Josephson junctions with ferromagnetic layers for memory applications

S. V. Bakurskiy
World Electronics
Large Scale Projects:

K-computer, Japan
Power consumption 12.7 MW

Facebook Data Center, Sweden
Power consumption 84 MW

Nuclear Power Plant
Capacity 1000 MW
Superconductive Way to Energy Efficiency

![Graph showing power and performance with a note indicating a lack of acceptability.](image-url)
Contents:

• Room temperature memory
• S-F proximity effect
• Spin-valve superconducting memory
• SFQ superconducting memory
• Superconducting phase memory
Magnetic core memory: 1955-1975

Matrix: $N^2$ cells require 2 $N$ wires
Destroying Read operation.

Operational Time $\sim$ 1 $\mu$s
Density $\sim$ 10 bits/mm$^2$
Giant magnetoresistance (GMR) effect

Realistic spin-split DOS

N↑(E)  N↓(E)  N↑(E)  N↓(E)

Cu  Co

Nobel prize 2007
Giant magnetoresistance (GMR) effect

\[ H = H_{\text{sat}} \]

\[ H = 0 \]

\[ \frac{\Delta R}{R} = \frac{R_{\text{AP}} - R_{\text{p}}}{R_{\text{p}}} \]
Hard drive disk (HDD)

Anisotropy keeps the moment pointing in the direction of the track.

The transition width $d$ is affected by both the anisotropy and the magnetization.

Magnetic Random Access Memory (MRAM)
Spin torque devices

Schematic representation of OST device.

Landau–Lifshitz–Gilbert equation

$$\frac{dM}{dt} = -\gamma \left( M \times H_{\text{eff}} - \eta M \times \frac{dM}{dt} \right)$$

Fast deterministic switching in orthogonal spin torque devices via the control of the relative spin polarizations

EPROM and 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)

1 cell = 2 elements
Capacitors only!
Need restore data every 10 ms

Static RAM (SRAM)
1 cell = 8 elements
Trigger based
Too expensive

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

<table>
<thead>
<tr>
<th>Metric</th>
<th>DRAM</th>
<th>NAND flash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data retention</td>
<td>~10 ms</td>
<td>3 months to 10 years</td>
</tr>
<tr>
<td>Cycling endurance</td>
<td>&gt;10 years continuous use</td>
<td>$10^5$–$10^6$ rewrites</td>
</tr>
<tr>
<td>Read latency</td>
<td>10–20 ns</td>
<td>10–25 ns</td>
</tr>
<tr>
<td>Write latency</td>
<td>10–20 ns</td>
<td>~100 μs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metric</th>
<th>ST-MRAM (EMD3M064M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data retention</td>
<td>3 months to 10 years</td>
</tr>
<tr>
<td>Cycling endurance</td>
<td>&gt;10 years continuous use</td>
</tr>
<tr>
<td>Read latency</td>
<td>10–50 ns</td>
</tr>
<tr>
<td>Write latency</td>
<td>10–50 ns</td>
</tr>
</tbody>
</table>

Contents:

• Room temperature memory
• S-F proximity effect
• Spin-valve superconducting memory
• SFQ superconducting memory
• Superconducting phase memory
Superconductor-Ferromagnet proximity effect

\[ \pi \text{-transition at } d_F \approx \pi \xi_{F2} \]

\[ I_S(\varphi) = I_C \sin(\varphi + \pi) = -I_C \sin(\varphi) \]

\[ \begin{array}{c}
\text{S} \\
\text{F} \\
\text{S}
\end{array} \rightarrow \begin{array}{c}
\text{S} \\
\text{F} \\
\text{S}
\end{array} \]

\[ H_{ex} \]

\[ Nb - Cu_{0.47} Ni_{0.53} - Nb \]

---


Coherence length

In calculations and normalization, it is convenient to use the characteristic length of material determined by diffusion coefficient

\[
\xi_{N,F}^2 = \frac{D_{N,F}}{2\pi T_C}
\]

The effective damping and oscillations length depend on temperature, exchange field, and geometrical parameters. In a ferromagnet, it has the form:

\[
\xi_{1,2}^* = \sqrt{\frac{\hbar D}{\sqrt{\pi^2 T^2 + H^2} \pm \pi T}}
\]

