# Physical principles of organization of superconducting memory elements

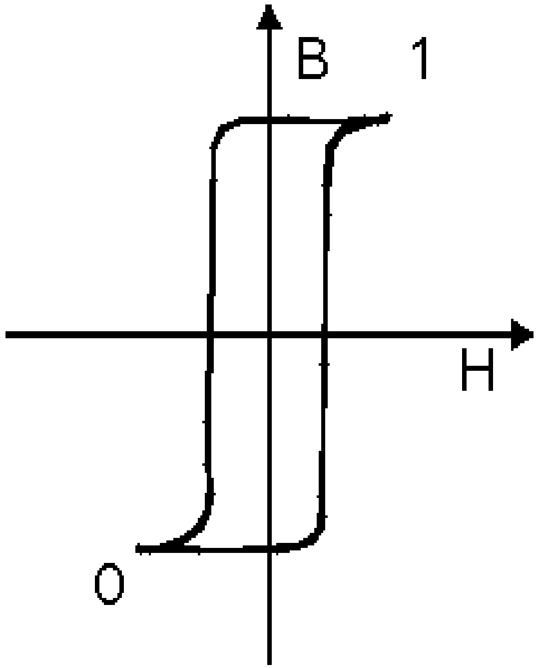
S. V. Bakurskiy

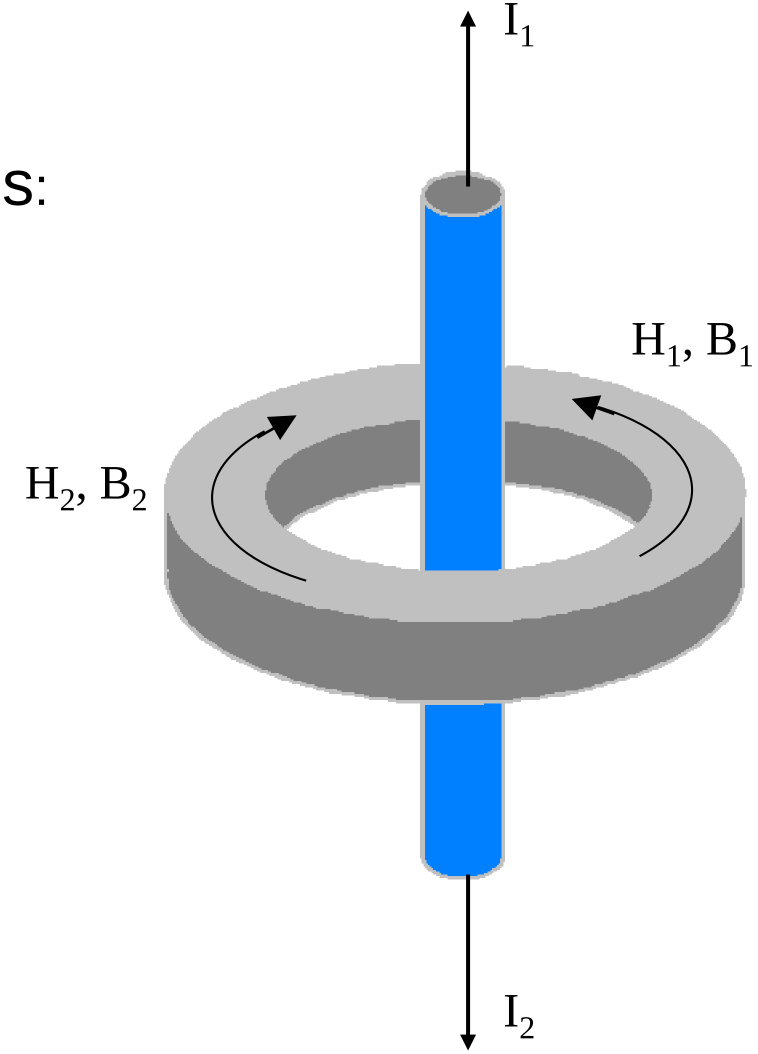
Contents:

- Memory in personal computer in your room
- Spin-valve superconducting memory
- SFQ memory
- Superconducting phase memory

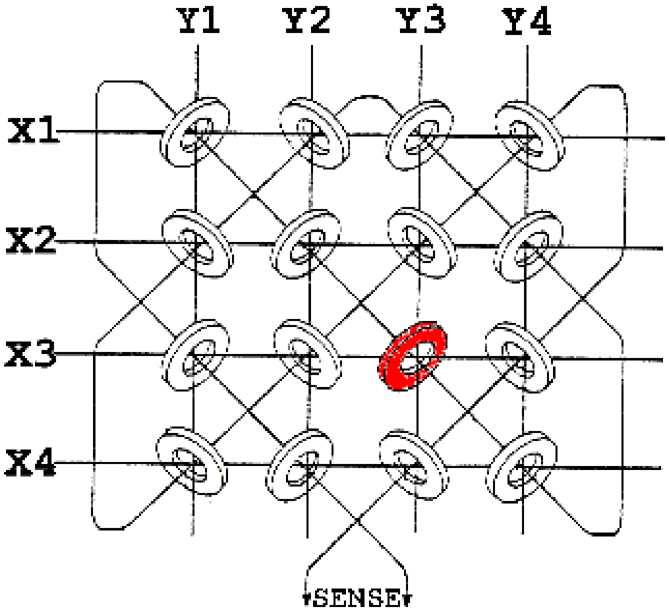
# Magnetic core memory: 1955-1975

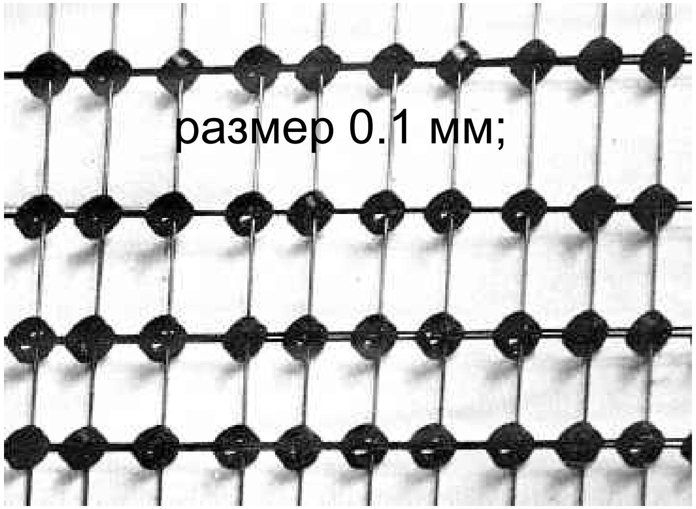
Ferrit magnetic torroids:



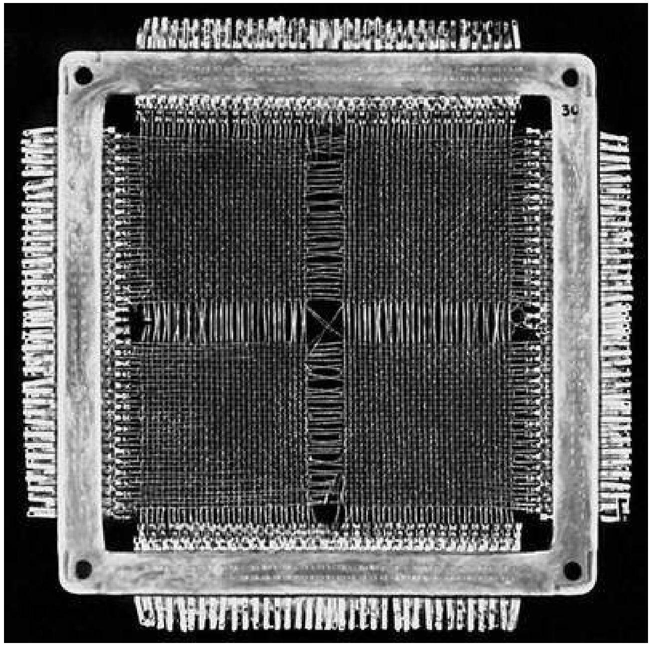


# Magnetic core memory: 1955-1975





размер 0.1 мм;



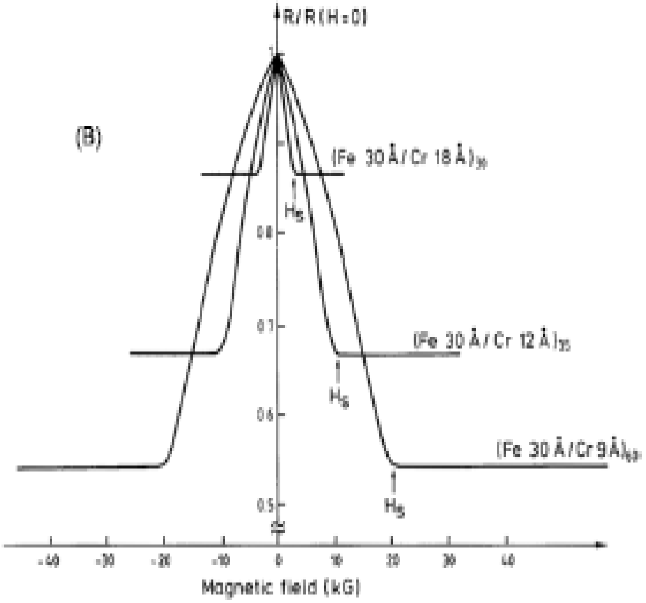
Matrix: N^2 cells require 2 N wires

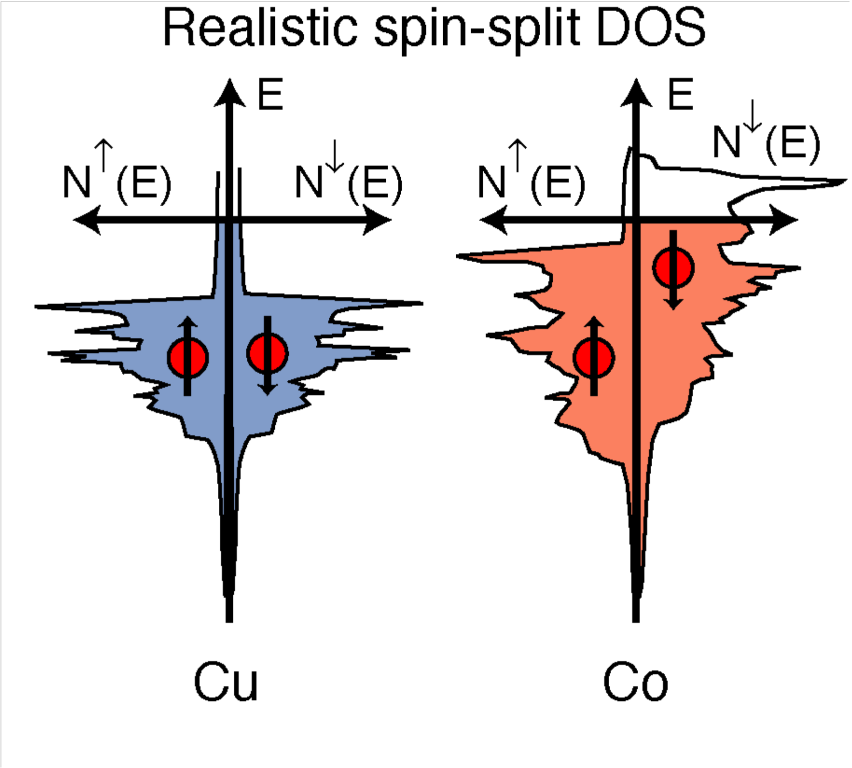
Destroying Read operation.

Operational Time ~ 1 μs

Density ~ 10 bits/mm$^2$

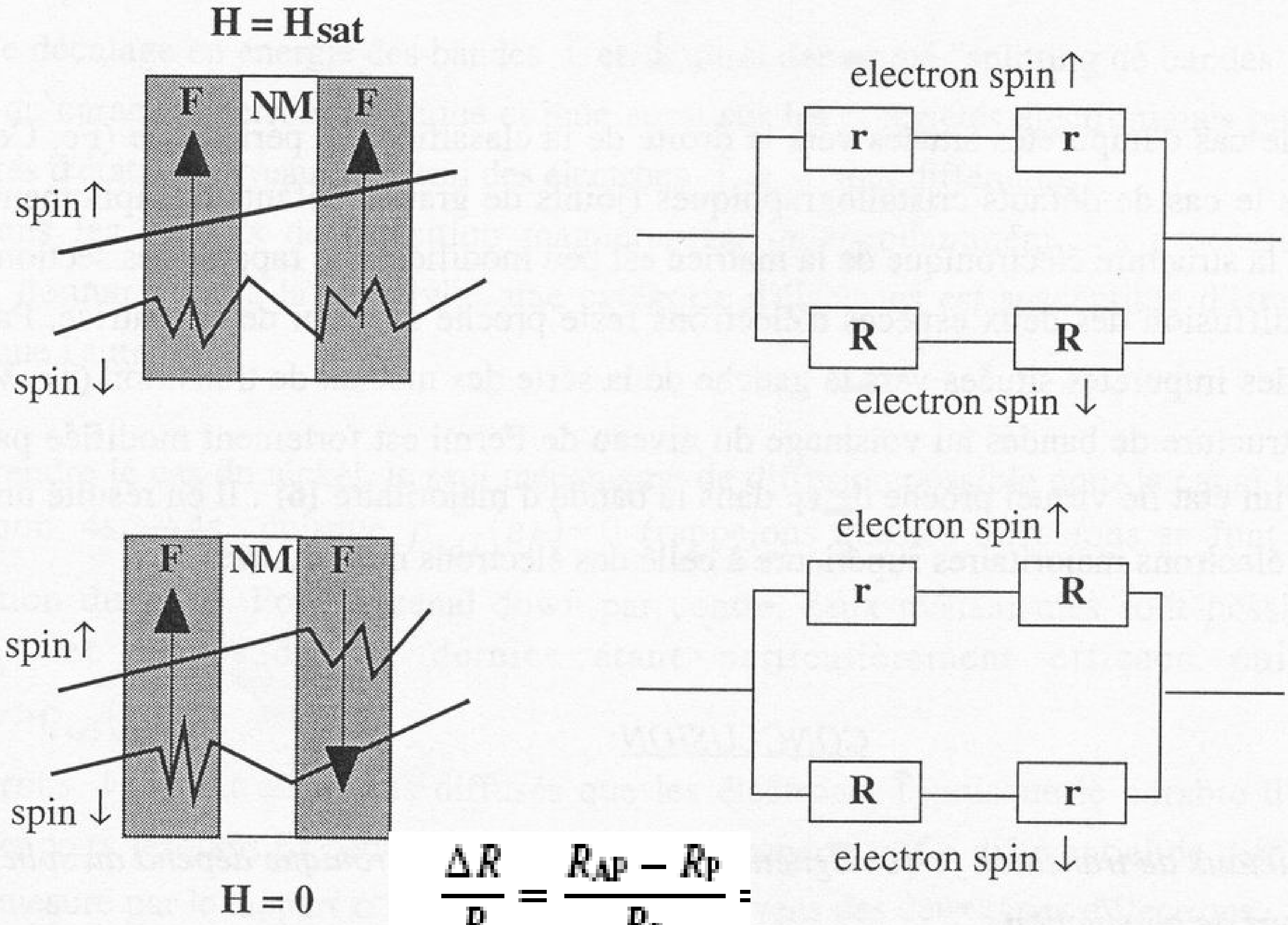
# Giant magnetoresistance (GMR) effect





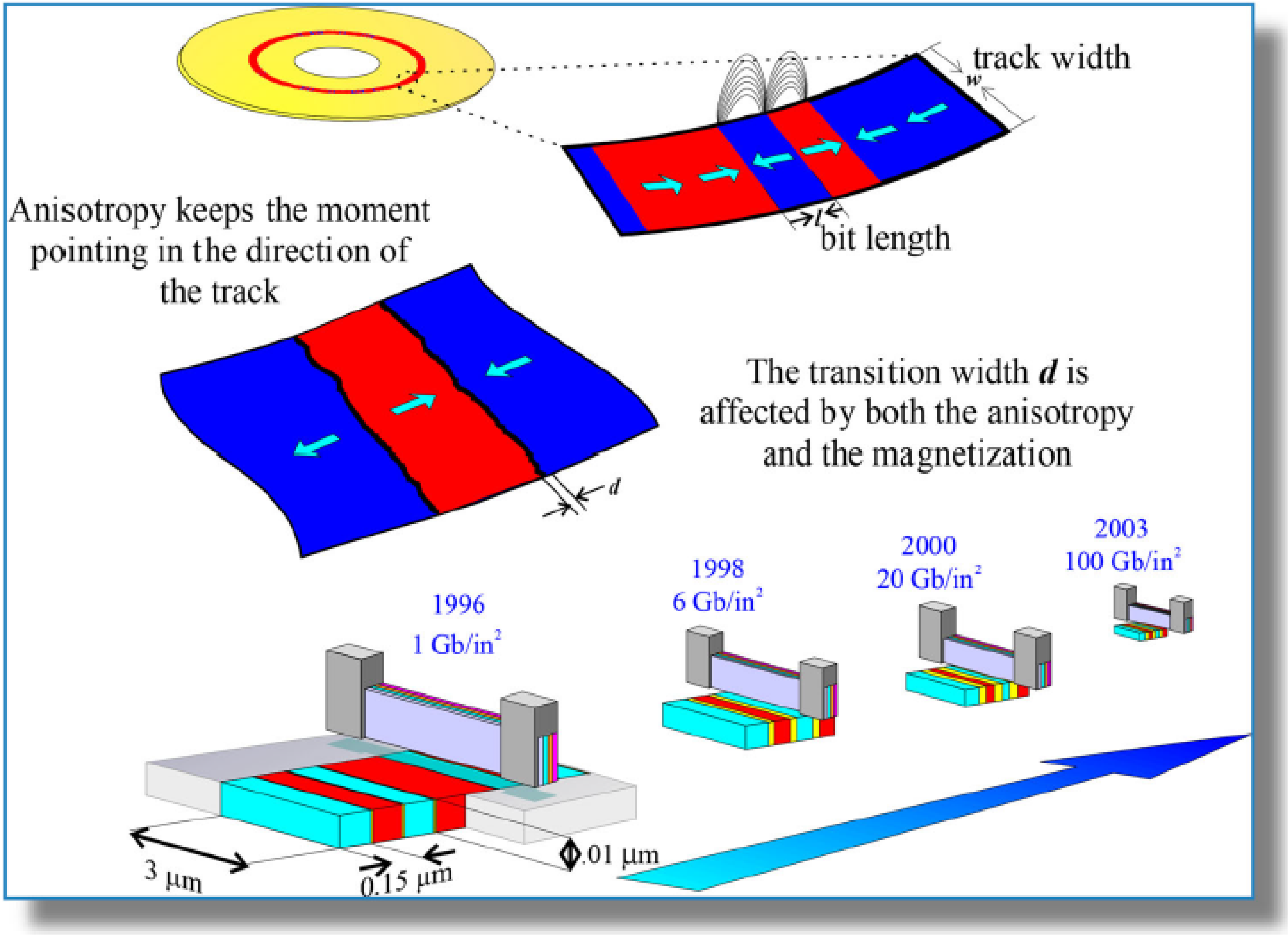
GMR - A.Fert and P. Gruinberg (1987)
Nobel prize 2007

# Giant magnetoresistance (GMR) effect



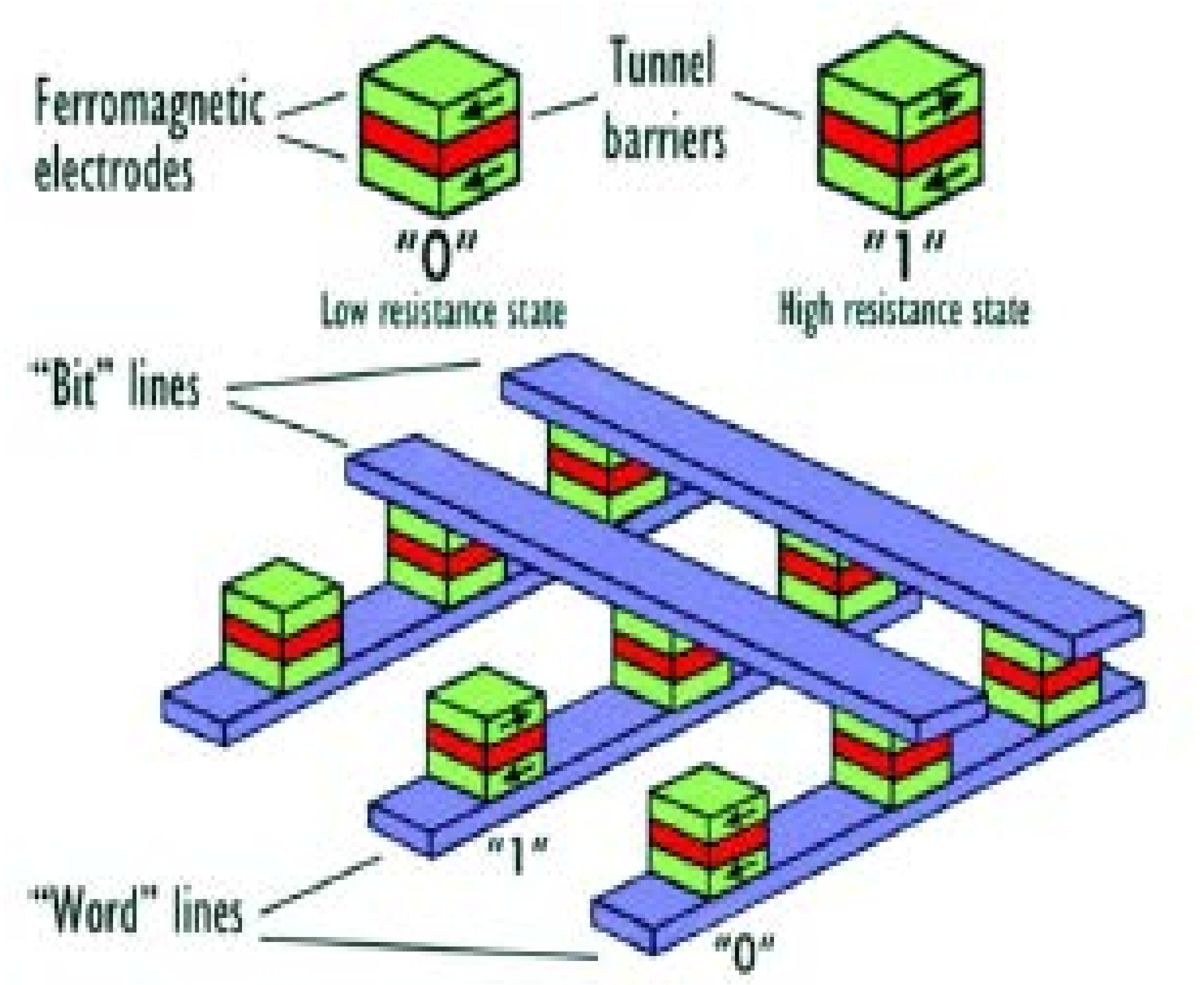
$$\frac{\Delta R}{R} = \frac{R_{AP} - R_{P}}{R_{P}} =$$

# Hard drive disk (HDD)

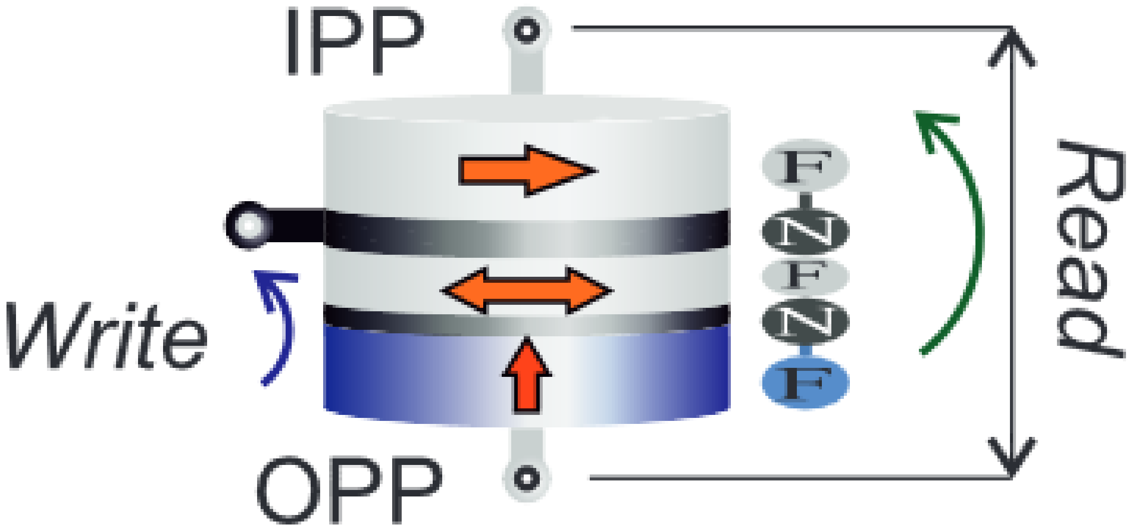


*J. W. Lu, E. Chen, M. Kabir, M. R. Stan & S. A. Wolf (2016) Spintronics technology: past, present and future, International Materials Reviews, 61:7, 456-472*

# Magnetic Random Access Memory (MRAM)



# Spin torque devices



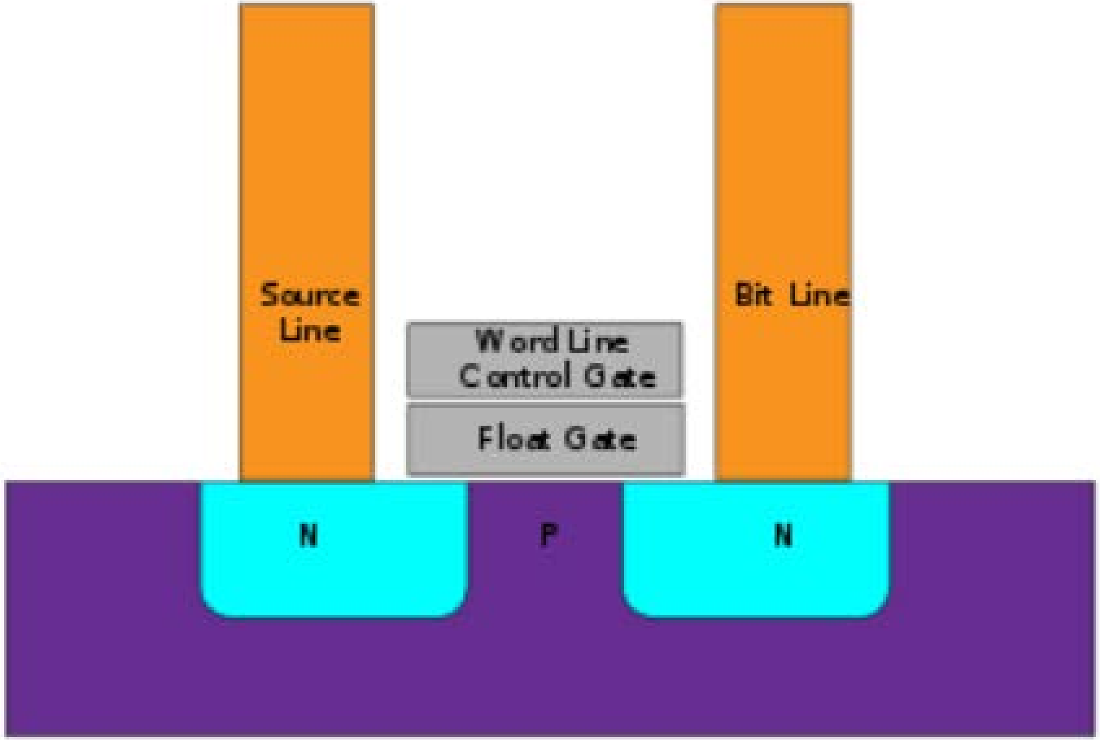
Schematic representation of OST device.

## Landau–Lifshitz–Gilbert equation

$$\frac{d\mathbf{M}}{dt} = -\gamma\left(\mathbf{M}\times\mathbf{H}_{\text{eff}} - \eta\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

Fast deterministic switching in orthogonal spin torque devices via the control of the relative spin polarizations
J Park, DC Ralph, RA Buhrman - Applied Physics Letters, 2013

# Flash Memory



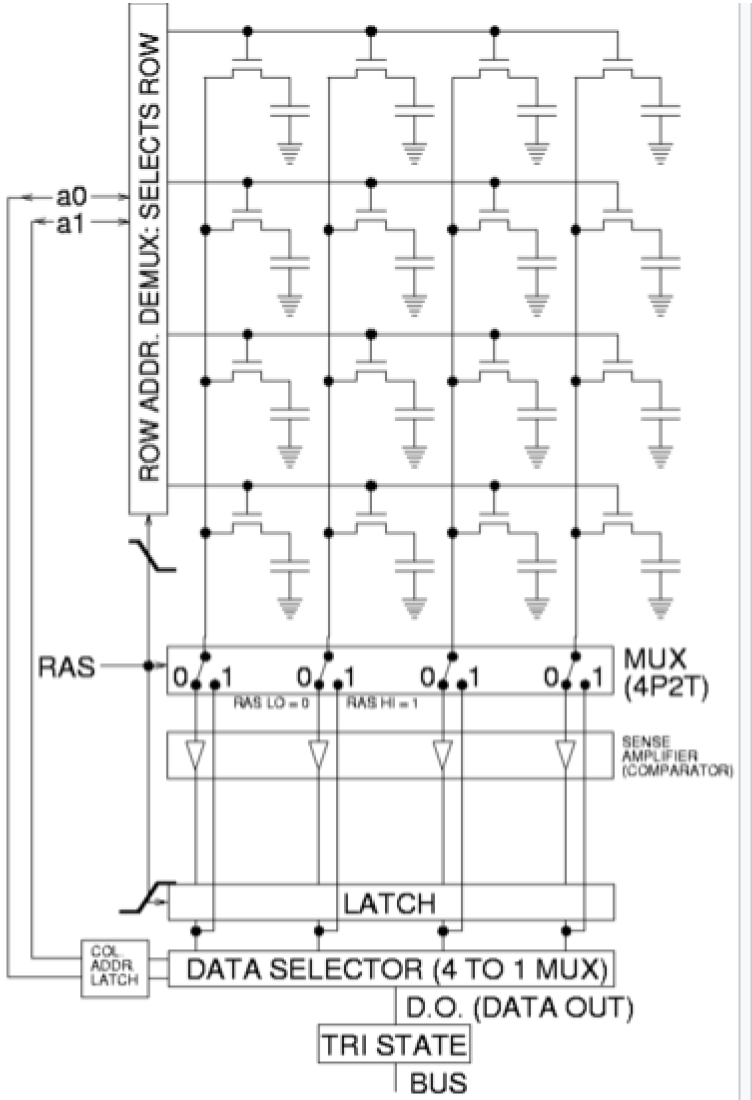
Transistor with float gate:

“0” – Float gate has charge
“1” – Float gate has no charge

To charge float gate:

- injection of hot electrons
- voltage on control gate

# Dynamic RAM (DRAM)



The principles of operation for reading a simple 4 by 4 DRAM array.

1 cell = 2 elements

Capacitors only!

Need restore data every 10 ms

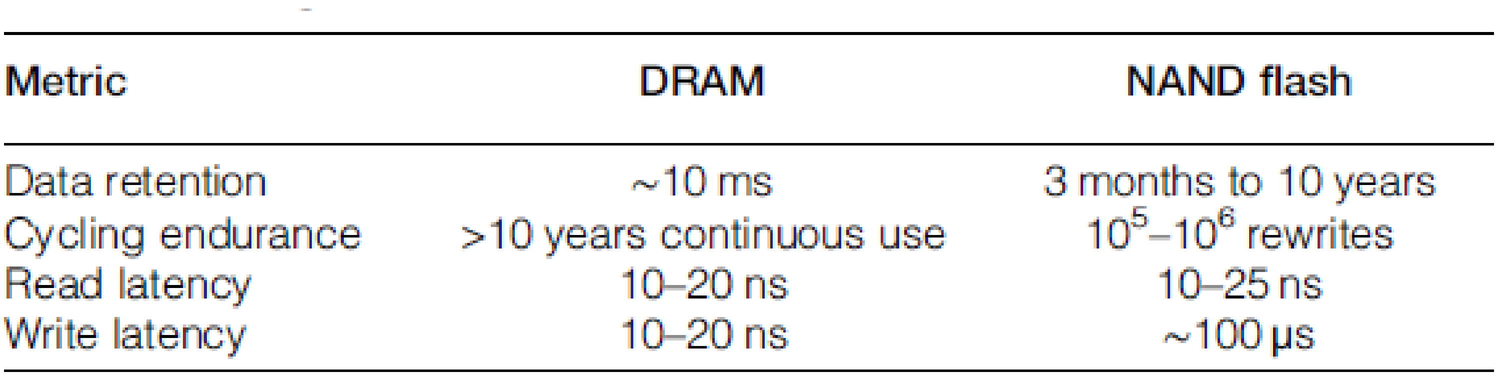
## Static RAM (SRAM)

1 cell = 8 elements

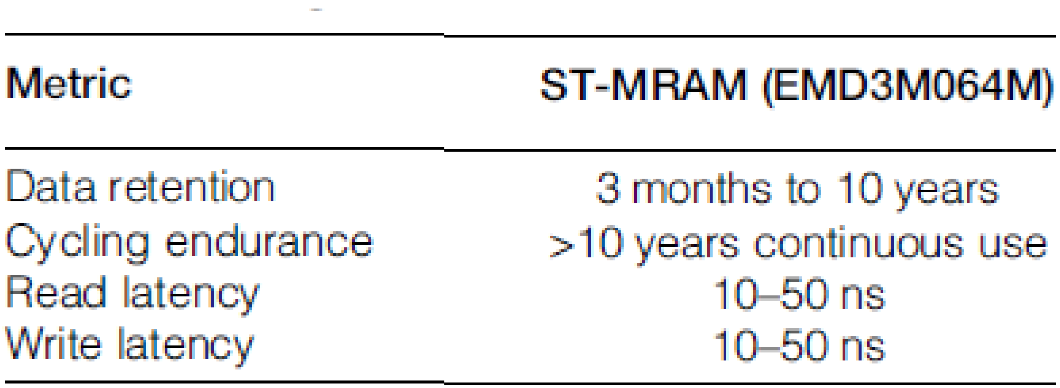
Trigger based

Too expensive

# Comparison of different RAM



| Metric | DRAM | NAND flash |
|---|---|---|
| Data retention | ~10 ms | 3 months to 10 years |
| Cycling endurance | >10 years continuous use | $10^5$–$10^6$ rewrites |
| Read latency | 10–20 ns | 10–25 ns |
| Write latency | 10–20 ns | ~100 μs |



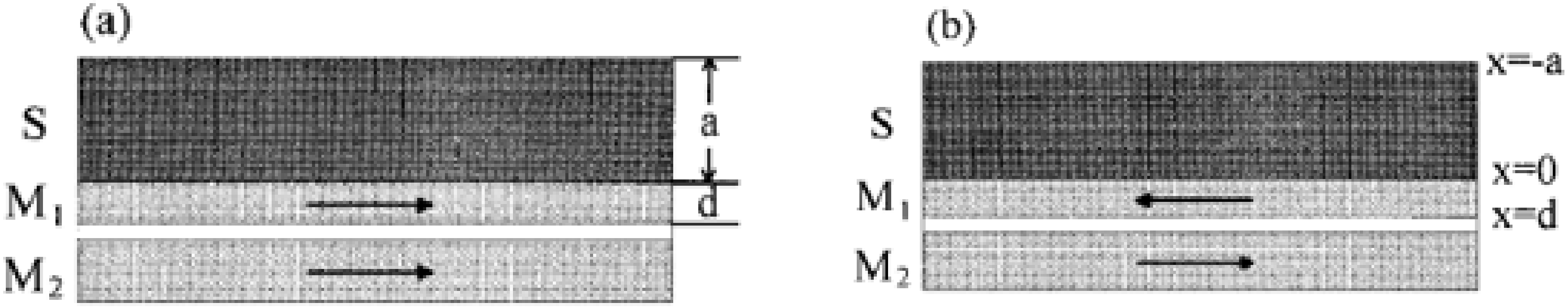
| Metric | ST-MRAM (EMD3M064M) |
|---|---|
| Data retention | 3 months to 10 years |
| Cycling endurance | >10 years continuous use |
| Read latency | 10–50 ns |
| Write latency | 10–50 ns |

*J. W. Lu, E. Chen, M. Kabir, M. R. Stan & S. A. Wolf (2016) Spintronics technology: past, present and future, International Materials Reviews, 61:7, 456-472*

Contents:

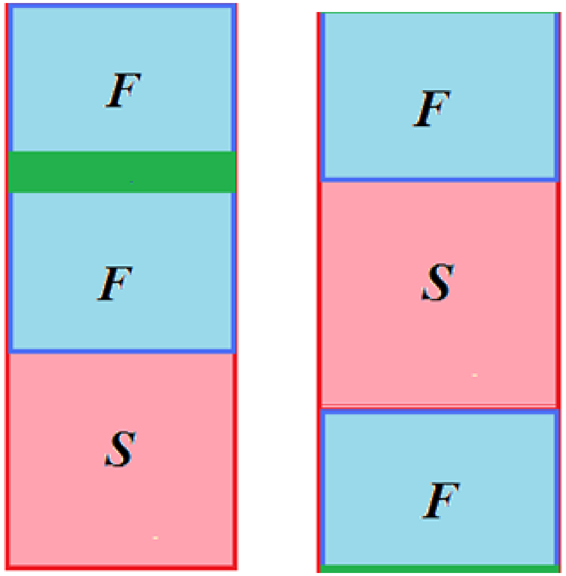
- Memory in common personal computer
- Spin-valve superconducting memory
- SFQ memory
- Superconducting phase memory

# Spin valve

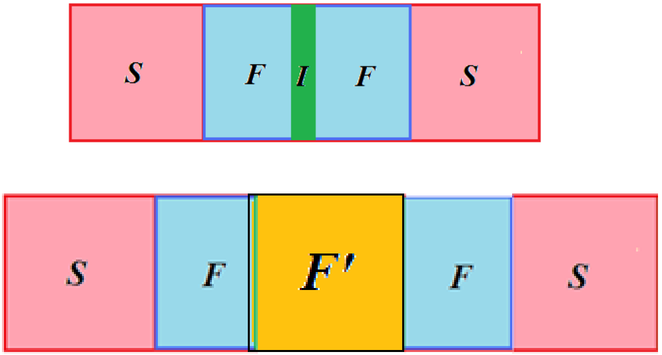


Sangjun Oh, D. Youm, and M. R. Beasley
Appl. Phys. Lett. 71, 2376 (1997);

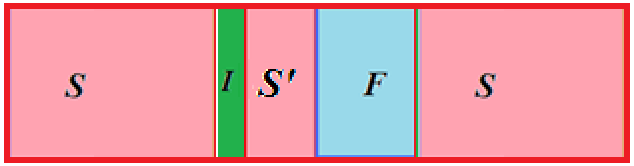
# What are the possible configurations of a spin valve?



Control of the critical temperature



Control of the Josephson junction critical current by changing mutual orientation of F layer magnetization

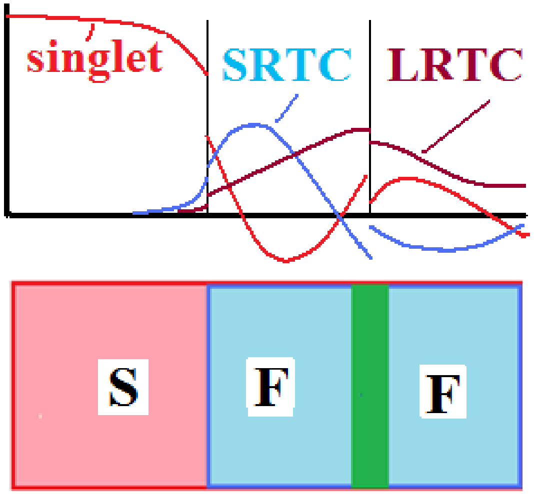


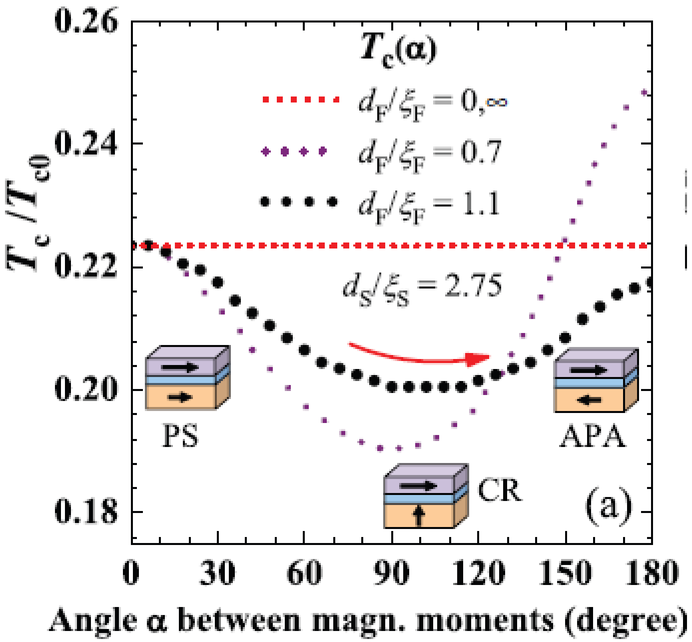
Control of the Josephson junction critical current by changing magnetization of single F layer.

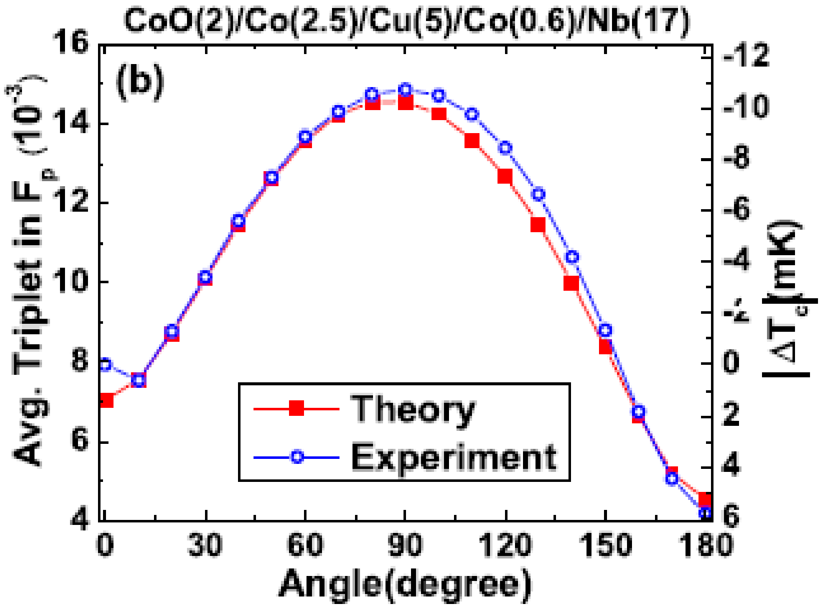
# SFF spin valves for control of the critical temperature of S film.

Y. V. Fominov, et al.,
JETP Lett.
91, 308 (2010).

R.G. Deminov et al.,
JMMM (2014).







A.A. Jara et al.,
Phys. Rev. B
89, 184502 (2014)

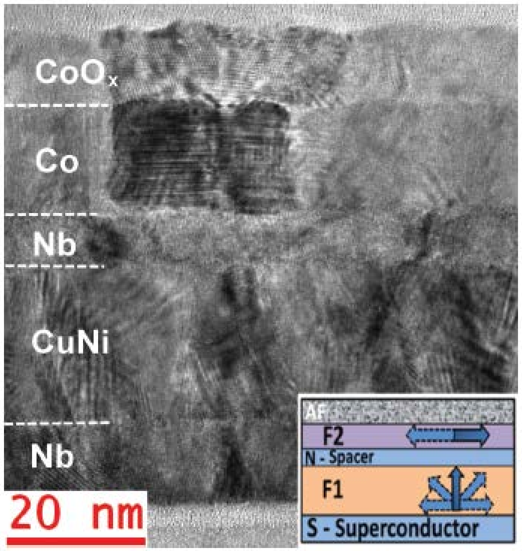
$$F_t(y,t) \equiv \sqrt{|f_0(y,t)|^2 + |f_1(y,t)|^2},$$

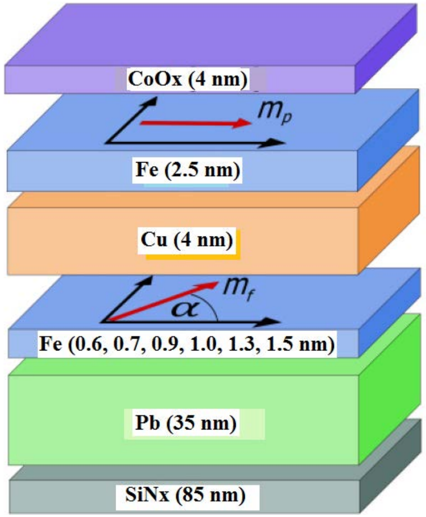
# SFF spin valves for control of the critical temperature of S film.

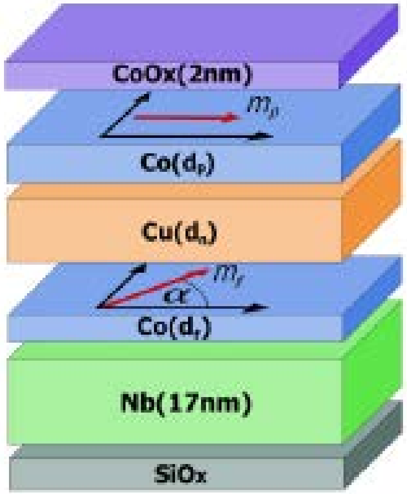
V. I. Zdravkov et al,
Phys. Rev. B
87, 144507 (2013)
$\Delta T_C -10$ mK

P.V. Leksin et al,
Phys. Rev. Let.
109, 057005 (2012)
$\Delta T_C -50$ mK

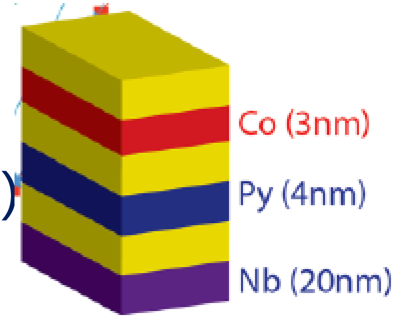
A.A. Jara et al.,
Phys. Rev. B
89, 184502 (2014)
$\Delta T_C -20$ mK



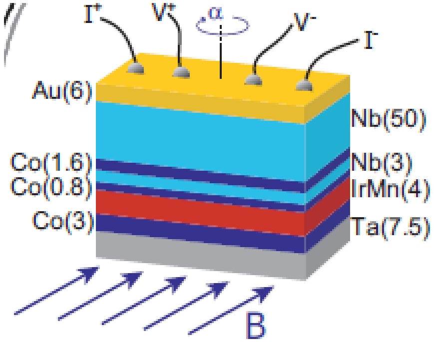




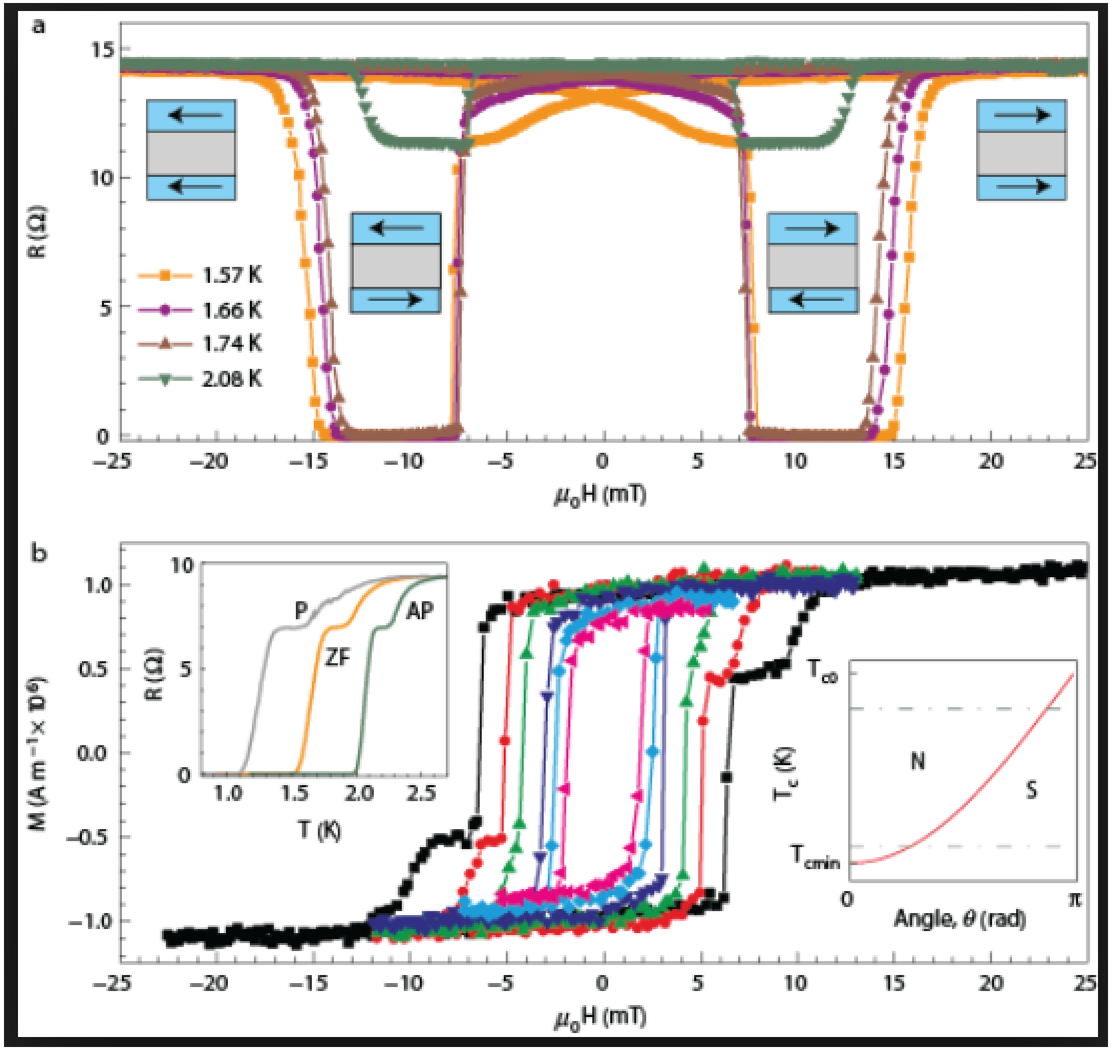
X. L. Wang et al.,
Phys. Rev. B
89, 184508 (2014)
$\Delta T_C -120$ mK



M.C. Floxtra et al.,
cond. mat. arXiv
1404. 2950 (2014)
$\Delta T_C -10$ mK



# Spin valve with ferromagnetic insulator



Stronger effect!

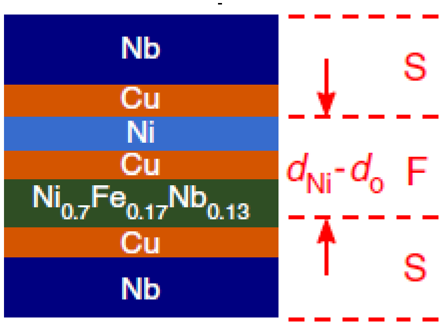
You can even control magnetization with superconductive order

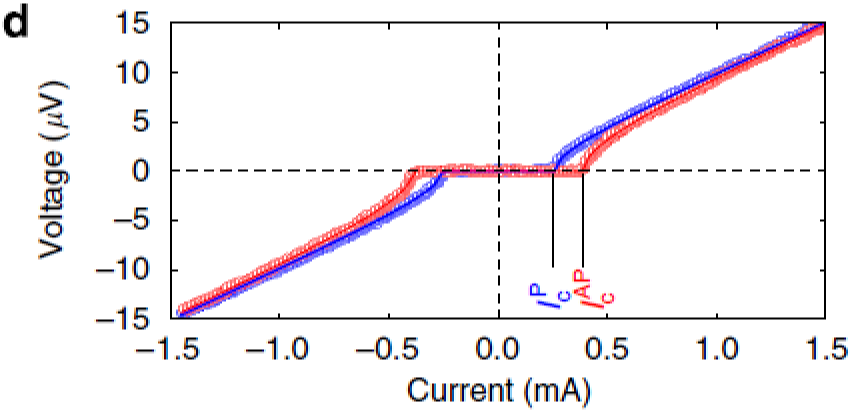
*Y. Zhu, A. Pal, M. G. Blamire, Z. H. Barber, Nature Materials, 16, 195–199 (2017)*

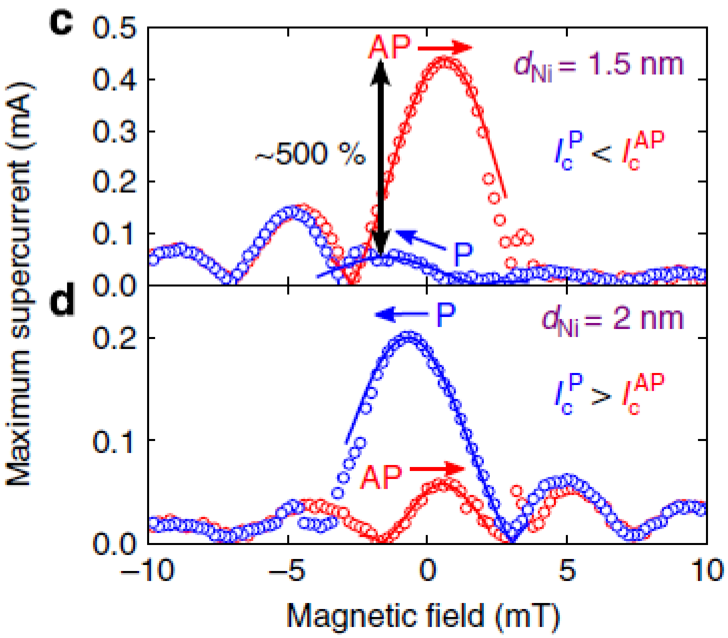
# Josephson spin valve devices

B. Baek et al., Nature Communications, 5, 3888 (2014)

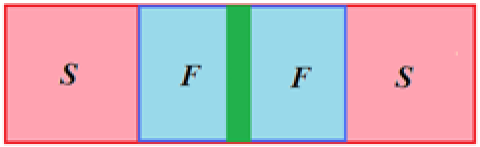
Nb/Cu(3 nm)/$Ni_{0.7}Fe_{0.17}Nb_{0.13}$(2.1 nm)/Cu(5 nm)/Ni/Cu(3 nm)/Nb.







# SFFS pseudo spin valves



Makram Abd El Qader et al., Appl. Phys. Lett., 104, 022602 (2014)

Nb(100 nm)/permalloy(2.4 nm)/Al(9 nm)/$Cu_{0.7}(Ni_{80}Fe_{20})_{0.3}$/Nb(100 nm)

B. Baek et al., Nature Communications, 5, 3888 (2014)

Nb(100 nm)/Cu(3 nm)/$Ni_{0.7}Fe_{0.17}$Nb0.13(2.1 nm)/Cu(5 nm)/Ni(3 nm)/Cu(3 nm)/Nb(70 nm).

J. W. A. Robinson et al., Phys. Rev. B 89, 104505 (2014).

Nb/Fe/Cr/Nb, Nb/Fe/Cr/Fe/Nb, NbCr/Fe/Cr/Nb,

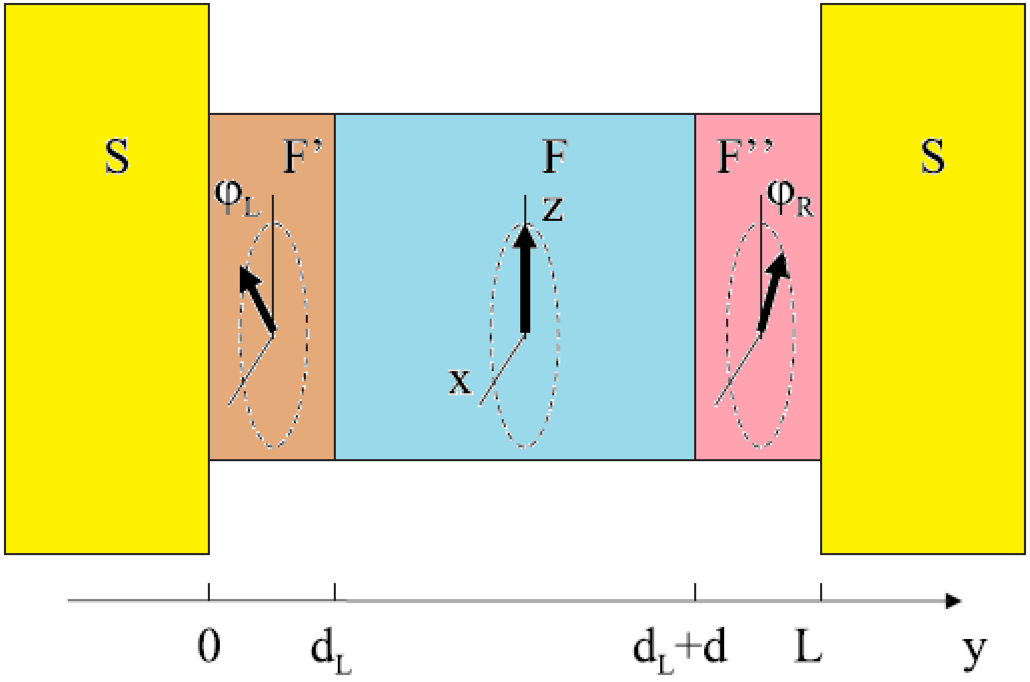
A. Iovan et al., arXiv:1405.4754v1 [cond-mat.supr-con] 19 May 2014

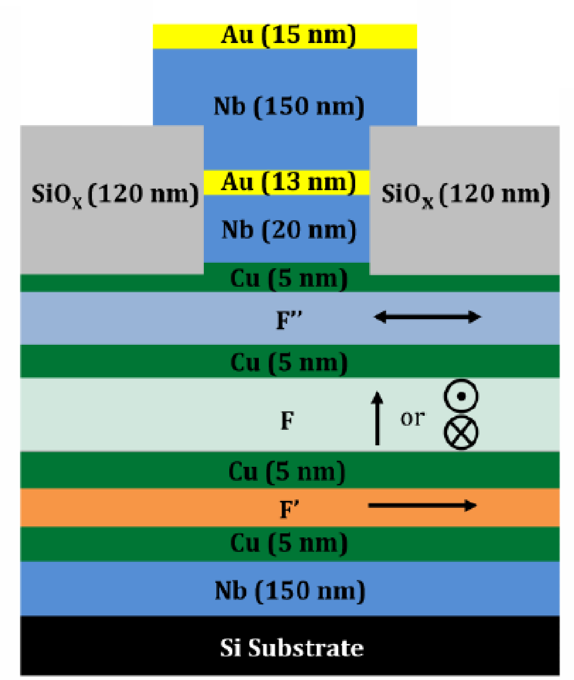
(Nb/$Cu_{0:5}Ni_{0:5}$/Cu/$Cu_{0:4}Ni_{0:6}$/Nb 200/10/20/10/200 nm)
(Nb/$Cu_{0:5}Ni_{0:5}$/Nb/$Cu_{0:4}Ni_{0:6}$/Nb 200/10/10/10/200nm)

M. Alidoust, and K. Halterman, Phys. Rev. B 89, 195111 (2014)
Theory of SFSFS and SFSFFS spin valve devices

# Structures with long range proximity effects

M. Houzet and A. I. Buzdin, Phys. Rev. B 76, 060504_R_ (2007)





$$I_c = \frac{2\pi T G}{e}\sum_{\omega>0}\frac{\Delta^2}{\omega^2}\left(\mathrm{Re}\,\frac{q_+ d}{\mathrm{sh} q_+ d} - \frac{q_0 d}{\mathrm{sh} q_0 d}\frac{d_L^2 d_R^2}{\xi_f^4}\sin\phi_L \sin\phi_R\right)$$

# Structures with long range proximity effects

B. M. Niedzielski et al., IEEE Tran. on Appl. Supercond. (2014)

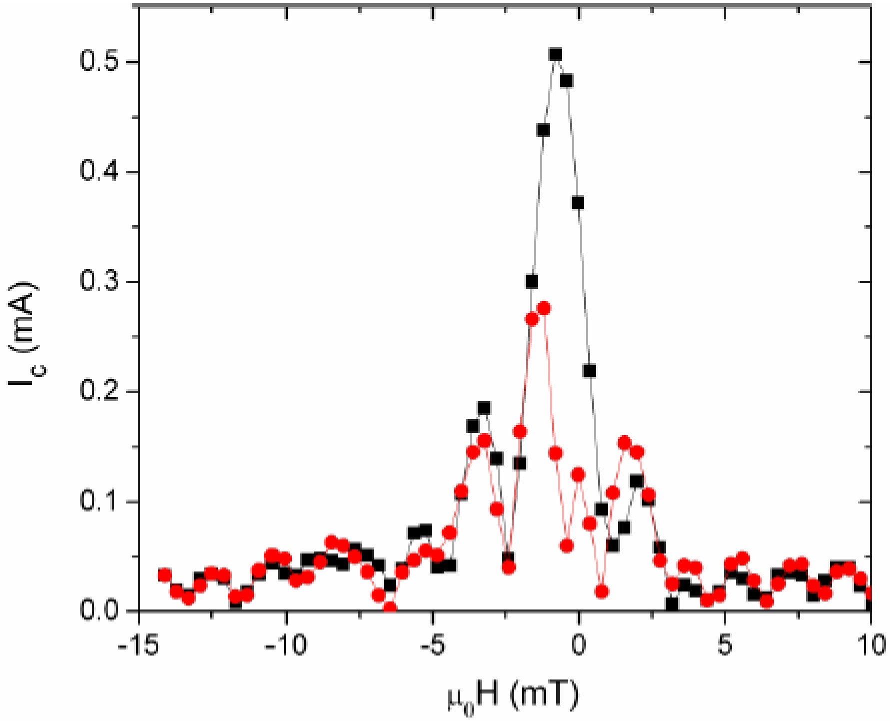


Fig 4. Critical current vs applied magnetic field for a Josephson junction of diameter 3 μm with F=Co(6)/Ru(0.6)/Co(6) and F″=Pd-Fe(15) alloy. The black squares and red circles represent data taken with the external field increasing in the positive and negative directions, respectively. At low field values, hysteresis is observed.

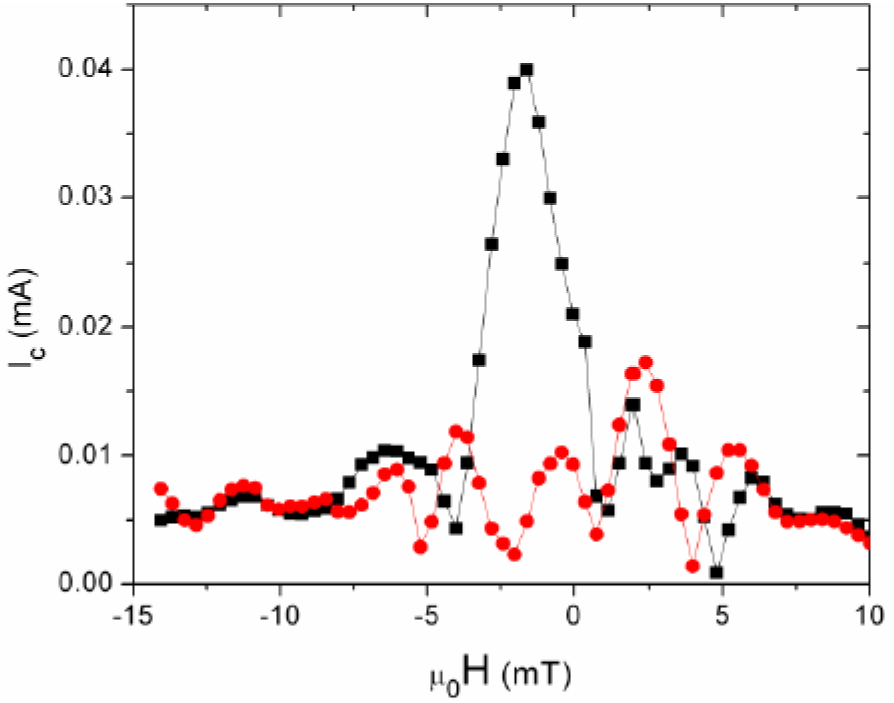
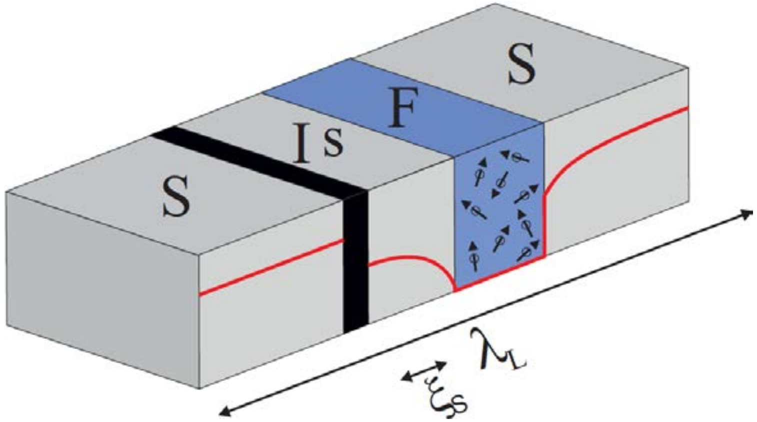
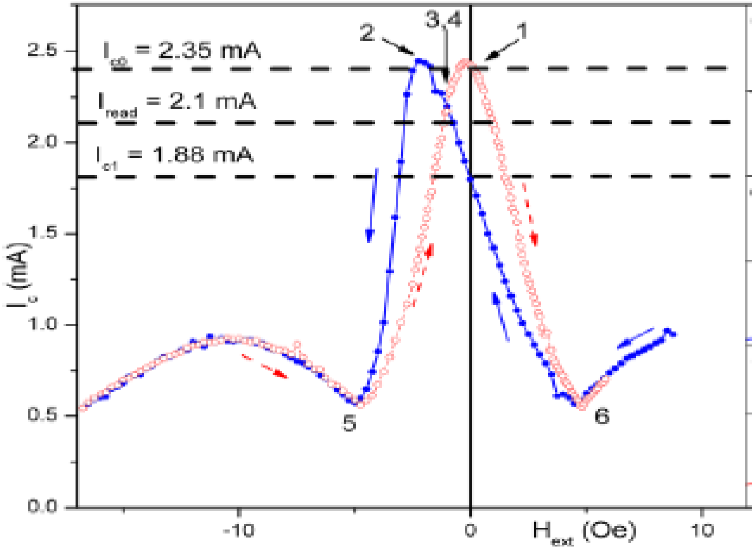


Fig 6. Critical current vs applied field for a Josephson junction of diameter 3 μm with F= Co(6)/Ru(0.6)/Co(6) and F″=Ni-Fe-Nb(1.5) alloy. The black squares and red circles indicate positive and negative field sweep directions respectively. Again, hysteresis is observed at low field values.

The largest value of $I_cR_N$ observed in these samples is only 50 nV

# Devices with single ferromagnetic layer

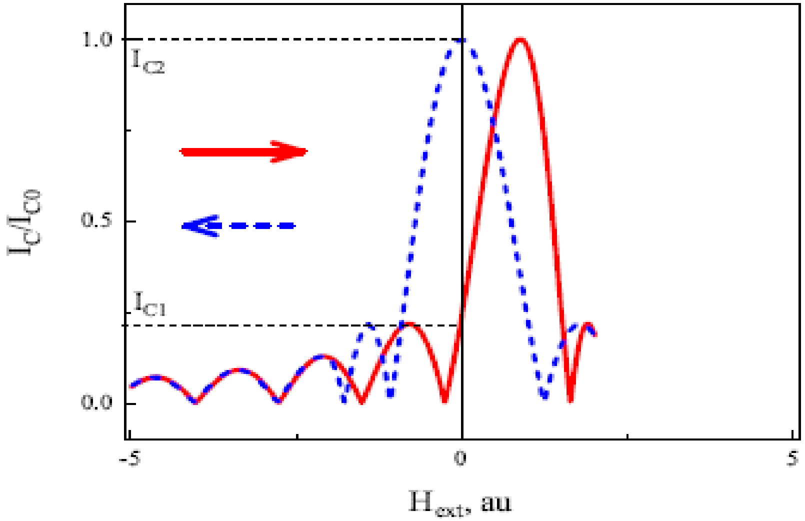




## Control of the shift on Fraunhofer dependence

$$I_C(H_{ext}) = I_{C0}\left|\frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}\right|,$$

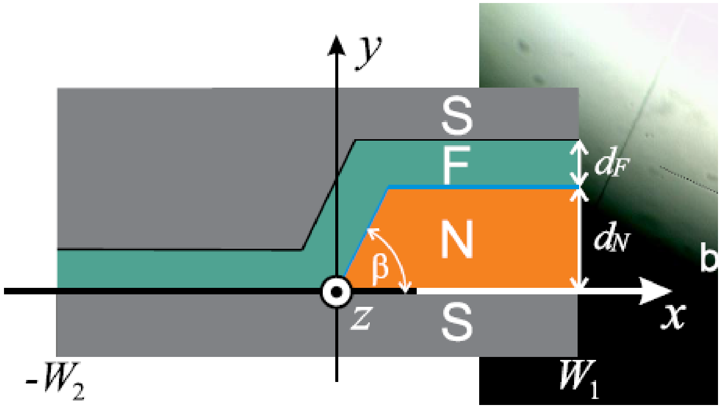
$$\Phi = W|L_{eff}H_{ext} + L_F H_0 N(n_\uparrow - n_\downarrow)|$$

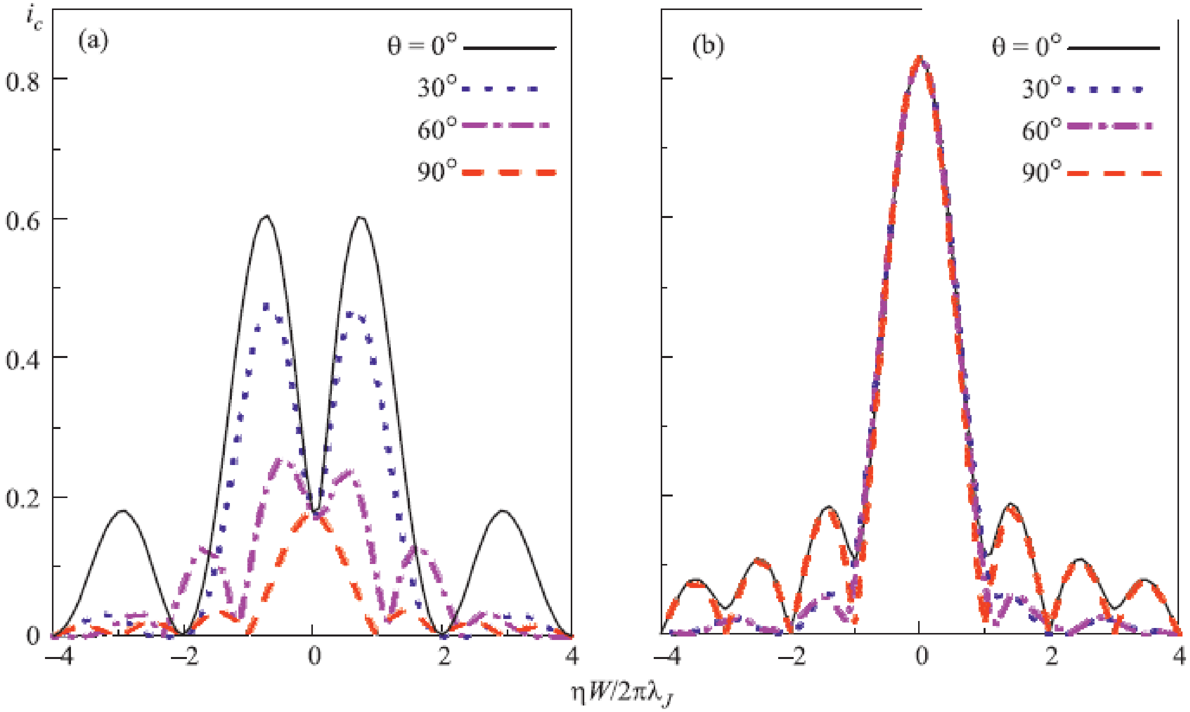


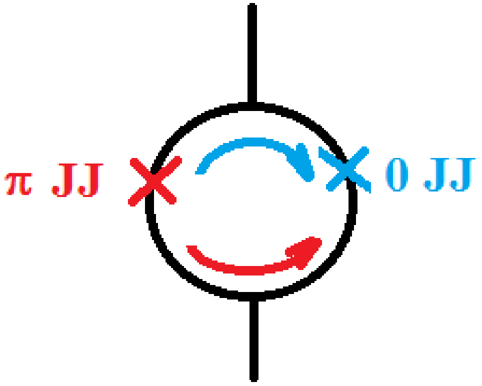
*Bol'ginov V.V., Stolyarov V.S et al, JETP letters, 95, 7, 366, (2012)*
*I.V. Vernik et al, IEEE Trans on Appl. Supercon., 23, 1701208 (2013)*
*I. A. Golovchanskiy et al., Physical Review B 94 (21), 214514, (2016)*

*T. I. Larkin et al, Appl. Phys. Lett. 100, 222601 (2012)*
*S.V. Bakurskiy et al., Appl. Phys. Lett., 102, 192603, (2013)*

# Josephson magnetic rotary valve






π JJ

0 JJ

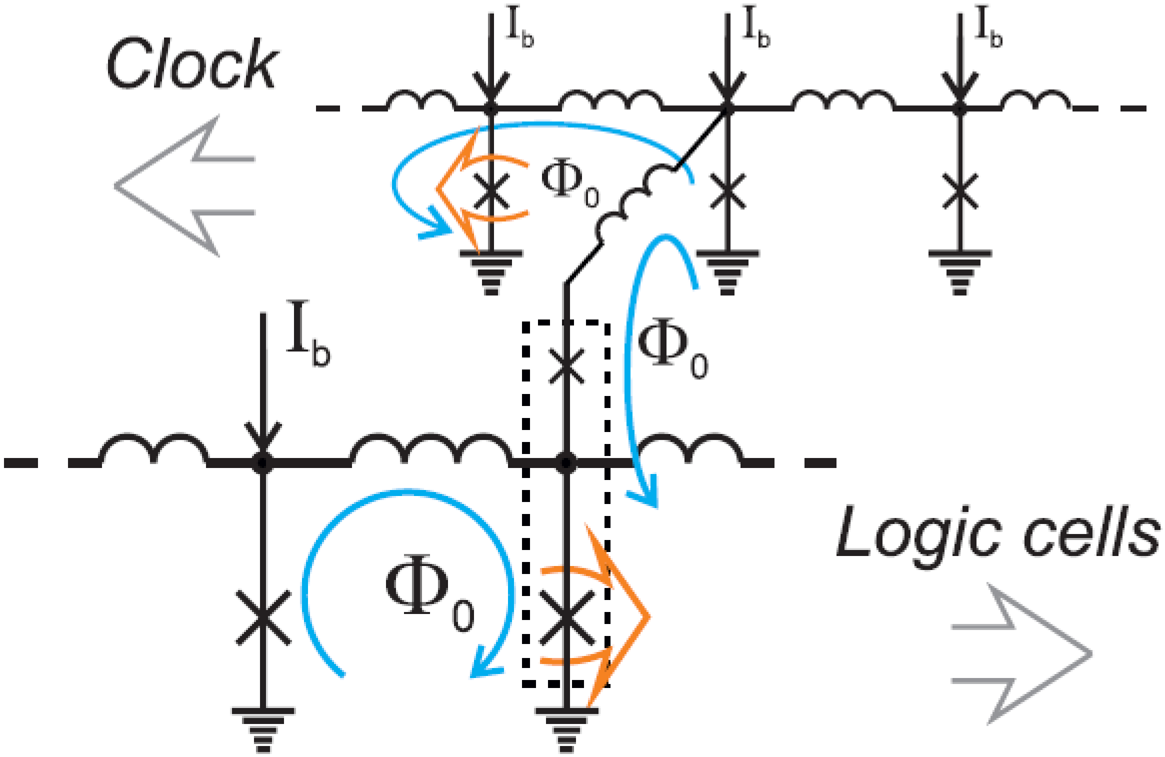
I. I. Soloviev,[1,2] N. V. Klenov,[3,2] S. V. Bakurskiy,[3,4,5] V. V. Bol'ginov,[6,7] V. V. Ryazanov,[6,7]
M. Yu. Kupriyanov,[1,4] and A. A. Golubov[4,5]

APPLIED PHYSICS LETTERS **105**, 242601 (2014)

Contents:

- Memory in common personal computer
- Spin-valve superconducting memory
- SFQ memory
- Superconducting phase memory

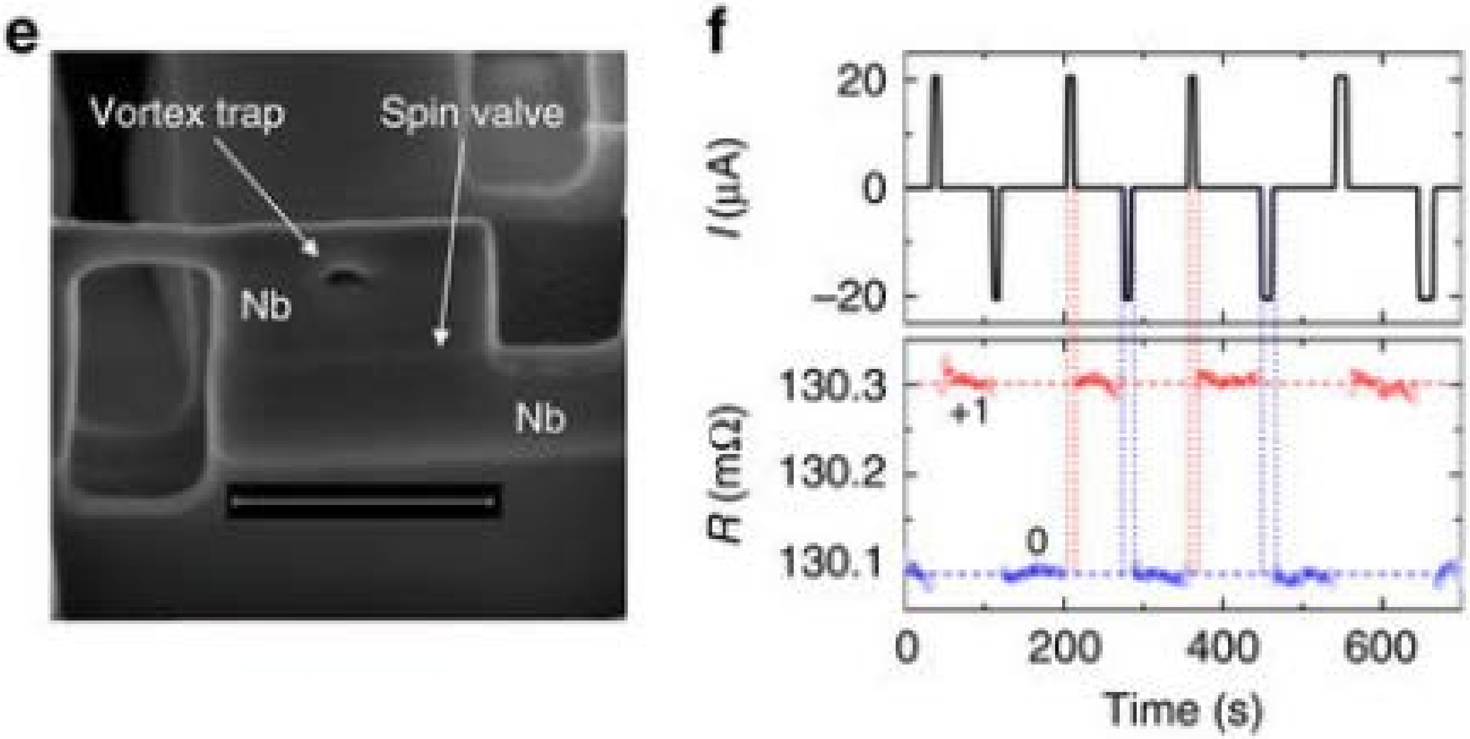
# RSFQ logic



Semenov, V. K. Erasing logic-memory boundaries in superconductor electronics. In *Rebooting Computing (ICRC), IEEE International Conference on* (pp. 1-6). IEEE. (2016).

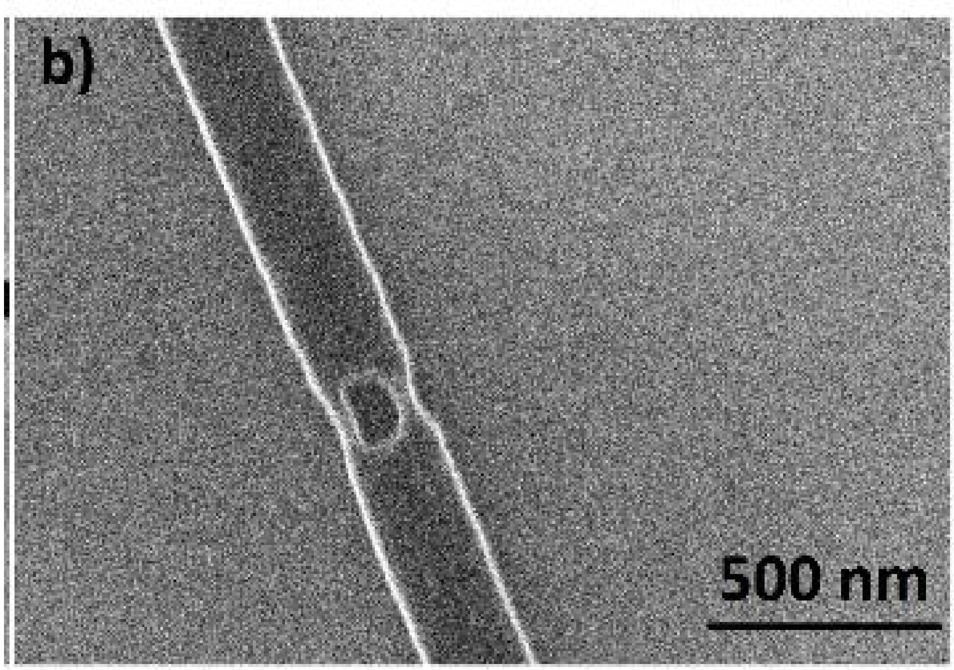
Soloviev I.I. et al, . After Moore's technologies: operation principles of a superconductor alternative, arXiv preprint arXiv:1706.09124 (2017)

# Flux trap near Josephson junction



*T **Golod**, **A Iovan**, VM **Krasnov** - Nature communications, Nature communications, 6, 8628 (2015)*

# Flux trap in nanowire

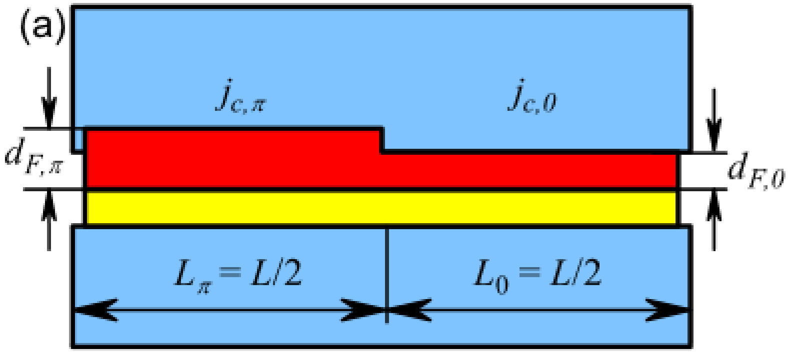


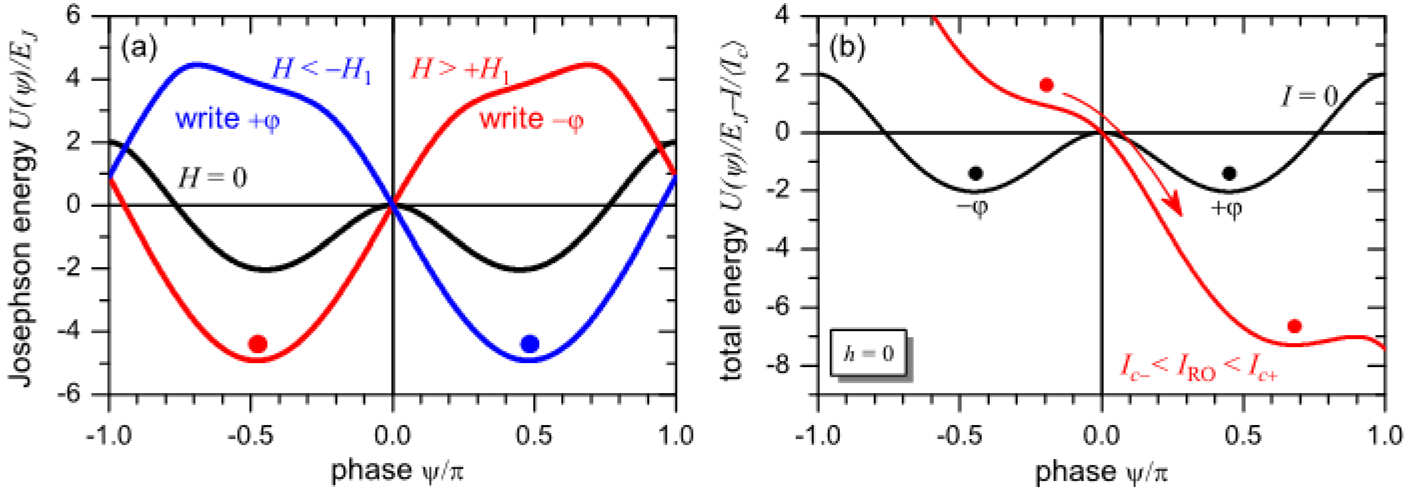
Murphy, A., Averin, D. V., & Bezryadin, A. Nanoscale superconducting memory based on the kinetic inductance of asymmetric nanowire loops. *New J. Phys*, *19*, 063015, (2017).

Contents:

- Memory in common personal computer
- Spin-valve superconducting memory
- Flux memory
- Superconducting phase memory

# Memory cell based on φ-junction





H Sickinger, A Lipman, M Weides, RG Mints, H Kohlstedt, D Koelle, R Kleiner, E Goldobin, Physical review letters 109 (10), 107002

E Goldobin, H Sickinger, M Weides, N Ruppelt, H Kohlstedt, R Kleiner, D Koelle Applied Physics Letters 102 (24), 242602-242602-4

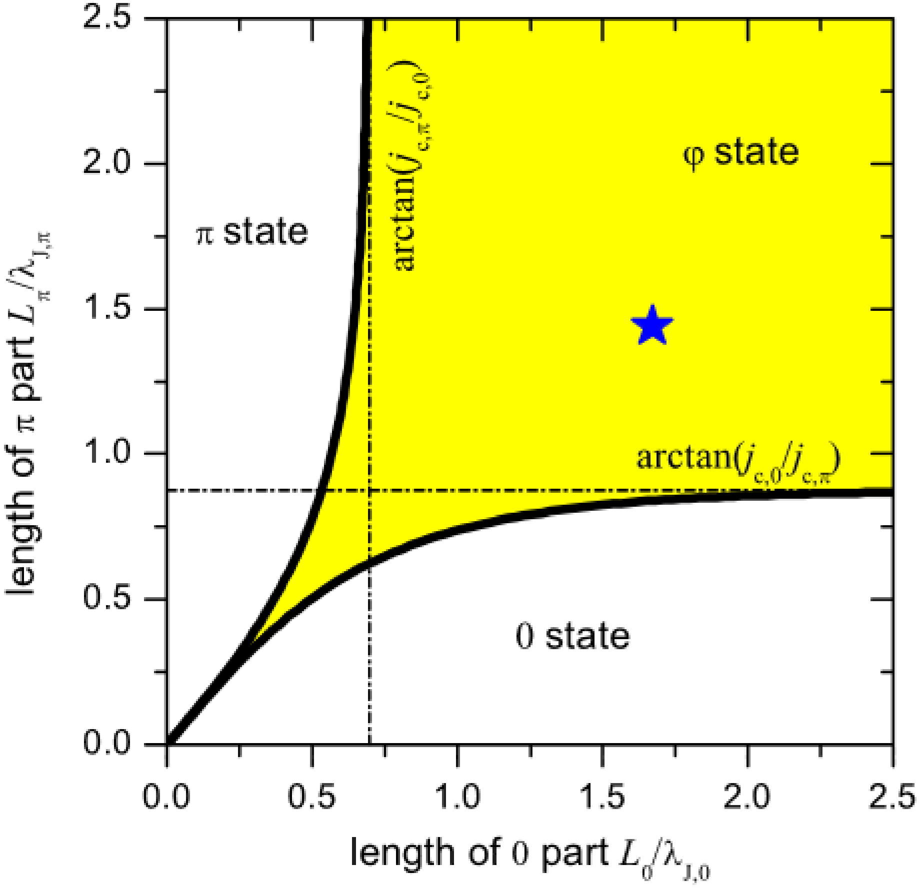


FIG. 3 (color online). Domain of existence of $\varphi$ state. The ⋆ shows the position of the investigated JJ at $T = 2.35$ K.

# Current Phase Relations

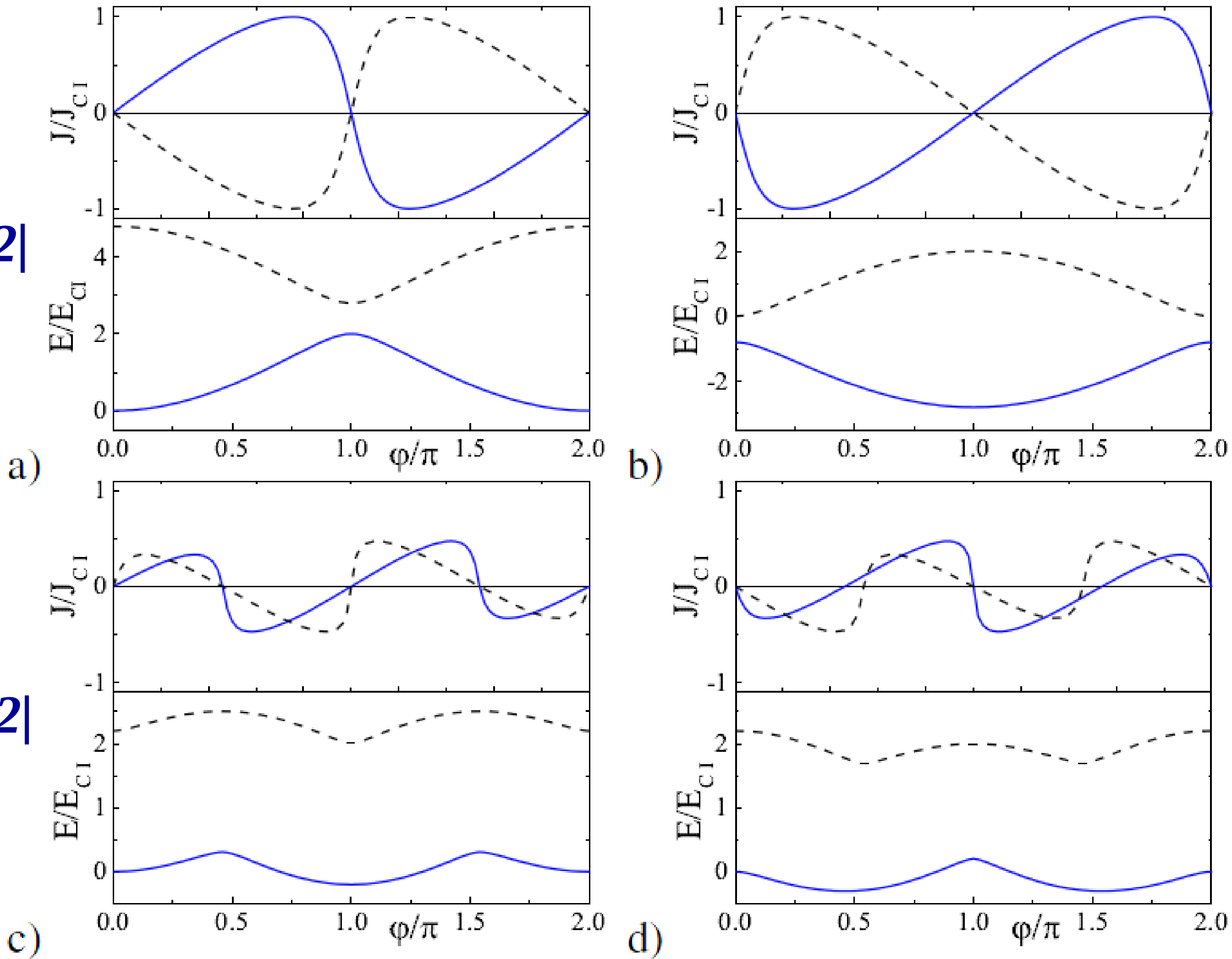
$I_S(\varphi) = A \sin(\varphi) + B \sin(2\varphi) + \ldots$

