

Road to scalable superconducting phase memory devices

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I. I. Soloviev, M. Yu. Kupriyanov, A. A. Golubov



Outline:

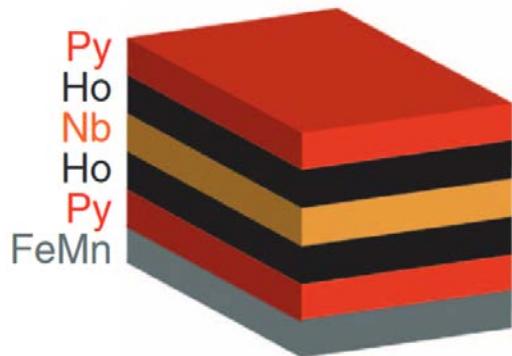
- Types of superconducting memory
 - Spin-valve devices on control of the critical temperature
 - Josephson spin-valve devices
 - Valves with single F layer
 - Single Flux Quantum (SFQ) memory devices
 - Superconducting phase memory devices
- SIsFS element for superconducting phase memory
- Phase memory element compatible with RSFQ

Types of superconducting memory

I: Spin-valve devices on control of the critical temperature

Change mutual magnetization -> Change T_C of superconductive layer S
-> Switch S from superconductive state to normal one

F-S-F type:



N. Banerjee et al.,
Nat. Comm.
5 3048 (2014)

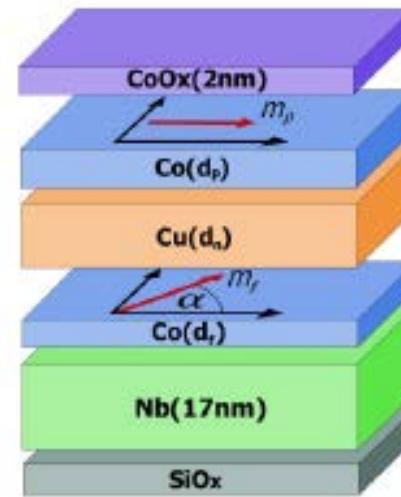
Y. Zhu, et al,
Nature Materials,
16, 195–199 (2017)

S-layer can be superconductive if $d_S > \xi_S$

Spin valve works effectively if $d_S > \xi_S$

Proposed to use ferromagnetic insulators

S-F-F type:



P.V. Leksin et al,
Phys. Rev. Lett.
109, 057005 (2012)

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

Benefit: F-layer can be fixed with antiferromagnetic layer (true spin-valve)

General Drawbacks: Require additional circuit for remagnetization: contour to apply strong field and source of spin polarized electrons for spin-torque

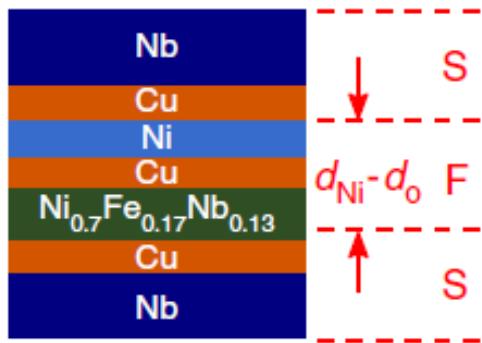
Difficulties with integration of these elements into circuit

Types of superconducting memory

II: Josephson spin-valve devices

Change mutual magnetization \rightarrow Critical current of Josephson junction

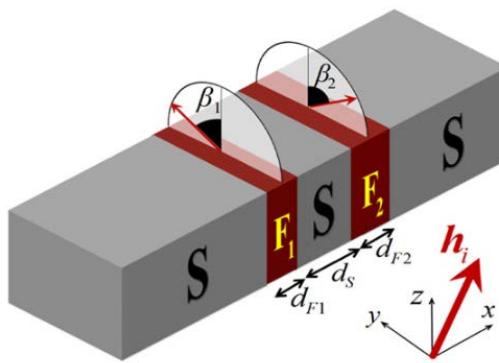
S-F-N-F-S type:



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

B. M. Niedzielski et al.,
arXiv:1709.04815 (2017)

S-F-s-F-S type:



K. Halterman and M. Alidoust,
SUST 29, 5, 055007 (2016)

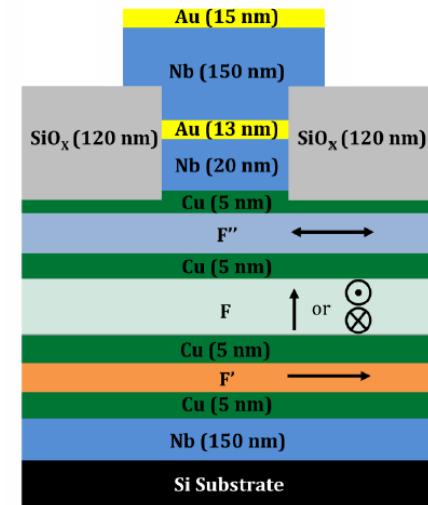
M. Yu. Kupriyanov et al.,
Patent RU 2554612 (2013)

