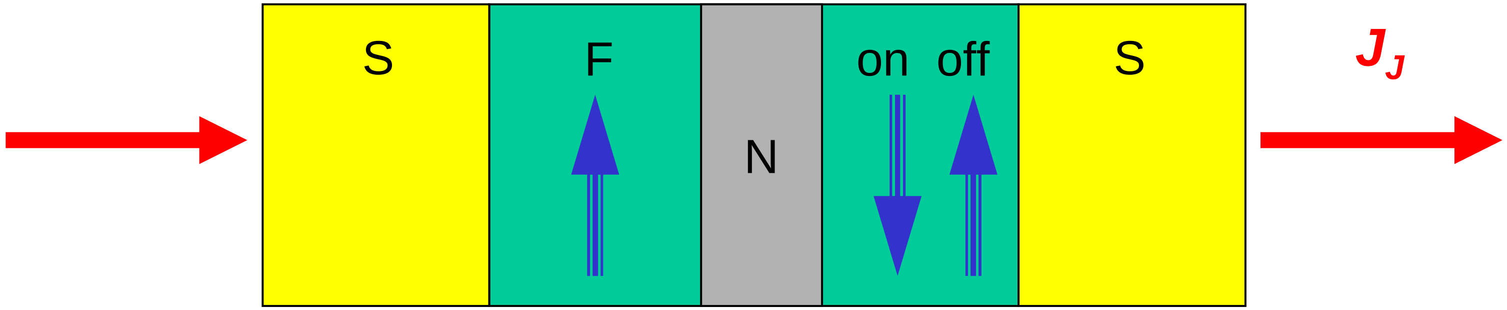
Half-metallic ferromagnet CrO_2

A. Singh, S. Voltan, K. Lahabi, J. Aarts, PRX 5, 021019 (2015)

CrO_2/Cu/Ni/MoGe



Josephson spin valves



Controllable Josephson effect

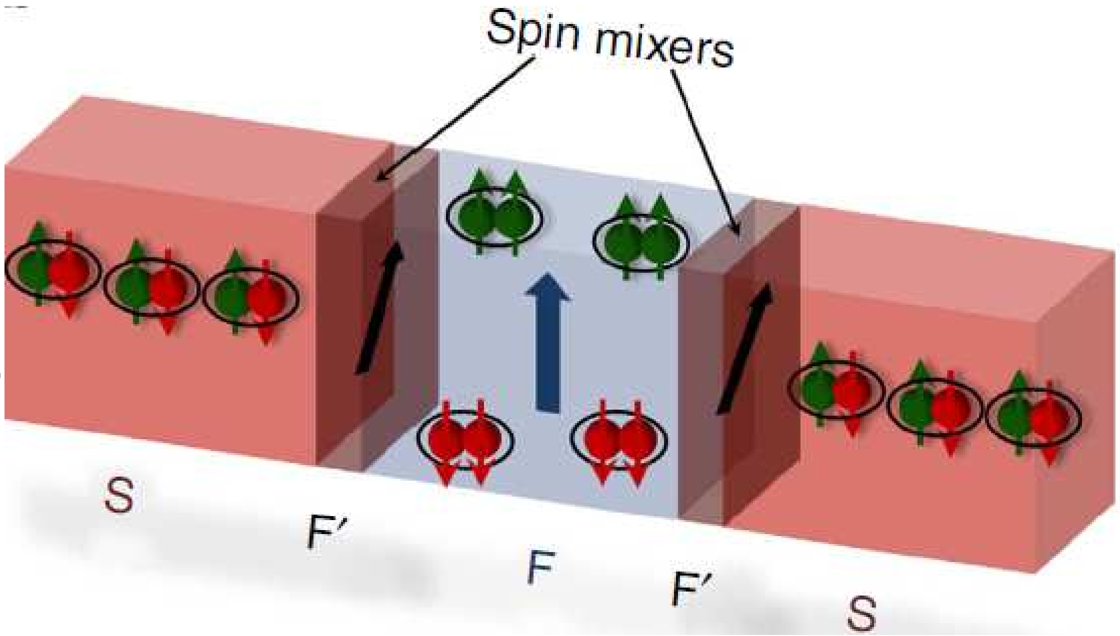
A. Vedyayev, C. Lacroix, N. Pugach and N. Ryzhanova. Europhys. Lett. **71**, 679 (2005).
Spin-valve magnetic sandwich in a Josephson junction