It is often suitable for describing experimental data, but it is not always possible to introduce it.
Proximity effect in SF…F structure in antiferromagnetic configuration for different F layers thickness $d_i$

$\sum \gamma_B = 0.3, \ H = 10T_C, \ T = 0.5T_C \quad d_i = 0.2\xi, 0.51\xi, 0.8\xi, \xi, 1.5\xi, 3\xi, 5\xi.$

$\Psi(x) = \exp \left(-\frac{x}{\xi_1}\right) \left(A + B \cos \left(\frac{x}{\xi_2} + \varphi\right)\right).$
Proximity effect in SF structures: domain effect

$e_C R_N \gamma_{BS} / 2 \pi T \Delta^2$

$W/\xi_F = 0.3$

$W/\xi_F = 0.5$

$W/\xi_F = 0.7$

$W/\xi_F = 1.0$

$W/\xi_F = 1.2$

$d_F / \xi_F$
Proximity effect in SF structures: domain effect

\[ \frac{eI_CR_N}{2\pi T_C} = \frac{T}{2WT_C} \sum_{\omega>0} \frac{ZG_0\Delta}{\omega} S(\omega), \quad (18) \]

\[ S(\omega) = \sum_{n=-\infty}^{\infty} (-1)^n \left[ \frac{W}{q_+^2} + \frac{W}{q_-^2} - \frac{2S_-S_+ (q_-^2 - q_+^2)^2}{\delta q_+^3 q_-^3} \right]. \]

\[ I_C(d_F) = A \exp(-d_F/\xi_1) \cos(d_F/\xi_2 + \varphi), \]

Pis'ma v ZhETF, vol. 101, iss. 11, pp. 863–868
Contents:

• Room temperature memory
• S-F proximity effect
• Spin-valve superconducting memory
• SFQ superconducting memory
• Superconducting phase memory
# IARPA Metrics

## Table 7. Program Metrics and Goals by Program Period

<table>
<thead>
<tr>
<th>Metric</th>
<th>BP</th>
<th>OP1</th>
<th>OP2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cryogenic Memory</strong></td>
<td>Memory cell</td>
<td>Array</td>
<td>Chip</td>
</tr>
<tr>
<td>Functional capacity (bit)*</td>
<td>1</td>
<td>$2^6$ ; $2^6$</td>
<td>$2^{10}$ ; $2^{10}$</td>
</tr>
<tr>
<td>Density (bit/cm$^2$)*</td>
<td>$10^6$ ; $10^5$</td>
<td>$5 \times 10^6$ ; $5 \times 10^5$</td>
<td>$10^7$ ; $10^6$</td>
</tr>
<tr>
<td>Data rate, burst mode (Gbit/s)*</td>
<td>1</td>
<td>5; 30</td>
<td>5; 30</td>
</tr>
<tr>
<td>Access time, ave. (ps)*</td>
<td>10,000; 1,000</td>
<td>5,000; 400</td>
<td>5,000; 400</td>
</tr>
<tr>
<td>Access energy, ave. (J/bit)*</td>
<td>$5 \times 10^{-16}$ ; $5 \times 10^{-17}$</td>
<td>$5 \times 10^{-16}$ ; $5 \times 10^{-17}$</td>
<td>$10^{-16}$ ; $10^{-17}$</td>
</tr>
<tr>
<td><strong>Logic, Comm. &amp; Systems</strong></td>
<td>Subcircuits</td>
<td>Circuits</td>
<td>Processors</td>
</tr>
<tr>
<td>Benchmark circuits &amp; applications</td>
<td>Circuits 1</td>
<td>Circuits 2</td>
<td>Circuits 3</td>
</tr>
<tr>
<td>Complexity (JJ)</td>
<td>$10^4$</td>
<td>$5 \times 10^4$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Density (JJ/cm$^2$)</td>
<td>$10^5$</td>
<td>$5 \times 10^5$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Throughput (bit-op/s)</td>
<td>$10^9$</td>
<td>$5 \times 10^{10}$</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Efficiency @ 4 K (bit-op/J)</td>
<td>$10^{16}$</td>
<td>$5 \times 10^{16}$</td>
<td>$10^{17}$</td>
</tr>
</tbody>
</table>

* Memory metrics: The first number refers to Main Memory and the second to Cache 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.