Benefit: Josephson junctions (integration)

Drawbacks: Remagnetization required

Small $I_C R_N$ due to multiple F-layers (in comparison with SIS junctions) – small performance

Long-range triplet
S-F-F-F-S type:



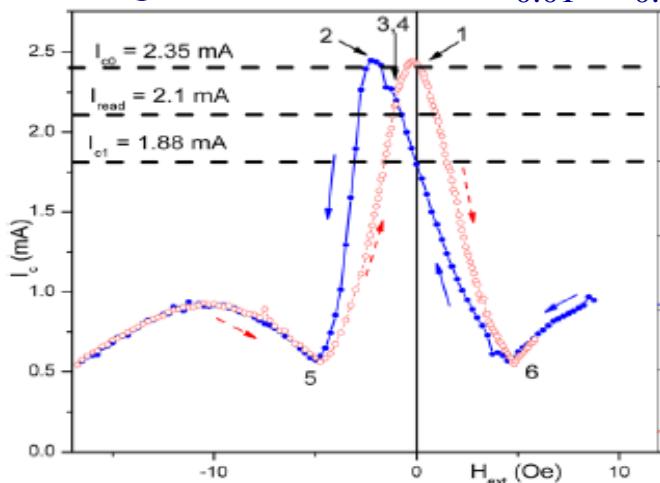
M. Houzet and A. I. Buzdin, Phys.
Rev. B, 76, 060504(R) (2007)

B. M. Niedzielski et al.,
IEEE Tran. on Appl.
Supercond. , 24, 4 (2014)

Types of superconducting memory

III: Valves with single F layer Control of Fraunhofer pattern

S-I-S-F-S type with cluster magnetic material $\text{Fe}_{0.01}\text{Pd}_{0.99}$:



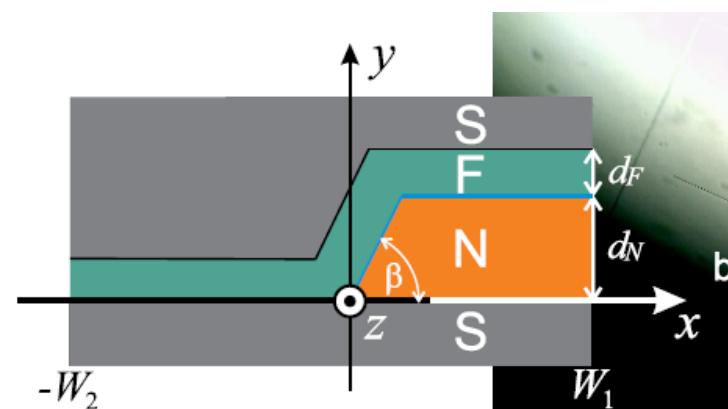
T. I. Larkin et al, Appl. Phys. Lett.
100, 222601 (2012)

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

Benefit: Single F layer

Drawback: Devices are not scalable
Still requires remagnetization

Magnetic Rotary Valve
S-F/NF-S structure



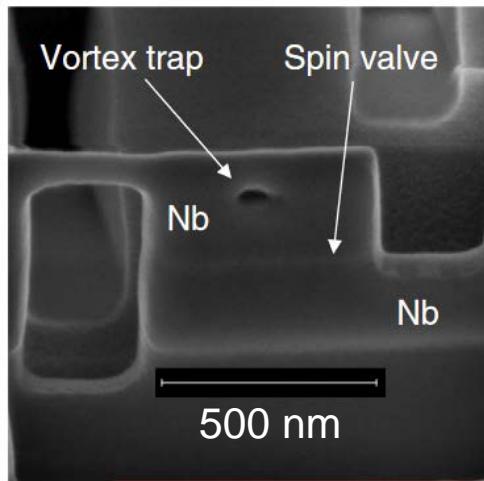
I. I. Soloviev et al, Appl. Phys. Lett.
105 (24), 242601 (2014)

Types of superconducting memory

IV: Single Flux Quantum (SFQ) devices

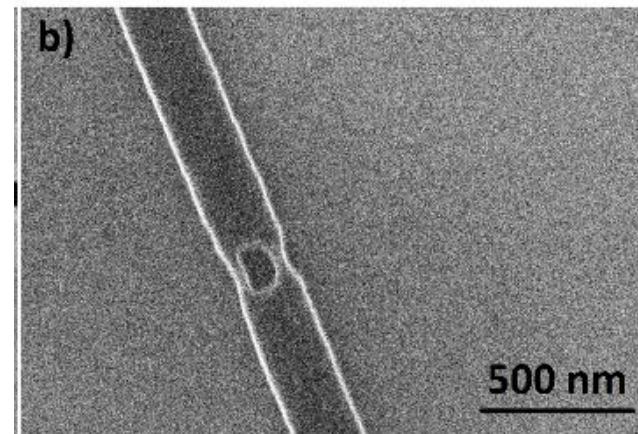
Try to catch a flux quantum inside device