Эксперименты:

Iovan, T. Golod, and V. M. Krasnov.
PRB 90, 134514 (2014) “Scissors” **SFFS**

N. Banerjee, J.W.A. Robinson, M.G. Blamire,
Nature Comm. 5, 4771 (2014). **SFFFS**

W. Martinez, W.P. Pratt, Jr., N. O. Birge,
arXiv:1510.02144 (2015) **SF…F”…FS**



Spiral superconducting spin valve

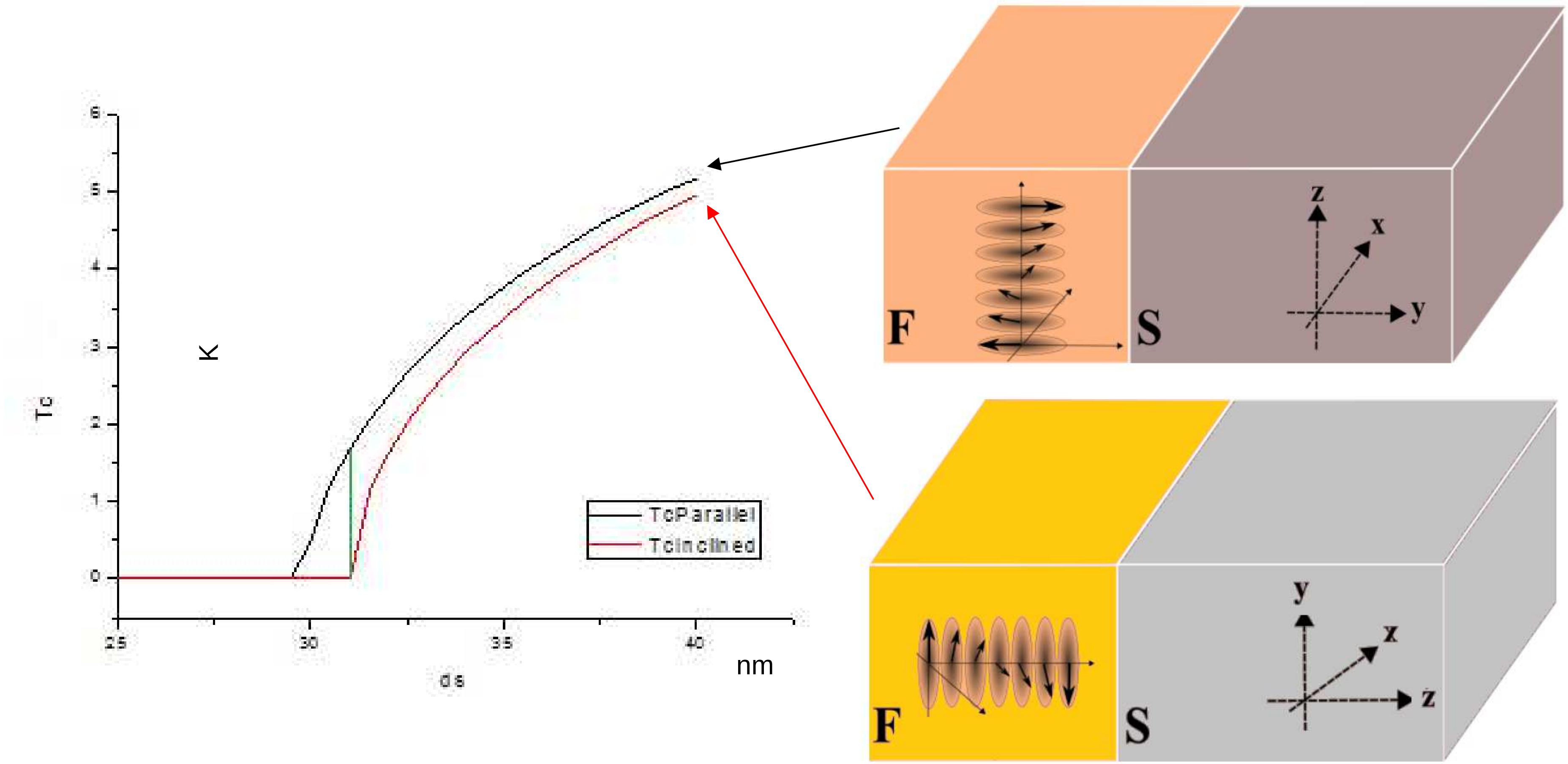
MnSi family compounds (CoSi, FeCoSi, MnGe, FeGe, MnFeGe)

Cubic and complex noncentrosymmetric crystal lattice => DM SO interaction

Magnetic spiral may be realized in 3 equivalent directions (111), (1-11), (-1-11)

λ~18nm (MnSi)>>ξ_f

The spiral direction may be switched => LRTC switch => T_c change

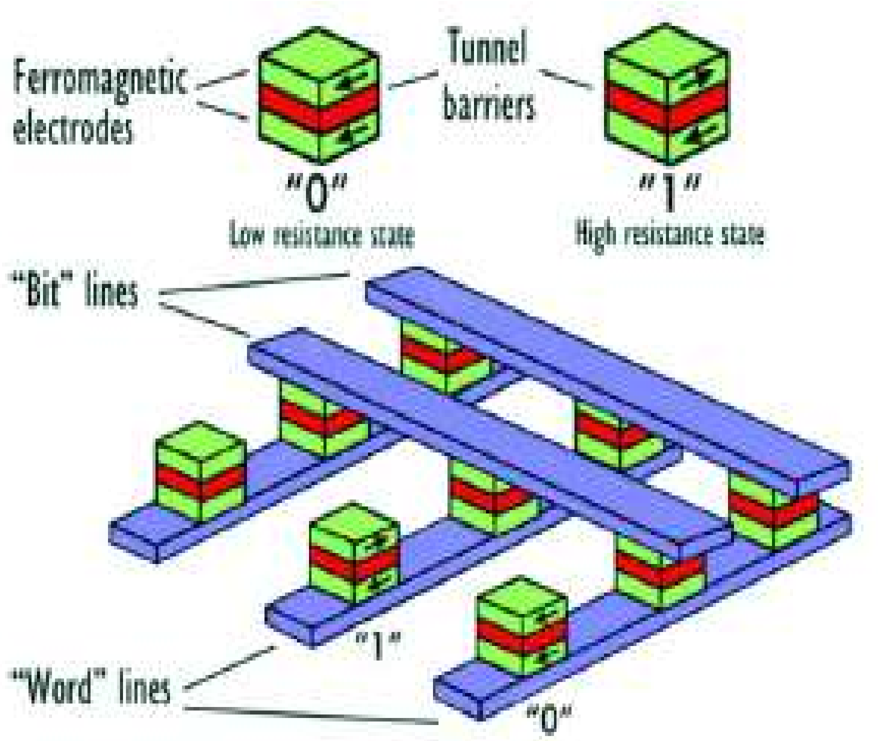


Advantages of spiral SSV as a memory element

• simple structure (bilayer with a bulk magnetic material)

• T_c change may be appreciable ~ 1K

• **half-select problem** solution



Savchenko scheme
In production from 2006

Очень красивая физика (теория)

* Теория сверхпроводимости

* Макроскопическое квантовое туннеллирование (эффект Джозефсона)

* Антагонизм и сосуществование сверхпроводимости и магнетизма

* Триплетная сверхпроводимость

Наталия Григорьевна Пугач

Старший научный сотрудник НИИЯФ МГУ им. М.В. Ломоносова

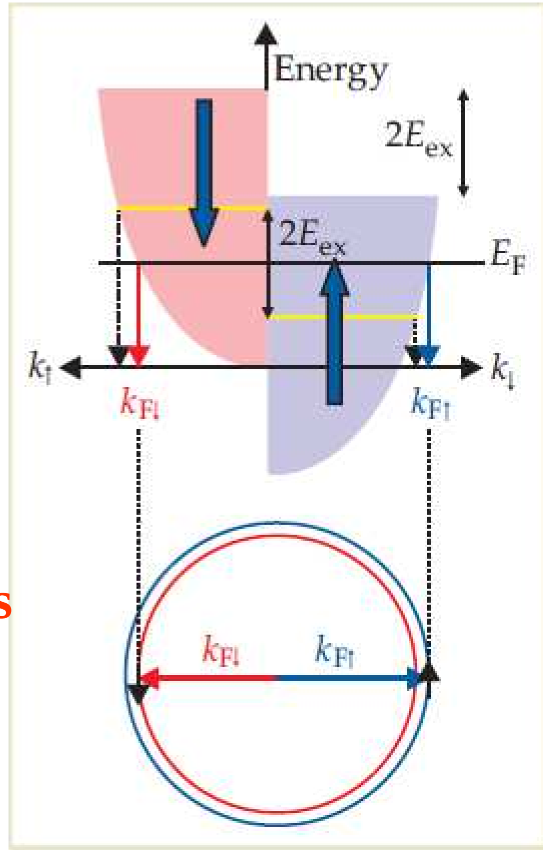
Доцент МИЭМ ВШЭ, комн.102,423 Чт, Пт

http://istina.msu.ru/profile/pugach/

e-mail: pugach@magn.ru, npugach@hse.ru

Тел. +7 915 26 111 84

SF proximity effect and FFLO states

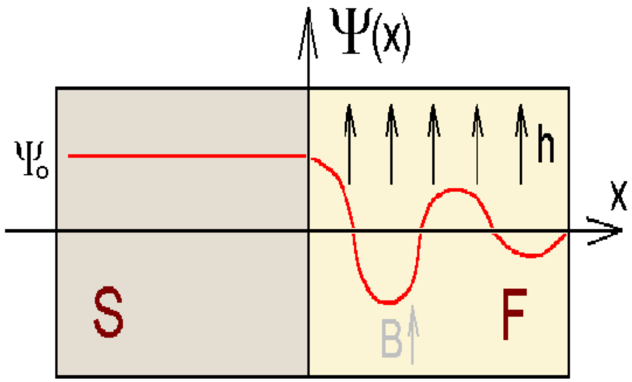


What happens when the Cooper pair ↑↓ penetrates into F?
In F the sum momentum of the pair ↑↓ cannot be zero.
$k_{F\uparrow} \neq k_{F\downarrow}$, $k_{F\uparrow} - k_{F\downarrow} \sim h$, ***h*** - exchange field, $\mu_B \boldsymbol{h} > \Delta$,
nonzero pair momentum

Non-uniform superconducting order parameter in F

$$\Psi = \Psi_0 \cos(Qr),$$

Q *is wave-vector*, **Q ~ *h*/*v*$_F$,**

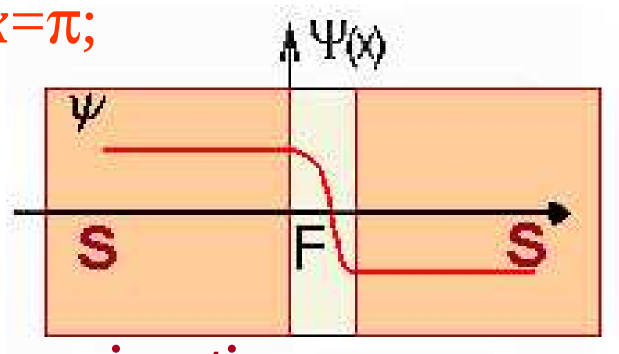


spatially nonuniform states

Fulde, Ferrel (1964),

Larkin, Ovchinnikov (1964)

Q*x*=π;



π-junction

Does the exchange magnetic field strongly suppresses the BCS correlation and destroys the Cooper pairs in F?

It is true, but not whole.

Nonuniform exchange field may produce the spin triplet (↑↑) superconducting correlation!

*A.F. Volkov PRB (2001)