R.G. Deminov et al., JMMM (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

You can even control magnetization with superconductive order

Stronger effect!

Josephson spin valve devices

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

$\text{Nb/Cu(3 nm)/Ni}_{0.7}\text{Fe}_{0.17}\text{Nb}_{0.13}(2.1 \text{ nm})/\text{Cu(5 nm)/Ni/Cu(3 nm)/Nb.}$
SFFS pseudo spin valves

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}Nb_{0.13}(2.1 nm)/Cu(5 nm)/Ni(3 nm)/Cu(3 nm)/Nb(70 nm).

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)

Theory of SFSFS and SFSFFS spin valve devices
Structures with long range proximity effects

B. M. Niedzielski et al., IEEE Tran. on Appl. Supercond. (2014)
Structures with long range proximity effects

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

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

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

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

Bol’ginov V.V., Stolyarov V.S et al, JETP letters, 95, 7, 366, (2012)
Josephson magnetic rotary valve

\[ 0 + \pi \]

\[ 0 + 0 \]

I. I. Soloviev, N. V. Klenov, S. V. Bakurskiy, V. V. Bol’ginov, V. V. Ryazanov, M. Yu. Kupriyanov, and A. A. Golubov

APPLIED PHYSICS LETTERS 105, 242601 (2014)
Contents:

• Room temperature memory
• S-F proximity effect
• Spin-valve superconducting memory
• SFQ superconducting memory
• Superconducting phase memory
RSFQ logic


Flux trap near Josephson junction

Flux trap in nanowire

Flux based memory

Density -1Mbit/cm²

Fig. 5. A ten by four fragment of the 12 x 6 memory cell array fabricated using 600 μA/μm² technology. The word selection and bit selection lines IX and IY are marked in the picture along with the readout line IS. The chip was rotated about 90° for electrical testing, giving a difference in cell labeling in Fig. 6.

arXiv:1902.08302 (cross-list from physics.app-ph) [pdf]

Very Large Scale Integration of Josephson-Junction-Based Superconductor Random Access Memories
Contents:

• Room temperature memory
• S-F proximity effect
• Spin-valve superconducting memory
• SFQ superconducting memory
• Superconducting phase memory
Current Phase Relations

\[ l_s(\phi) = A \sin(\phi) + B \sin(2\phi) + \ldots \]

**0-state**

- \( A > 0 \), \( |B| < \frac{|A|}{2} \)
- \( B > 0 \), \( |B| < \frac{|A|}{2} \)

**π-state**

- \( A > 0 \), \( |B| < \frac{|A|}{2} \)
- \( B < 0 \), \( |B| < \frac{|A|}{2} \)

**0+π-state**

- \( A > 0 \), \( |B| < \frac{|A|}{2} \)
- \( B > 0 \), \( |B| < \frac{|A|}{2} \)

**φ-state**

- \( A > 0 \), \( |B| < \frac{|A|}{2} \)
- \( B < 0 \), \( |B| < \frac{|A|}{2} \)
2nd harmonic in the current-phase relation of SFS junction

Red line is $\sin(\varphi)$ and blue line is $\sin(2\varphi)$ amplitudes
0-\(\pi\) transition

Critical current \(J_C\)  CPR  Energy

(a1) \(\frac{J_C}{J_{C0}}\)  (a2) 
(a3) \(\frac{E(\phi)}{E_c}\)  (a4) 
(a5) 

(b1) \(\frac{J_C}{J_{C0}}\)  (b2) 
(b3) \(\frac{E(\phi)}{E_c}\)  (b4) 
(b5) 

(c1) \(\frac{J_C}{J_{C1}}\)  (c2) 
(c3) \(\frac{E(\phi)}{E_c}\)  (c4) 
(c5) 

\(J_{CI} > J_{CF}\)

\(J_{CI} << J_{CF}\)
Memory cell based on $\phi$-junction

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

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

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

\[ \frac{I_s R_N}{2\pi T_C} \]