Vortex trap near JJ



T Golod et al.,- Nat. Comm.,
6, 8628 (2015)

Nanowire SQUID
with kinetic inductance



A. Murphy et al., New J. Phys,
19, 063015, (2017).

Benefit: Current control, don't need remagnetization circuits

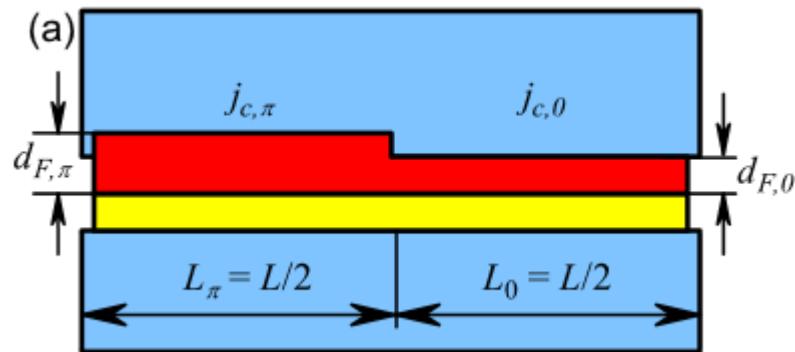
Drawback: You need enough inductance in SQUID to hold vortex
-> Scalability is limited

Types of superconducting memory

V: Superconducting Phase Memory devices

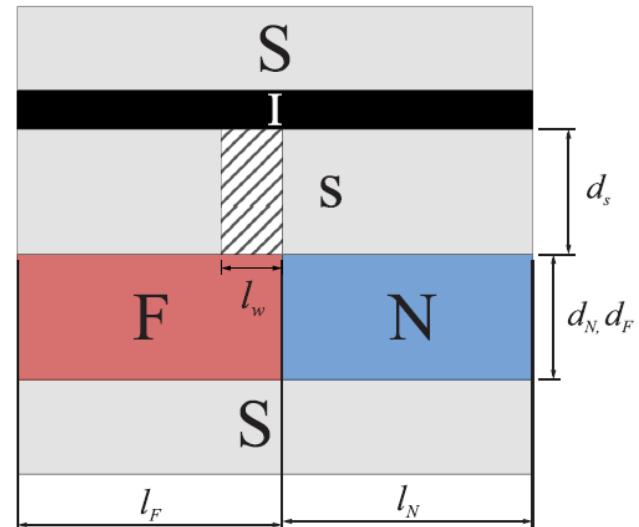
Direct control of the phase (or phase difference) of superconductor

φ -junction memory cell



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

Superconducting Phase Domains Memory



S.V. Bakurskiy et al., Appl.Phys. Lett.,
108(4):042602–1–5, (2016)

Benefit: It is possible to control with current
It is scalable, single F-layer (or even without it)

Drawback: Complex geometry

Phase memory devices

φ -junction memory element

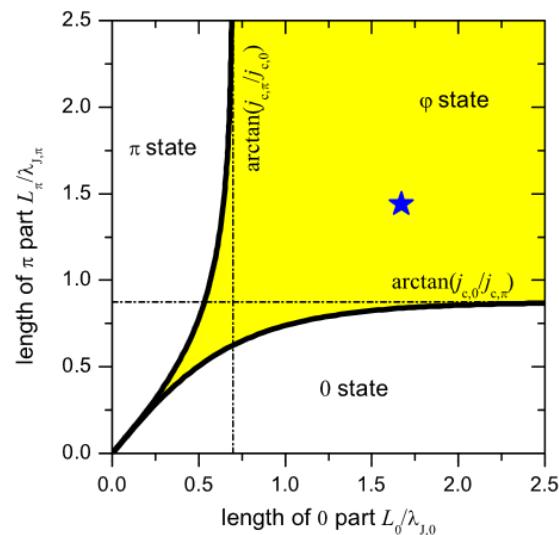
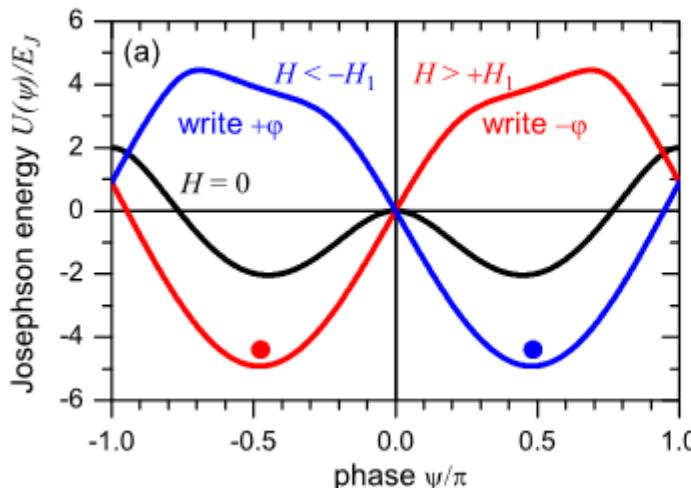
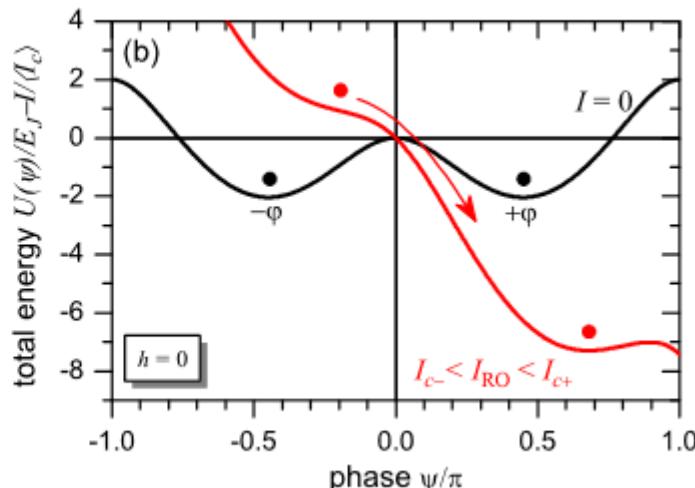


FIG. 3 (color online). Domain of existence of φ state. The \star shows the position of the investigated JJ at $T = 2.35$ K.

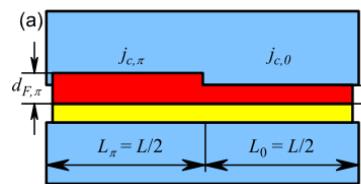


- Pioneer of direct phase control
- Write with field H
- Complex geometry
- Small characteristic voltage
- Destructive read operation
- Scalability is limited – device contains half flux quantum

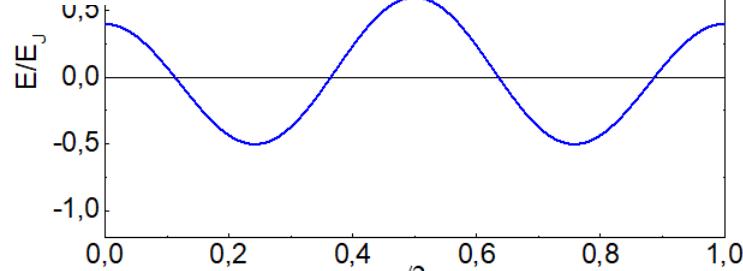
E. Goldobin et al., Appl. Phys. Lett. 102 (24), 242602 (2013)

φ -junction vs 0- π junction

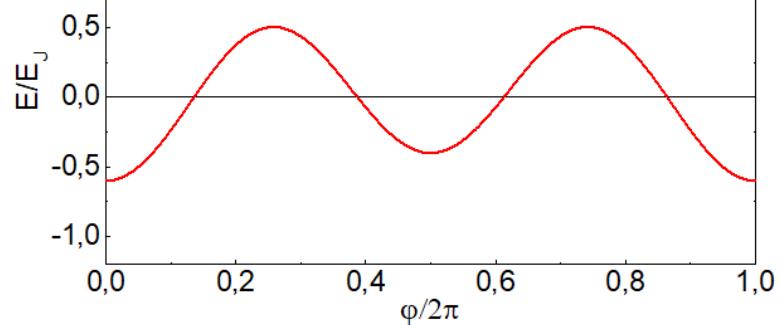
Compare Energy Phase Relations



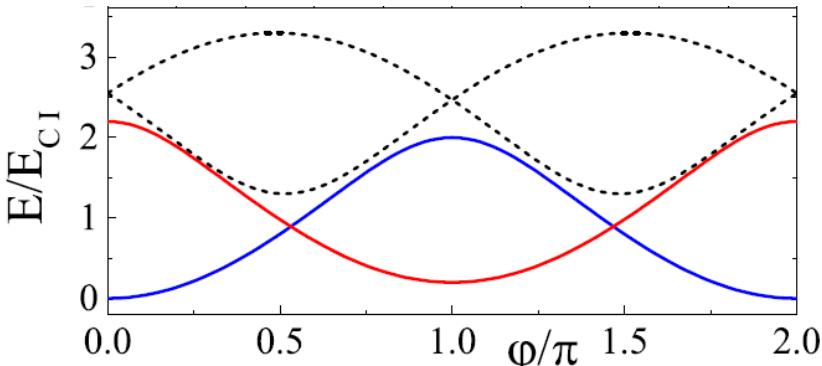
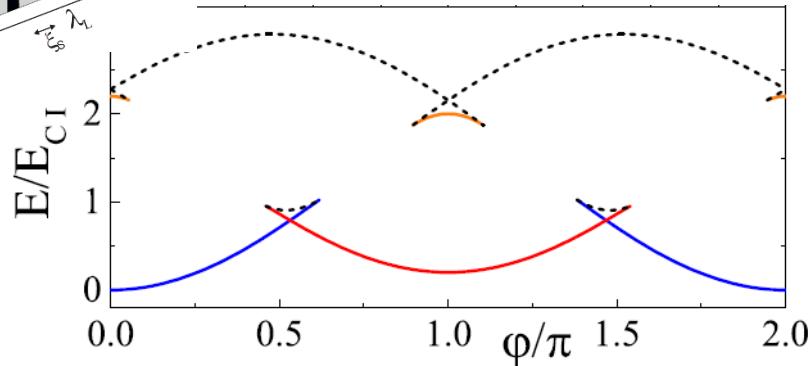
φ -junction S-F1/F2-S



0- π -junction SFS



0- π -junction SIsFS, $B < I_{CI}$



B – current amplitude of 2nd harm of SFs junction

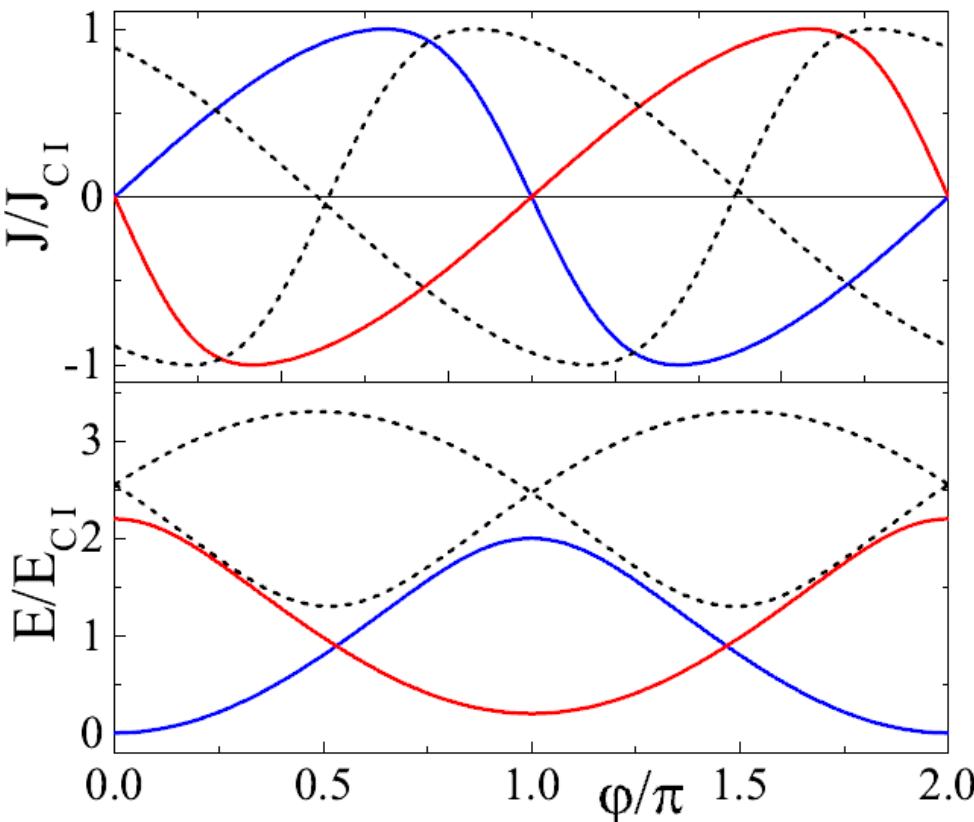
I_{CI} – critical current of sIS junction

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

- 2 stable energy states / 2 CPR branches
- Protected versus erase during read
- Tunnel layer I provides high $I_C R_N$

SIsFS 0- π junction in protected state

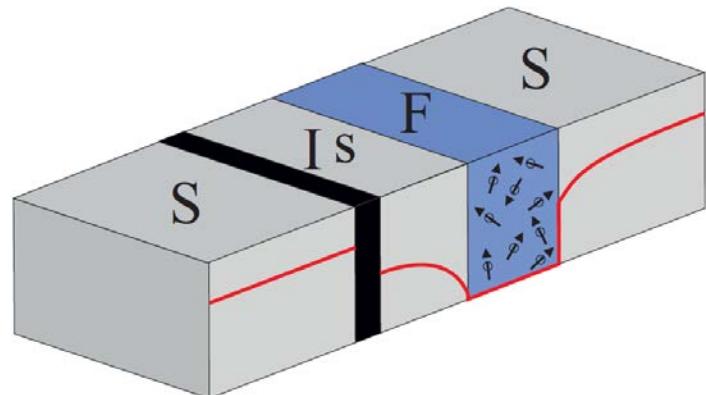
Current and Energy Phase Relations



B – current amplitude of 2nd harm of SFs junction

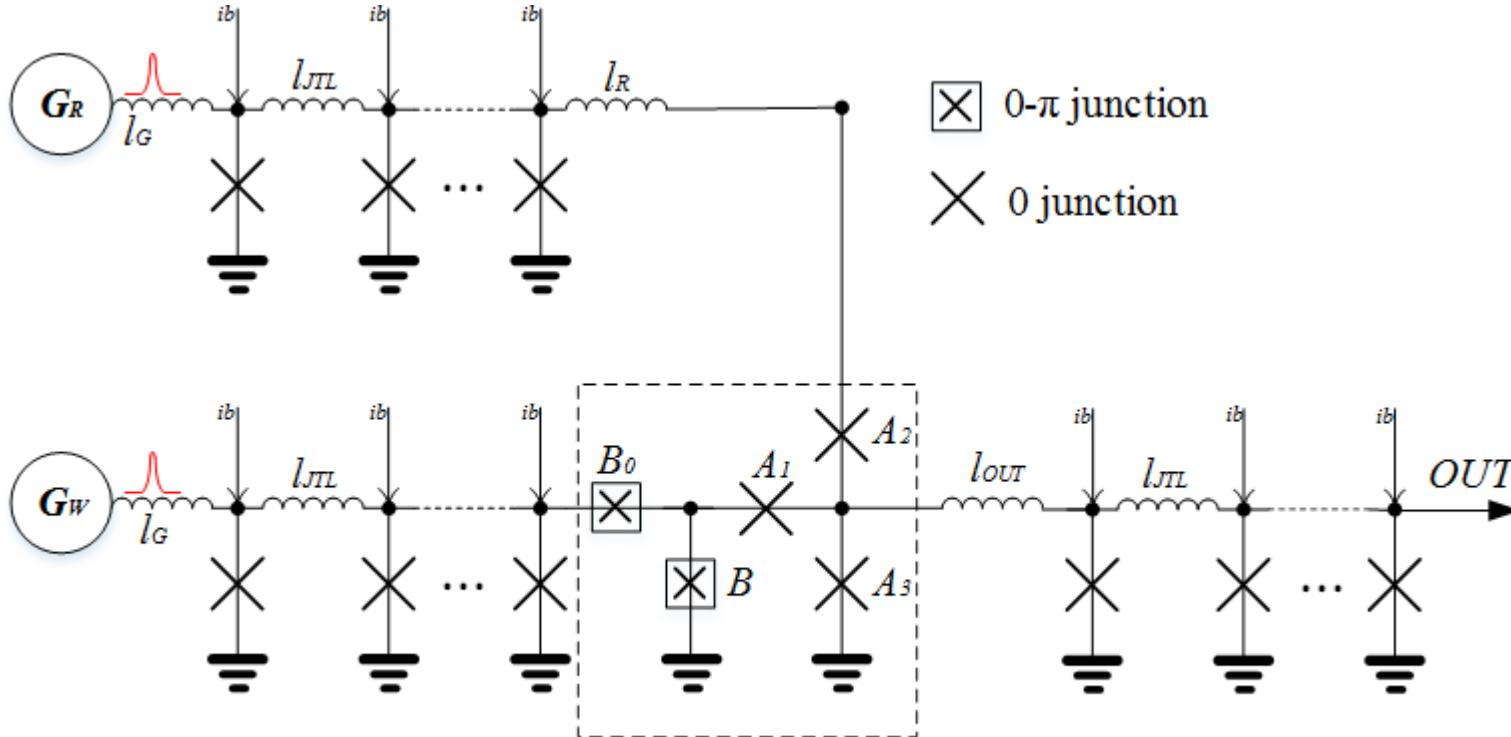
I_{CI} – critical current of sIS junction

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



- 2 stable energy states
- 2 independent branches of CPR
- Write operation – current $I > B$
- Read operation – current $I_C < I < B$
- Non-destructive read-out
- Tunnel layer I provides high $I_C R_N$
- Performance of SIS junction
- Stack geometry for fabrication
- Doesn't require remagnetization
- Need to hold the point of 0- π transition
- Require phase sensitive read-out

Example: phase memory compatible with RSFQ



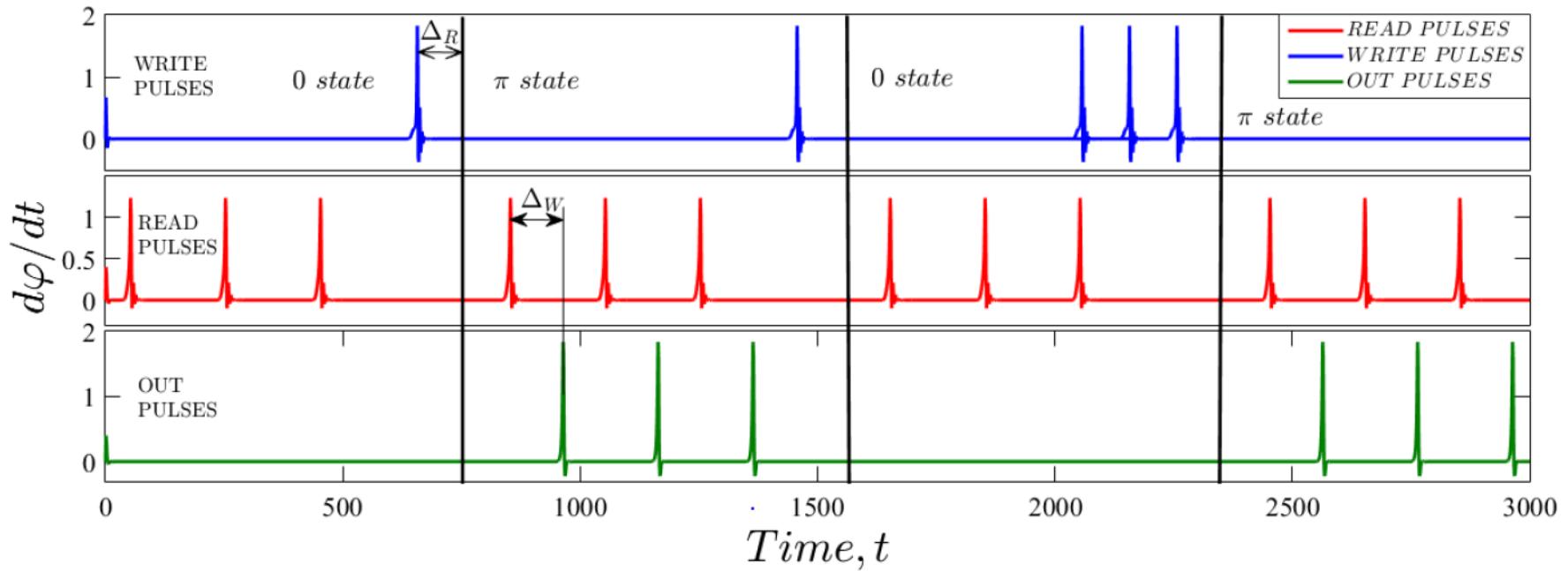
Write: Write pulse switch phase of B on π

Read: Junction B in π -state works as π -battery, then A_3 triggers on Write pulse

Memory cell doesn't contain inductance
Information stored in phase of 0- π or φ -junction
The cell is scalable

Example: phase memory compatible with RSFQ

Dynamic in RSJ model with 2-nd harmonic amplitude



Write: Write pulse switch phase on π

Read: Junction B in π -state works as π -battery, then device provides Out pulse

Highlights

Superconducting phase memory devices on $0/\pi$ or φ -junctions are

- Scalable
- Don't require remagnetization
- Provide non-destructive read-out with $I_C R_N$ of SIS junction
- Compatible with RSFQ

There are some possibilities to make $0/\pi$ or φ -junctions:

- SFS junction in $0-\pi$ transition point
- S-F1-F2-S junction with uncollinear magnetization (long range triplet effect)
- p-wave – s-wave Josephson junction
- Junction on d-wave grain boundaries

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)

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)

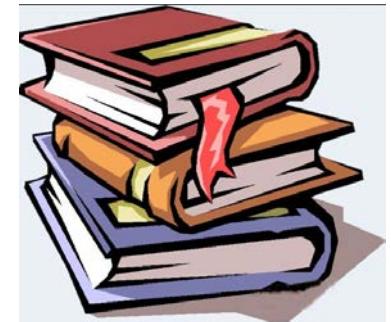
S. V. Bakurskiy *et al.*, *Physical Review B*, 88, 144519, (2013)

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)

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



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).

Model – Usadel equations

Usadel Equations

$$\frac{D}{2\omega G_\omega} \partial [G_\omega^2 \partial \Phi_\omega] - \Phi_\omega = -\Delta$$

$$G_\omega = \frac{\omega}{\sqrt{\omega^2 + \Phi_\omega \Phi_\omega^*}}$$

$$\omega = \pi T(2n+1) \quad \tilde{\omega} = \omega + iH$$

Kupriyanov-Lukichev
Boundary conditions

$$\gamma_{BFN} \xi_F \frac{\partial \Phi_F}{\partial z} = -\frac{G_N}{G_F} \left(\Phi_F - \frac{\tilde{\omega}}{\omega} \Phi_N \right),$$

$$\gamma_{BNF} \xi_N \frac{\partial \Phi_N}{\partial z} = \frac{G_F}{G_N} \left(\Phi_N - \frac{\omega}{\tilde{\omega}} \Phi_F \right),$$

$$\gamma_{BFN} = \frac{R_{BFN} \mathcal{A}_{BFN}}{\rho_F \xi_F} = \gamma_{BNF} \frac{\rho_F \xi_F}{\rho_N \xi_N},$$

$$D = 2\pi T_c \xi^2$$

Current Expression

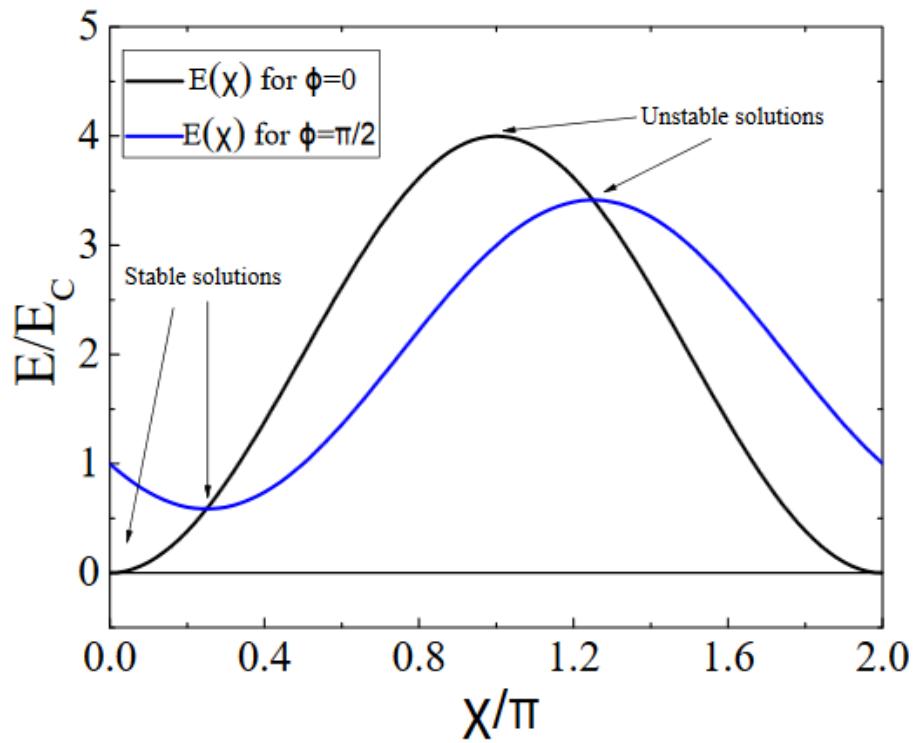
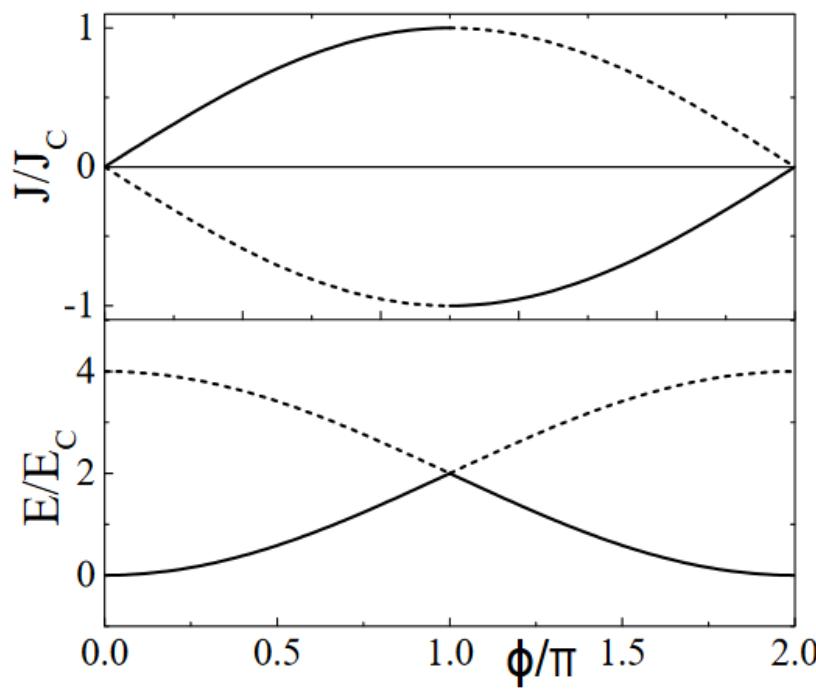
$$\frac{2ej(\varphi, z)}{\pi T} = \sum_{\omega=-\infty}^{\infty} \frac{iG_\omega^2}{\rho_q \tilde{\omega}_q^2} \left[\Phi_\omega \frac{\partial \Phi_\omega^*}{\partial x} - \Phi_\omega^* \frac{\partial \Phi_\omega}{\partial x} \right]$$

$$I_S(\varphi) = \int j(\varphi, z) W dz$$

Self-Consistency equation

$$\Delta \ln \left(\frac{T}{T_c} \right) + \pi T \sum_{\omega=-\infty}^{\infty} \left(\frac{\Delta}{|\omega|} - \frac{G_\omega \Phi_\omega}{\omega} \right) = 0$$

Unstable states in SIsFS



Two solutions of $I_{CI}=I_{CF}$
Stable over χ and not