**0-state**

**π-state**

***A>0***
***|B|<|A/2|***

***A>0***
***|B|<|A/2|***



***B>0***
***|B|<|A/2|***

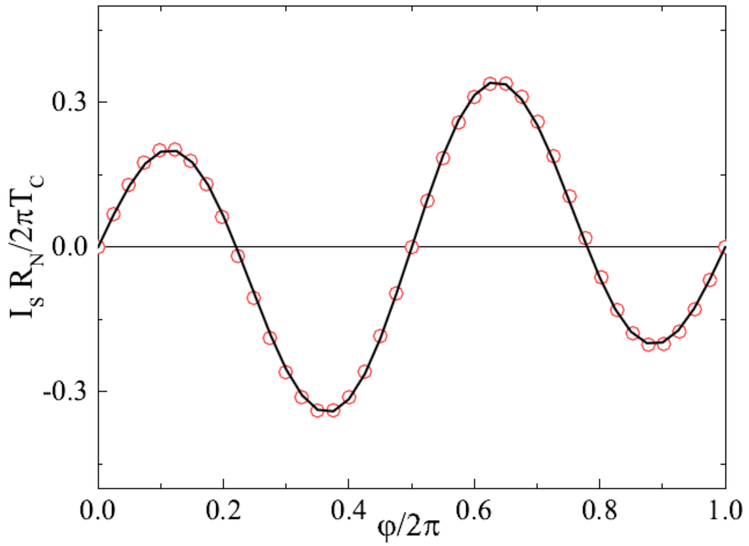
***B<0***
***|B|<|A/2|***

**0+π-state**

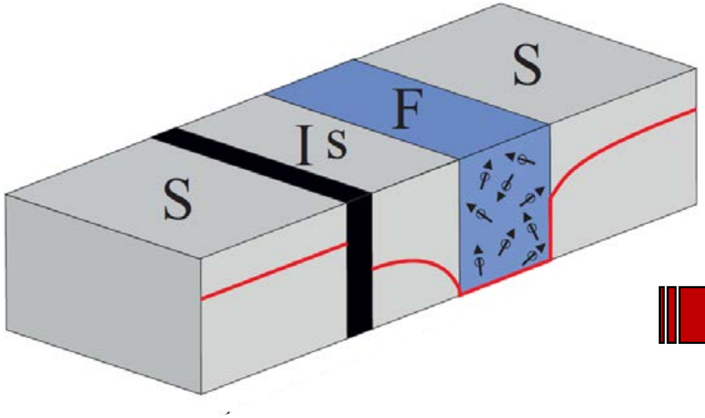
**φ-state**

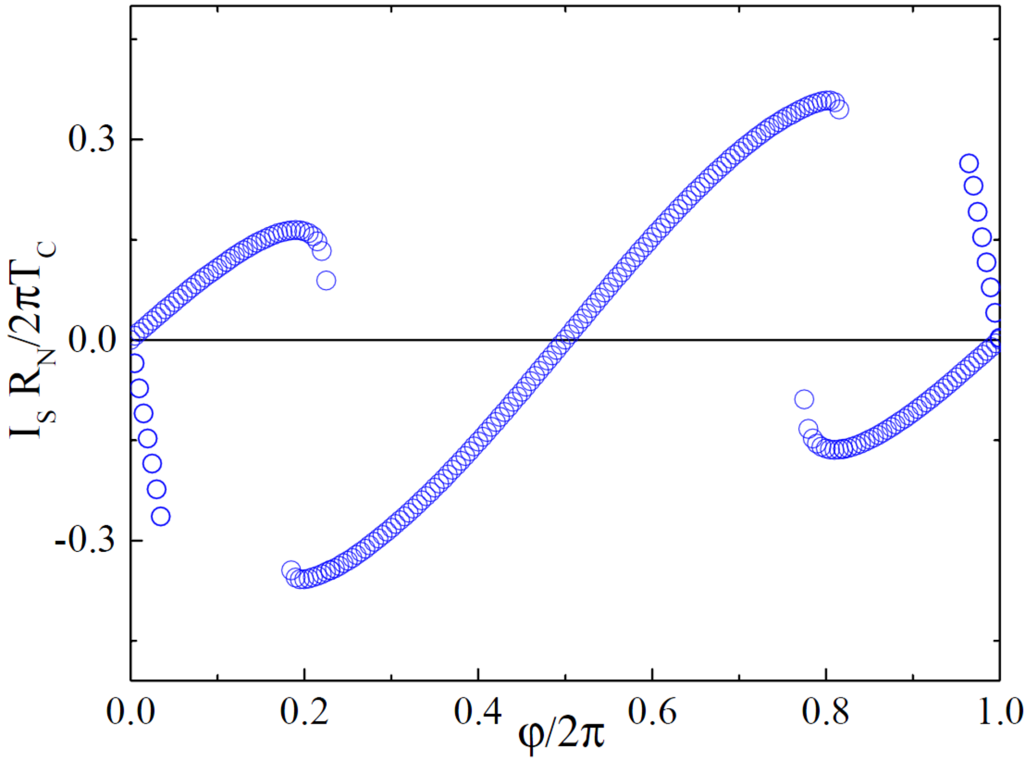
# Josephson SIsFS structure

**0+π-state** also has double-well potential,
It can be obtained in the structure with single F-layer

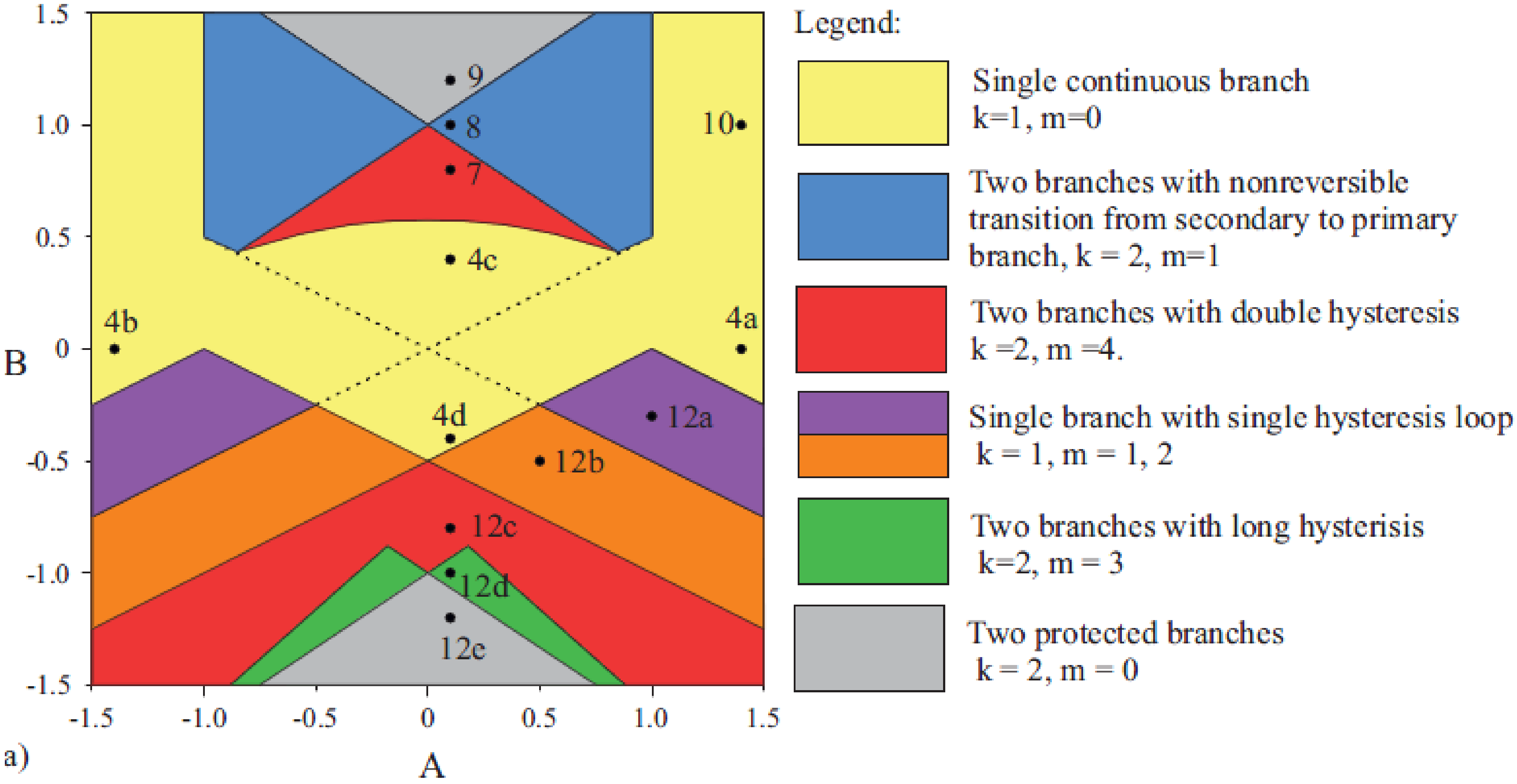


CPR of SFS junction
in the region of 0-π transition





# Regimes of SIsFS junction

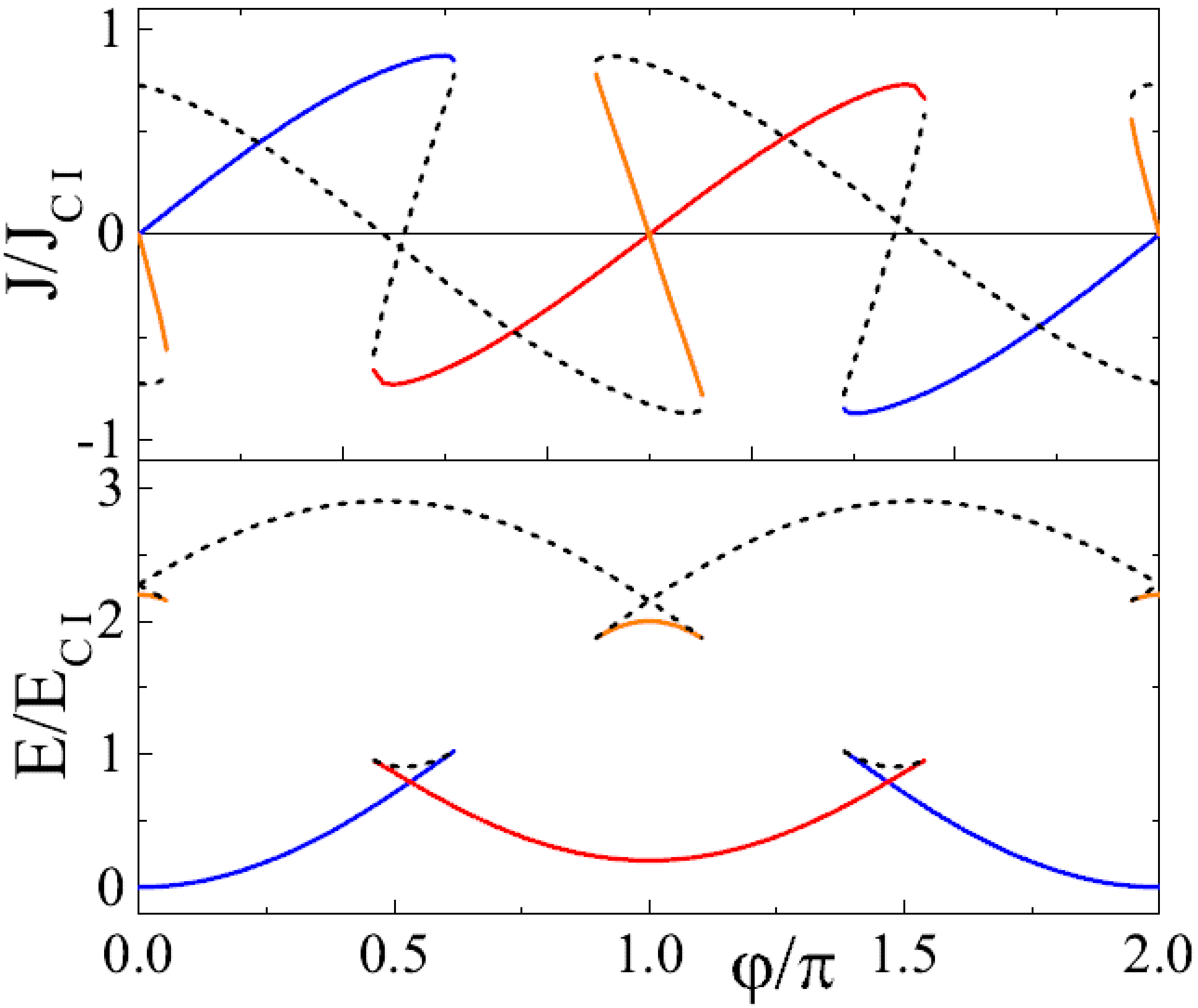


k – number of branches

m – number of breaks on branches

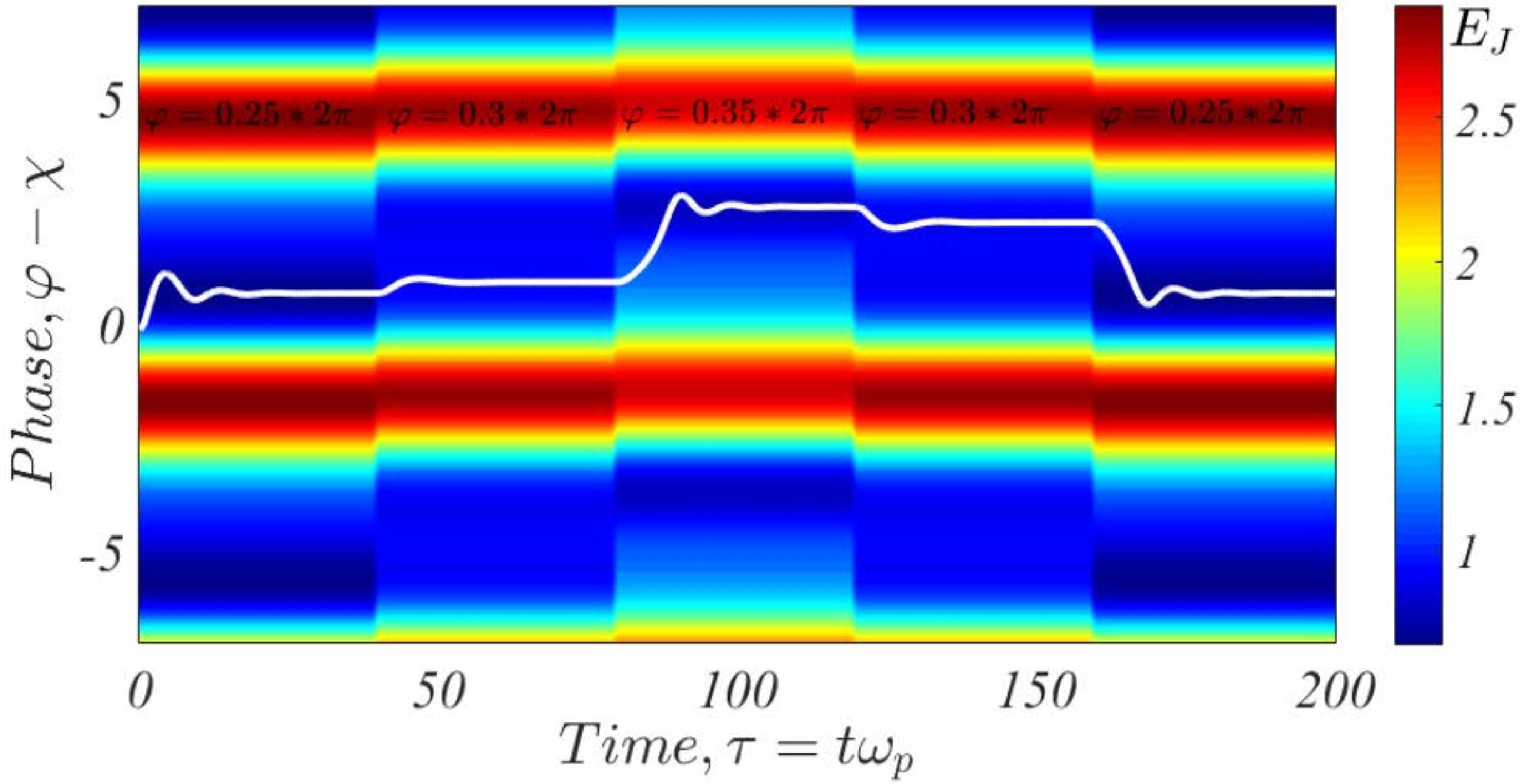
*Bakurskiy et al, Phys. Rev. B 95, 094522 (2017)*

# Hysteretic states, k=2, m=4

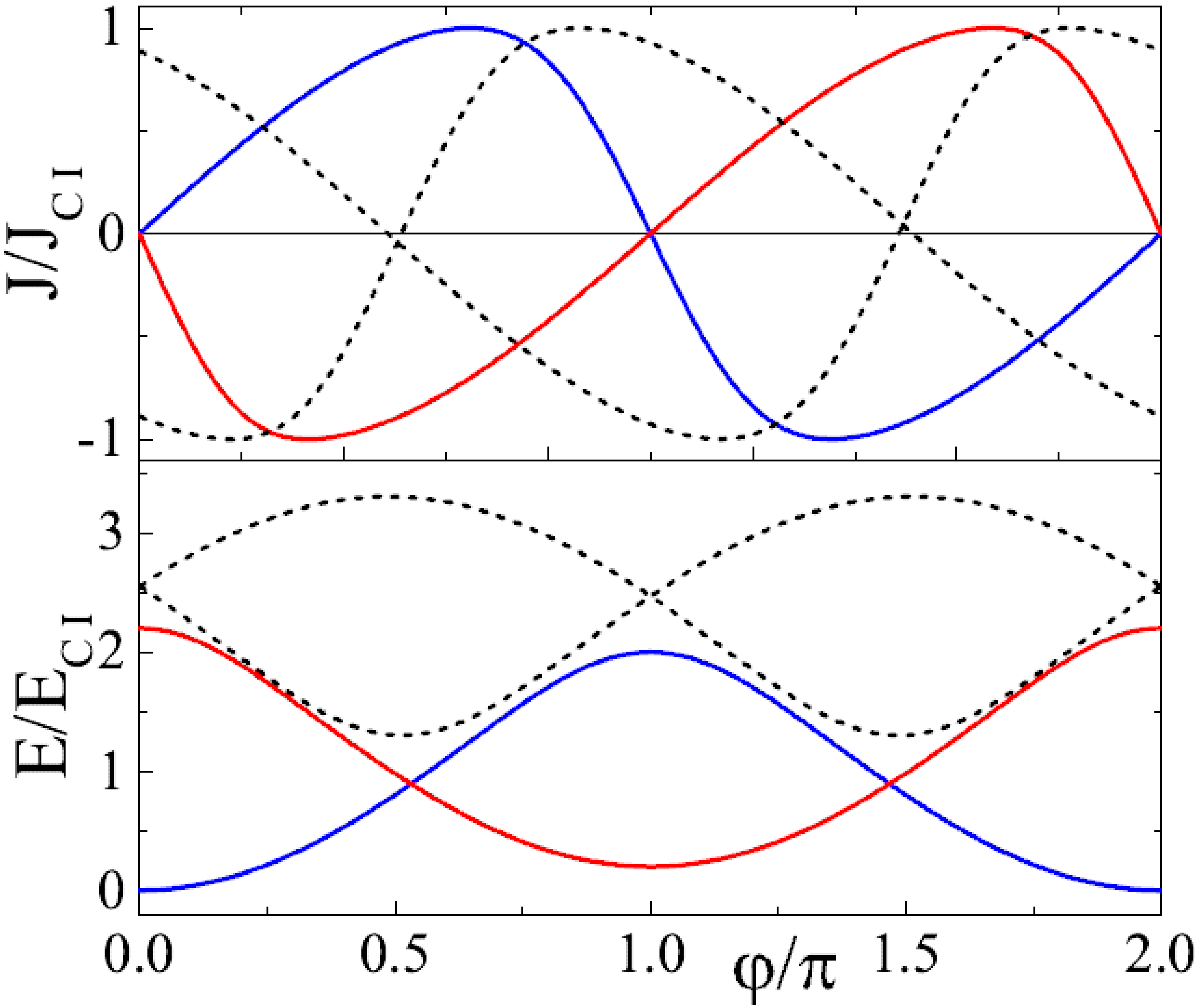


# Switching the states, k=2, m=4

RSJ-model of SIsFS structure



# Protected states, k=2, m=0

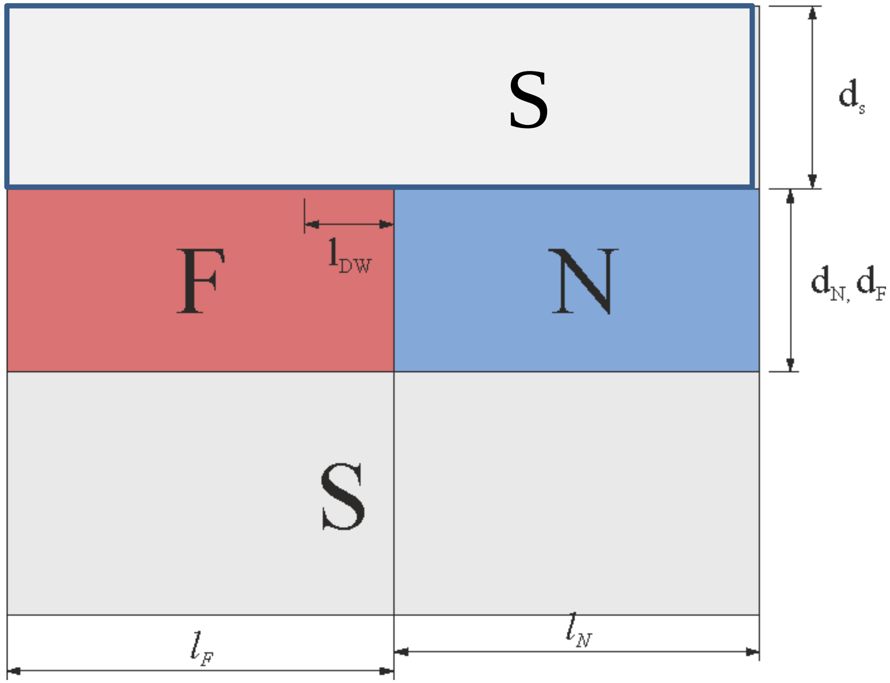


# Superconducting Phase Domain Memory Element

If the size of electrode $d_S$ is finite, the other solution exists.

Considering energy of the system we should take into account 3 terms

- Josephson Energy of SFs junction $\Delta E_{SFs}$
- Josephson Energy of SNs junction $\Delta E_{SNs}$
- Pairing Energy of certain volume $\Delta E_{DW}$



$$\Delta E_{DW} = \Delta F_{GL} l_{DW} d_s W + \frac{\hbar j_{Cs} d_s W}{e} \sim d_s$$
$$\Delta E_{SFs} = \frac{\hbar j_{CF} l_F W}{e} \sim l_F$$
$$\Delta E_{SNs} = \frac{\hbar j_{CN} l_N W}{e} \sim l_N$$

*S.V. Bakurskiy, N.V. Klenov, I.I. Soloviev, M.Yu Kupriyanov, A.A. Golubov, Appl.Phys. Lett., 108(4):042602–1–5, (2016)*

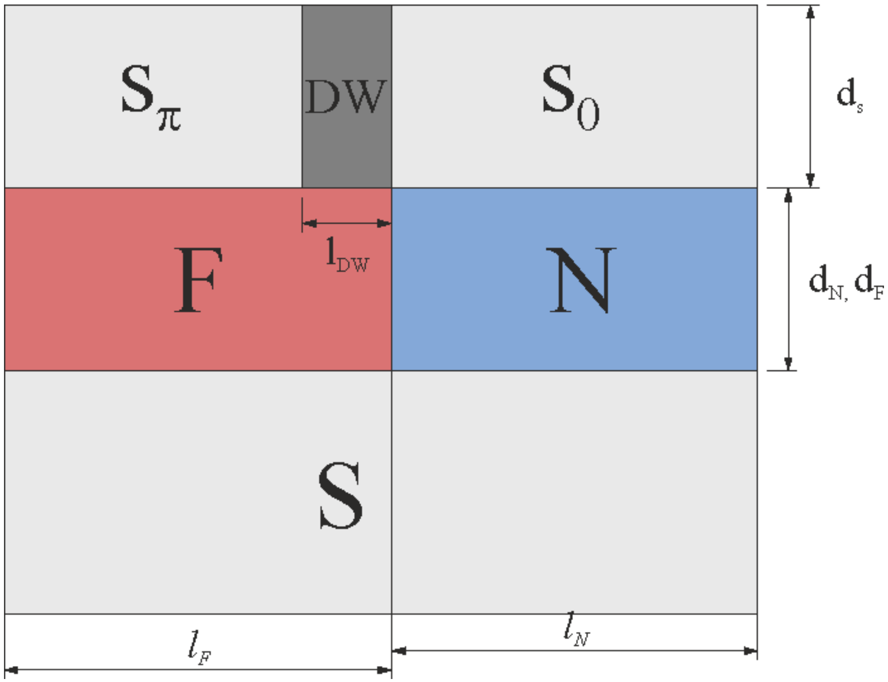
# Superconducting Phase Domain Memory Element

If the size of electrode $d_S$ is finite, the other solution exists.

Considering energy of the system we should take into account 3 terms

- Josephson Energy of SFs junction $\Delta E_{SFs}$
- Josephson Energy of SNs junction $\Delta E_{SNs}$
- Pairing Energy of certain volume $\Delta E_{DW}$

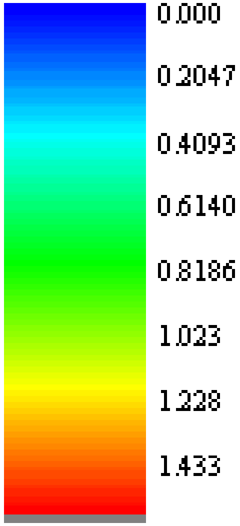
$$\Delta E_{DW} = \Delta F_{GL} l_{DW} d_s W + \frac{\hbar j_{Cs} d_s W}{e} \sim d_s$$
$$\Delta E_{SFs} = \frac{\hbar j_{CF} l_F W}{e} \sim l_F$$
$$\Delta E_{SNs} = \frac{\hbar j_{CN} l_N W}{e} \sim l_N$$



*S.V. Bakurskiy, N.V. Klenov, I.I. Soloviev, M.Yu Kupriyanov, A.A. Golubov, Appl.Phys. Lett., 108(4):042602–1–5, (2016)*

# S-F/N-s system with thin s electrode

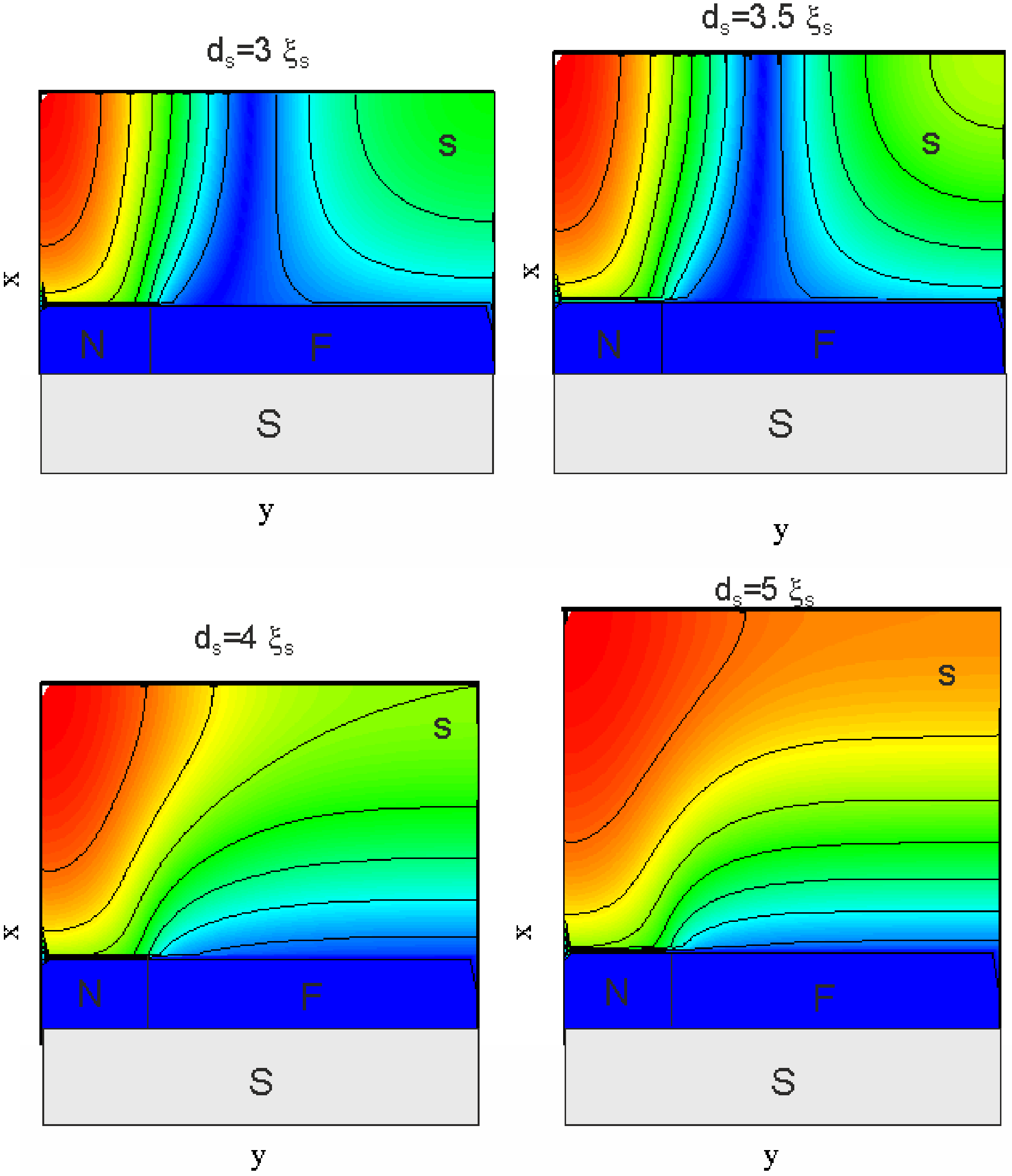
Numerical Solution for Pair Potential Δ



$d_F=1\,\xi_S$

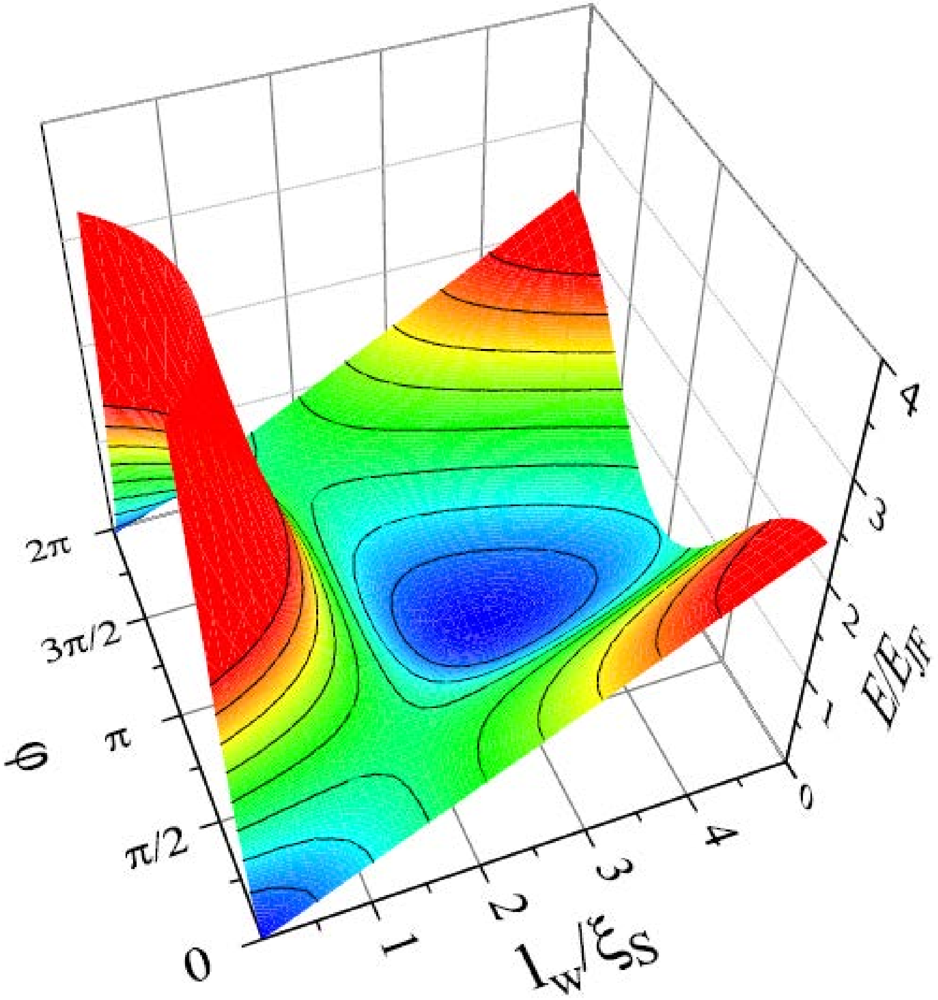
$W=16\,\xi_S$

$H=10\pi T_C$



# Is it possible to use it for memory element?

$$E = \frac{\hbar J_{Cs}(l_{DW})}{2e}(1-\cos\varphi) + \frac{\hbar J_{CSFs}}{2e}(1-\cos(\pi-\varphi)) + \Delta E_{DW}(l_{DW})$$



Yes!

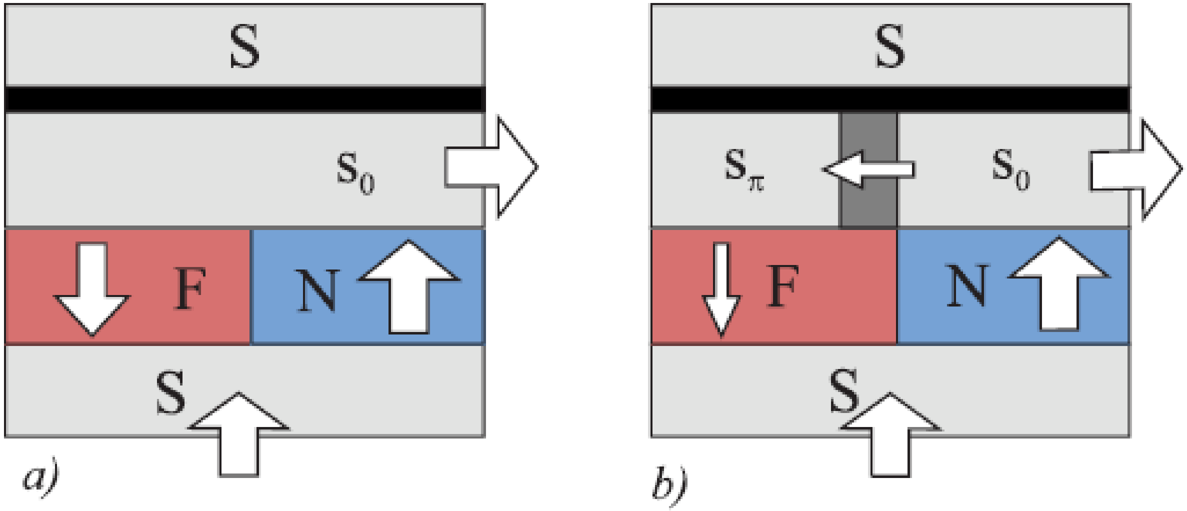
Choose critical parameters
$E_{SFS} = E_{Dwall}$

This system has double well potential with 2 possible states: domain and single

# Superconducting Phase Domain Memory Element

Domain states can be controlled by current pulses

## **WRITE SPD-state operation**



Critical current of SPD-wall < Critical current of SFS junction

→ Reverse current of SPD state is smaller than in single state

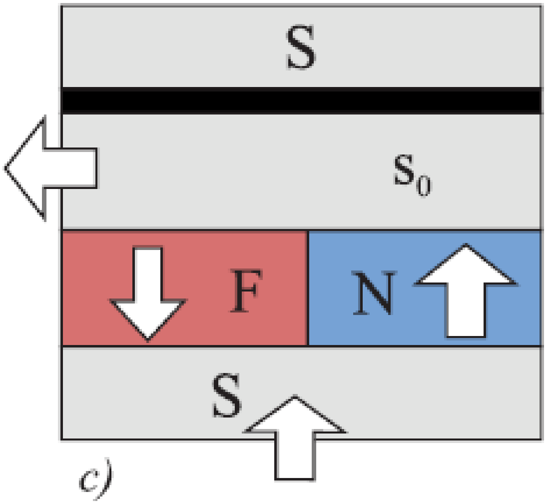
→ SPD-state has larger critical current

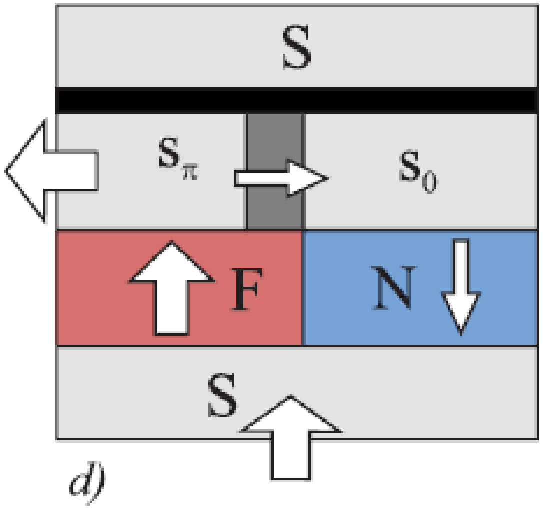
→ Switch to SPD state

# Superconducting Phase Domain Memory Element

Domain states can be controlled by current pulses

## **WRITE Single-state operation**





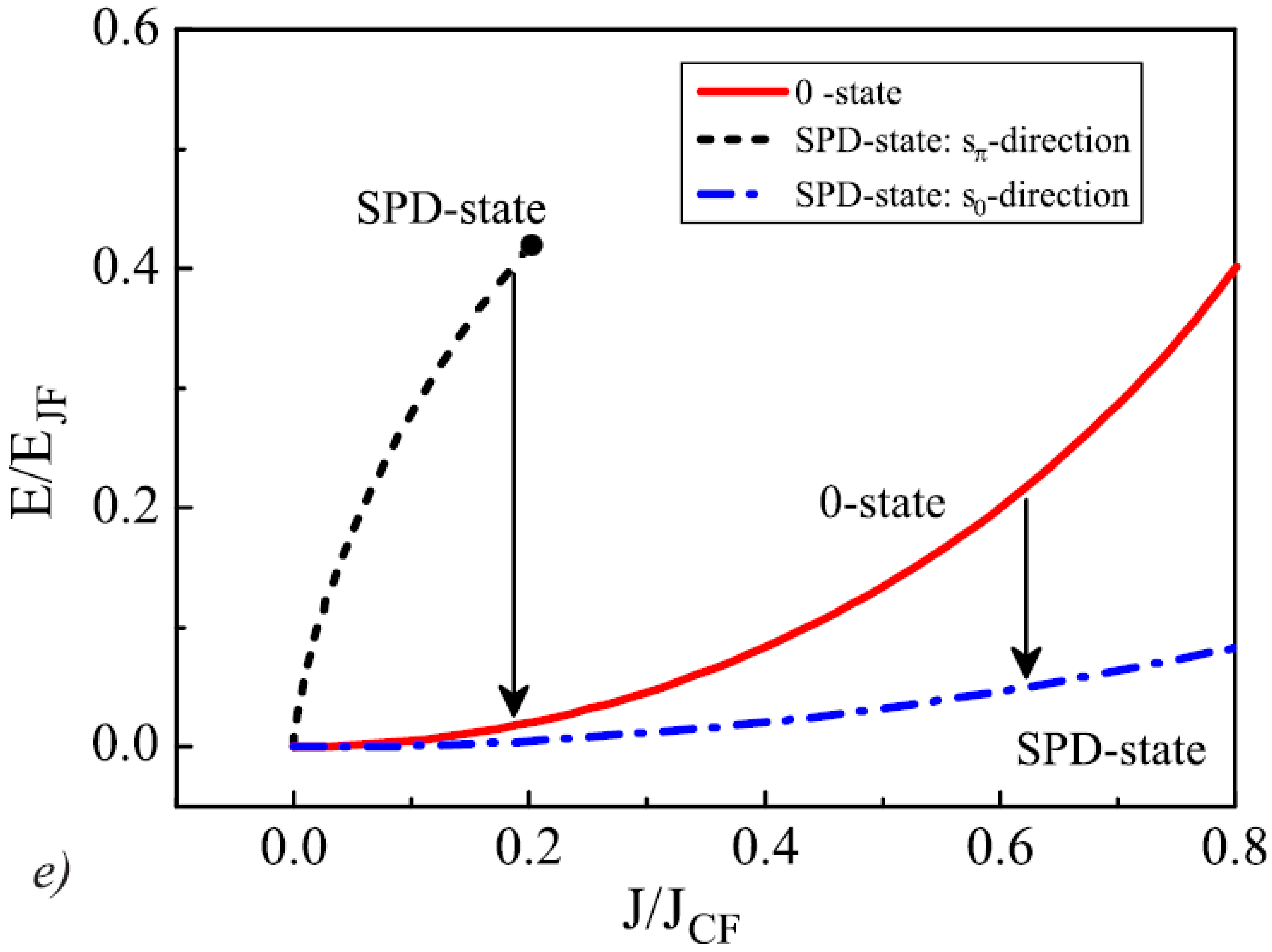
Critical current of SPD-wall < Critical current of SFS junction

Reverse current limited by SPD-wall

→ Total current: $J_{SFS}$-$J_{SPD}$ is much smaller $J_{SNS}$

→ Switch to Single state

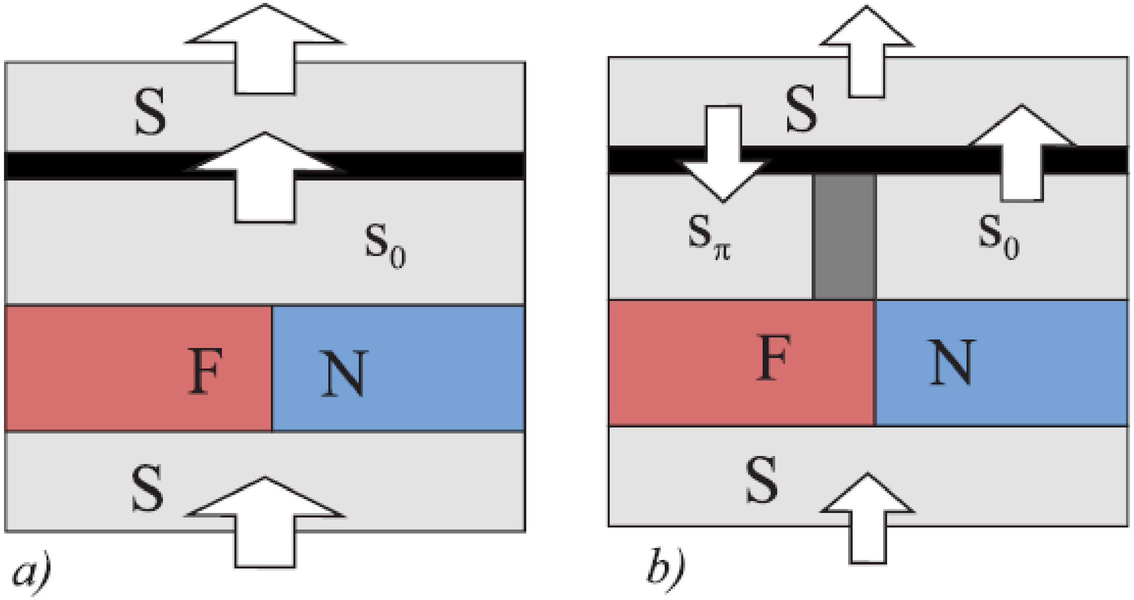
# Superconducting Phase Domain Memory Element



Energy of states for different current direction

# Superconducting Phase Domain Memory Element

## READ operation



Additional electrode is protected by tunnel barrier and doesn’t impact on the properties of the system

Critical current of domain state (b) is much less, than critical current of single state (a)!

*S.V. Bakurskiy, N.V. Klenov, I.I. Soloviev, M.Yu Kupriyanov, A.A. Golubov, Appl.Phys. Lett., 108(4):042602–1–5, (2016)*

# Thanks for your attention

You can check about this topic:

***Reviews:***

*A.A. Golubov et al, Rev. Mod. Phys. 76, 411 (2004).*

*M.G. Blamire et al, Journal of Phys. Cond. Matt., 26, 453201 (2014)*

*M. Eschrig, Reports on Progress in Physics, 78, 104501 (2015).*

*J. Linder, J. W. A. Robinson, Nature Physics, 11, 307 (2015)*

*J. W. Lu, et al, International Materials Reviews, 61:7, 456 (2016)*

*I. I. Soloviev et al., arXiv:1706.09124 (2017)*

***About SIsFS devices:***

*T. I. Larkin et al, Appl. Phys. Lett., 100, 222601 (2012)*

*I. V. Vernik et al, IEEE Tr. on Appl. Supercon., 23, 3, 1701208 (2013)*

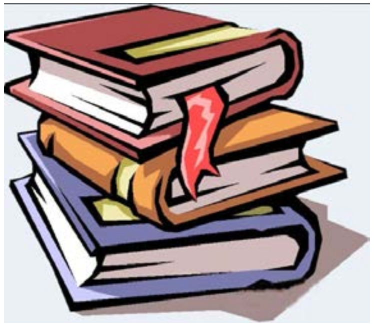
*S. V. Bakurskiy et al., Appl. Phys. Lett., 102, 192603, (2013)*

*S. V. Bakurskiy et al., Physical Review B, 88, 144519, (2013)*

*I. I. Soloviev et al., Appl. Phys. Lett., 105, 242601 (2014)*

*N. Ruppelt et al, Appl. Phys. Lett., 106, 022602 (2015)*

*I. A. Golovchanskiy et al., Phys. Rev. B 94 (21), 214514, (2016)*



***Complex CPRs and φ-junction:***

*A. Buzdin and A. E. Koshelev, Phys. Rev. B, 67,220504(R) (2003).*

*N. G. Pugach, et al, Phys. Rev. B, 81, 10, 104513 (2010)*

*E. Goldobin et al, Phys. Rev. Lett, 107, 227001 (2011).*

*H. Sickinger et al, Phys. Rev. Lett. 109, 107002 (2012).*

*S. V. Bakurskiy et al, Supercond. Sci. Technol. 26, 015005 (2013).*

*R. Menditto et al, Physical Review B, 93, 17, 174506 (2016).*

***Phase Memory Devices:***

*E. Goldobin et al, Appl. Phys. Lett. 102 (24), 242602 (2013).*

*T. Golod, et al, Nature communications,6, 8628 (2015).*

*S. V. Bakurskiy et al, Appl. Phys. Lett., 108 ,042602 (2016)*

*S. V. Bakurskiy et al, Phys. Rev. B 95, 094522 (2017)*

.