CPR of SFS junction
in the region of 0-\pi transition
Regimes of SIsFS junction

- **k**: number of branches
- **m**: number of breaks on branches

Hysteretic states, $k=2$, $m=4$
Switching the states, $k=2$, $m=4$

RSJ-model of SIsFS structure
Protected states, $k=2$, $m=0$
CPR transformation during decrease of $d_s$

CPR of SIsFS junction for decrease of s-layer thickness

(1) $d_s = 5\xi$, (2) $d_s = 3.5\xi$,
(3) $d_s = 3\xi$, (4) $d_s = 2.9\xi$,
(5) $d_s = 2.8\xi$, (6) $d_s = 2.7\xi$,
(7) $d_s = 2.6\xi$

Energy phase relation of sFS junction for decrease of s-layer thickness

Local minimum of 0-state disappears near critical thickness $d_s = 2.7\xi$
Characteristic energies in SIsFS

At small thickness of the s-layer the properties of s-layer in 0 and π are different

At small thickness of the s-layer the properties of s-layer in 0 and π are different.

Measurement of this effect requires very untransparent I layer.


CPR of SIsFS with thin s-layer

Truly Josephson Memory?
Electrical control
Read performance of SIS junction
Non-destructive read operation
Remagnetization is not need to write
Scalability
Narrow area of parameters
Small critical current
Nonequilibrium effects?

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

1. Josephson Energy of SFs junction $\Delta E_{SFs}$
2. Josephson Energy of SNs junction $\Delta E_{SNs}$
3. Pairing Energy of certain volume $\Delta E_{DW}$

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

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 $\Delta E_{DW}$

$$\Delta E_{DW} = \Delta F_{GL} l_{DW} d_S W + \frac{\hbar j_C s d_s W}{e} \sim d_s$$
$$\Delta E_{SFs} = \frac{\hbar j_C F l_F W}{e} \sim l_F$$
$$\Delta E_{SNs} = \frac{\hbar j_C N l_N W}{e} \sim l_N$$

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

Numerical Solution for Pair Potential $\Delta$

$d_s = 3 \xi_s$

$d_s = 3.5 \xi_s$

$d_s = 4 \xi_s$

$d_s = 5 \xi_s$

$d_F = 1 \xi_S$

$W = 16 \xi_S$

$H = 10\pi T_C$
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**

![Diagram showing phase domain states](image)

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)!

Instead of conclusion

Planarized Fabrication Process With Two Layers of SIS Josephson Junctions and Integration of SIS and SFS π-Junctions (2019)

Sergey K. Tolpygo, Senior Member, IEEE, Vladimir Bolkhovsky, Ravi Rastogi, Scott Zarr, Alexandra L. Day, Evan Golden, Terence J. Weir, Alex Wynn, and Leonard M. Johnson, Senior Member, IEEE

Fig. 1. (a) A scanning electron microscope (SEM) image of a cross section made by focused ion beam (FIB) of a new process, PSE2 with two layers of Josephson junctions placed near the bottom of the process stack. White labels indicate process layers in notations used in the SFQSee process: J5 is the first Josephson junction layer, C5J – top via to junction J5, R4 – the first resistor layer, C4 – via to the resistor R4, J4 – via to Nb layer M4, and so on. M7 is the base electrode of the second trilayer and J7 is the second layer of JJs. Note the difference in placement of the first resistor layer R4, which is below J5, relative to the second resistor layer R7, which is above J7.

(b) A zoom in on the PSE2 cross section, showing 700-nm diameter junctions J5 and J7. The anodic Nb oxide layer is clearly visible around the junctions J5 and J7; also visible on the surface of layers M5 and M7 is a columnar mixed-oxide (Nb/Al)Ox layer formed during anodization of the Al layer on Nb base electrode of the trilayers. The top surface of the wafer is passivated by SiO2 and chip contact pads are metallized by Pt/Au through passivation openings (PO).
Thanks for your attention

You can check about this topic:

Reviews:

About SIsFS devices:
R. Caruso, et al., IEEE Tr. on Appl. Supercon. 28(7), 1-6 (2018)

Complex CPRs and φ-junction:

Phase Memory Devices: