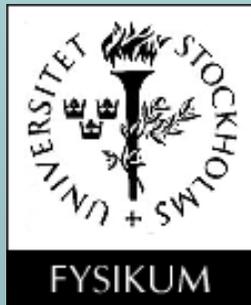


Cryogenic memory element based on a single Abrikosov vortex

Vladimir Krasnov, T. Golod and A. Iovan

Experimental Condensed Matter Physics Group

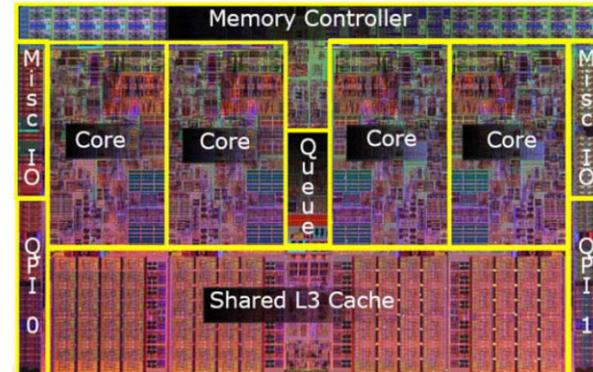
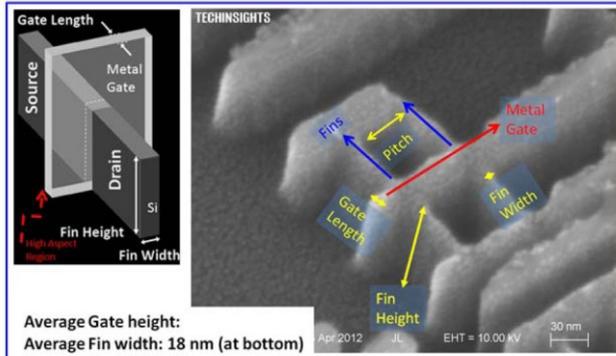


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Stockholm University
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4 September 2015, Chernogolovka

Starting with small (size) ending with **LARGE (Power)**



$E_{bit} \sim 1-10 \mu J \times 10^8 \text{ bit} \times 3 \text{ GHz} = 3 \times 10^{11} - 10^{12} \text{ W} \quad (0.1 - 1 \text{ kW})$

Data Centers: Facebook Data Center Luleå, Sweden



Specifications	
Performance*	27-51 PFLOP/s
Memory*	21-27 PB RAM 1900-6800 PB disk
Power	84 MW avg* (120 MW max)
Space	290,000 ft ² (27,000 m ²)
Cooling*	~1.07 PUE

* estimated

- 2014 completion target
- Cost: ~760 M\$
- Nearby Lule River generates 9% of Sweden's electricity (~4.23 GW)
- Average annual temperature: 1.3 °C

Courtesy of S. Holmes

Data Centers:

- Cloud computing
- Banking
- Shopping
- Social Networks
- Search Engines....

Luleå 
data center:
120 MW
(max power)

Supercomputers: K-Computer (Japan)



Top500 No. 4 supercomputer: K-computer (Japan):
10.51 petaflop/s, 12.7 MW

Top500 No. 1: Tianhe-2 (China):
33.9 petaflop/s, 17.8 MW



After O. A. Mukhanov, HYPRES Inc, USA



Motivation: Superconducting Computer

How many lives does it have ?

†: USSR '80, ††: USA '80, †††: USA + Russia '90,

Semiconductors beat Superconductors + Cryofobia

4: 2014 USA, Cryogenic Computing Complexity (C3) program

<http://www.iarpa.gov/index.php/researchprograms/c3/baa>

Power management problem for semiconductor technology.
Maintenance costs exceed the cost of refrigeration
For an exaflop computer $P \sim 100$ MW.

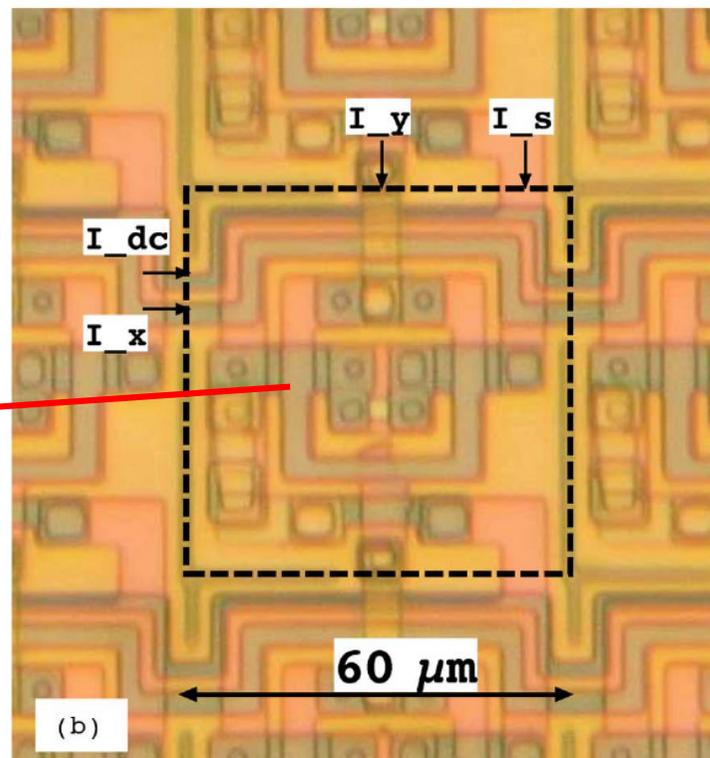
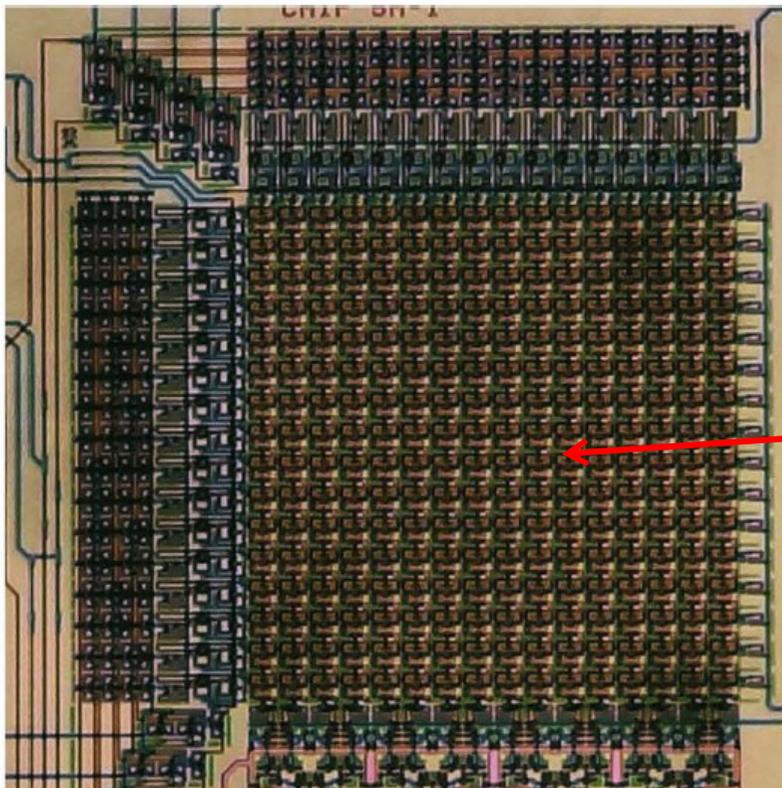
S-computer would not only drastically decrease the consumed power, but could also greatly increase the operation speed.

Lack of suitable cryogenic random access memory (RAM) is “...the main obstacle to the realization of high performance computer systems and signal processors based on superconducting electronics.”

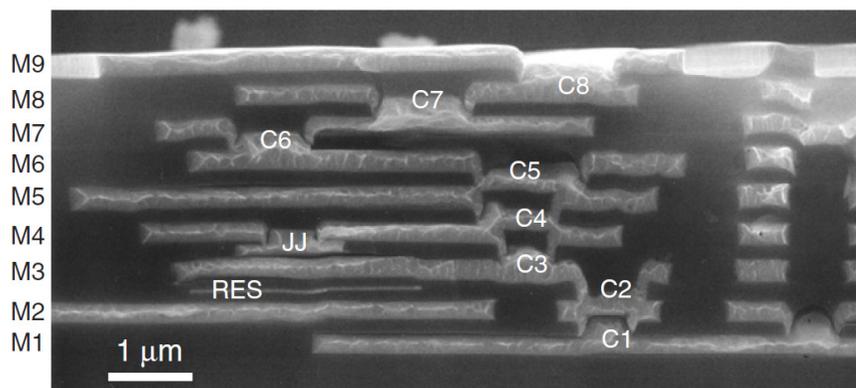
Ortlepp, T., and Van Duzer, T., IEEE Trans. Appl. Supercond., 24, 1300307 (2014).



SFQ memory: Flux quantum in a double SQUID loop



Major scalability problem: $I_{write} = \Phi_0 / L$



256 bit VT-RAM

Ortlepp, T., and Van Duzer, T., IEEE Trans. Appl. Supercond., 24, 1300307 (2014).

Nagasawa, S. Hinode, K., Satoh, T., Kitagawa, Y., and Hidaka, M., SuST 19, S325 (2006).

Proposed SFS memory cells (MRAM-like)

Larkin, T.I., Bolginov, V. V., Stolyarov, V. S., Ryazanov, V.V., Vernik, I.V., Tolpygo, S. K., and Mukhanov, O.A., *Ferromagnetic Josephson switching device with high characteristic voltage*, **Appl. Phys. Lett.**, **100**, 222601 (2012).

Herr, A.Y. , and Herr, Q.P., **US patent No US8270209 B2**, *Josephson magnetic Random Access Memory System and Method* (201

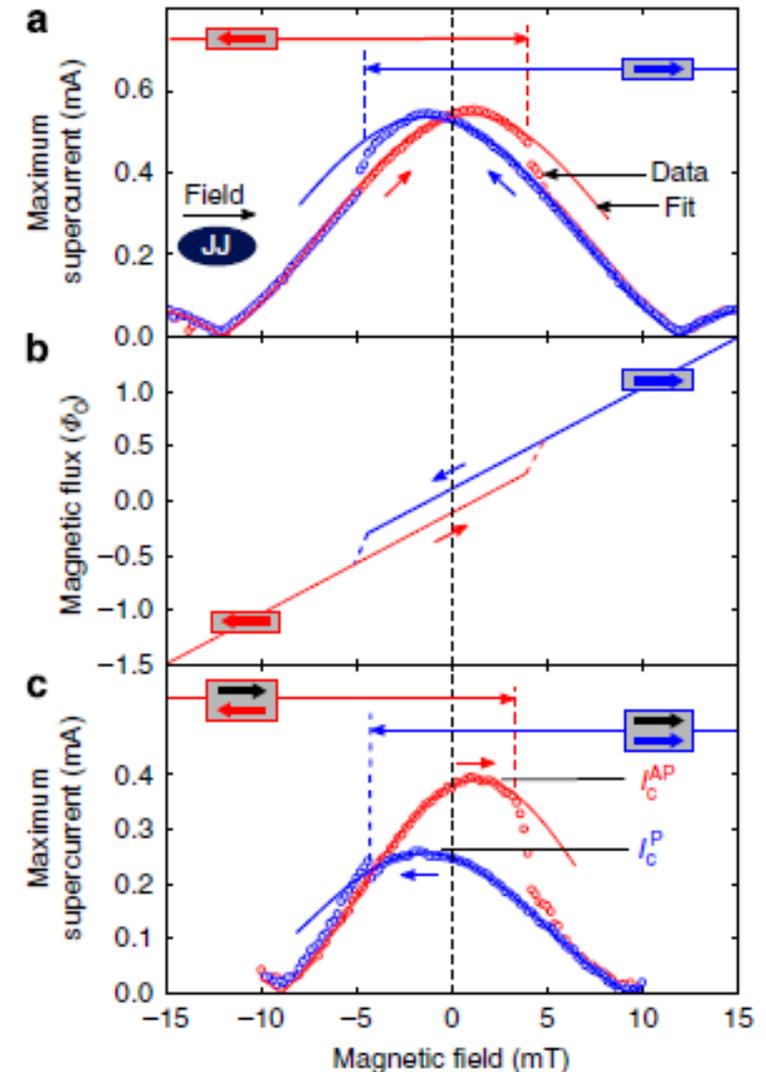
Naaman, O., Miller, D., Herr, A.Y., and Birge, N. **WO2013180946 A1**, *Josephson magnetic memory*

Zdravkov, V. I., Lenk, D., Morari, R., Ullrich, A., Nidda, H.-A., Sidorenko, A. S., Horn, S., Tidecks, F *effect and triplet pairing generation in the supercon Co/CoOx/Cu41Ni59/Nb/Cu41Ni59 layered heteros* **062604 (2013)**.

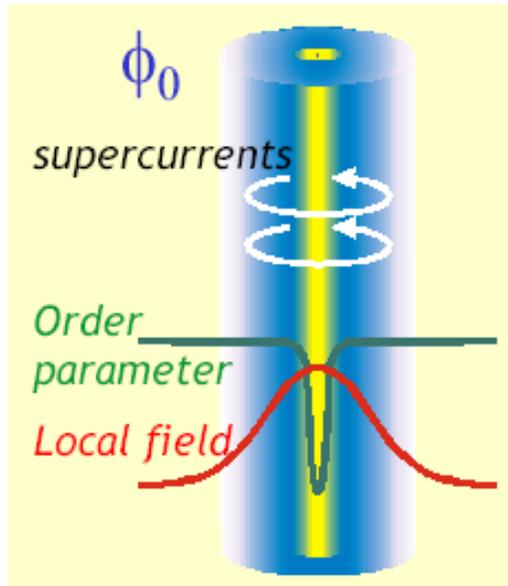
Baek, B, Rippard, W. H., Benz, S. P., Russek, S *Hybrid superconducting-magnetic memory device* **Nat. Commun.**, **5**, 3888 (2014) doi: 10.1038/ncom

Nevirkovets, I.P., Chernyashevskyy, O., Prokofyev, K., Ketterson, J.B., *Superconducting-Ferromagnetic Tunnel Junction* **Supercond.**, **24**, 1800506 (2014).

Performance remains to be studied...



Abrikosov vortex RAM : AVRAM

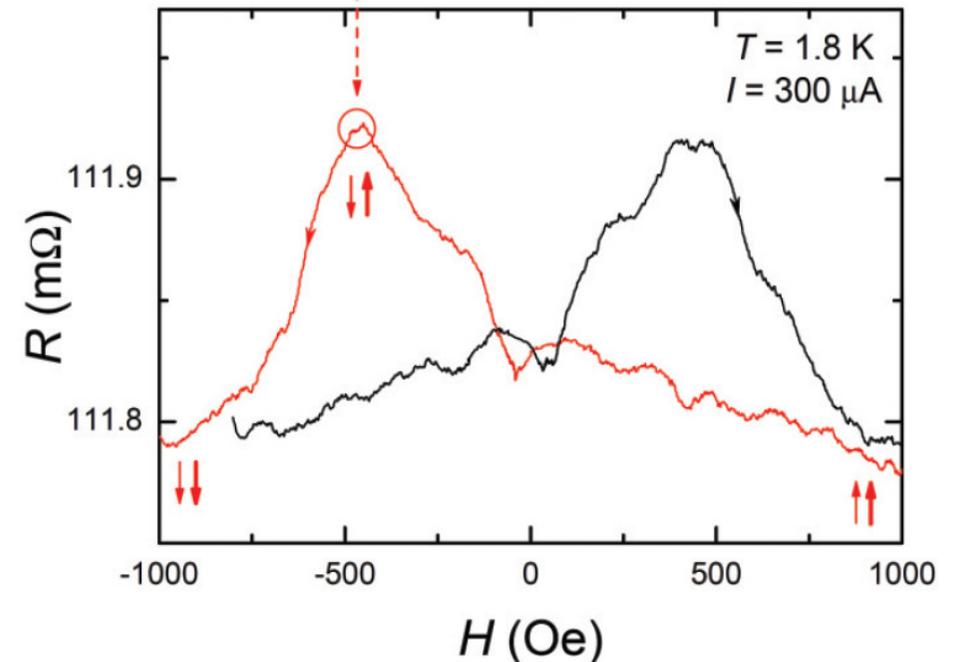
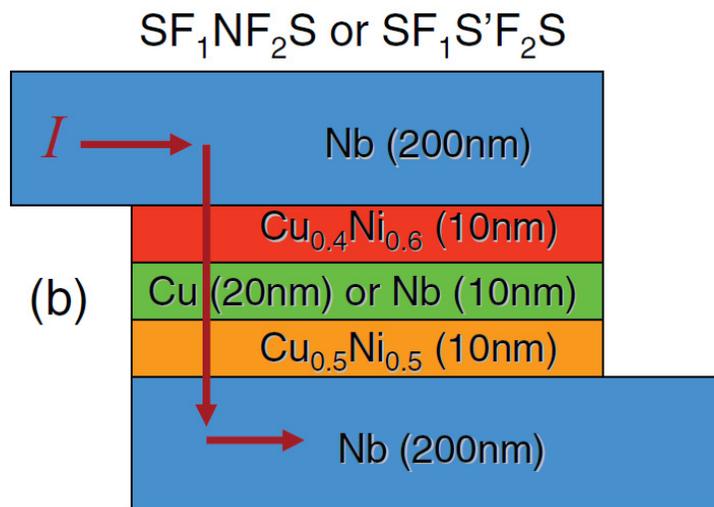
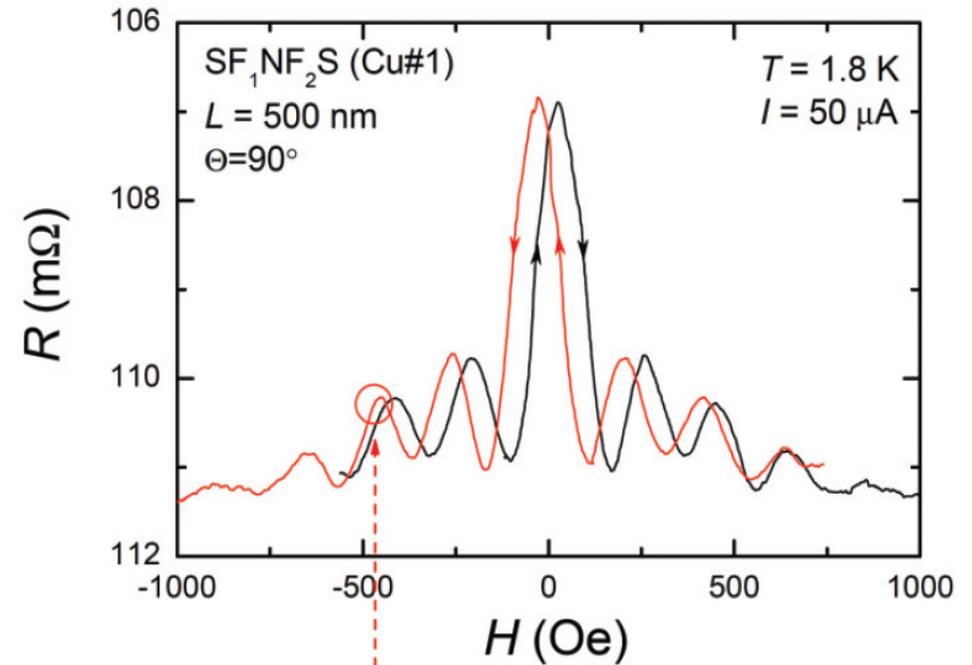
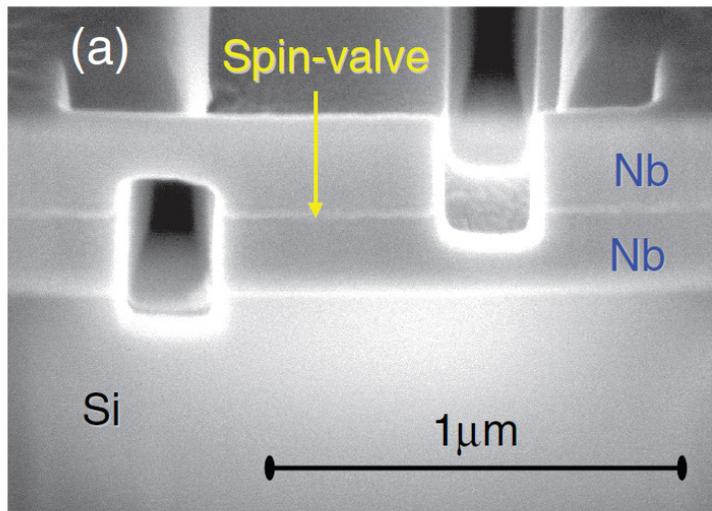


Short range: $r \sim \lambda$.
Magnetic Field/Flux,
Circulating current,
Phase shift.

- + Abrikosov vortex represents the most compact way of storing magnetic flux in a superconducting circuit.
- + Quantized = Non-volatile, Zero static consumption, Reproducibility
- + Easy to manipulate (write/erase) by current pulses
- + 2 ways of readout : Field or Phase

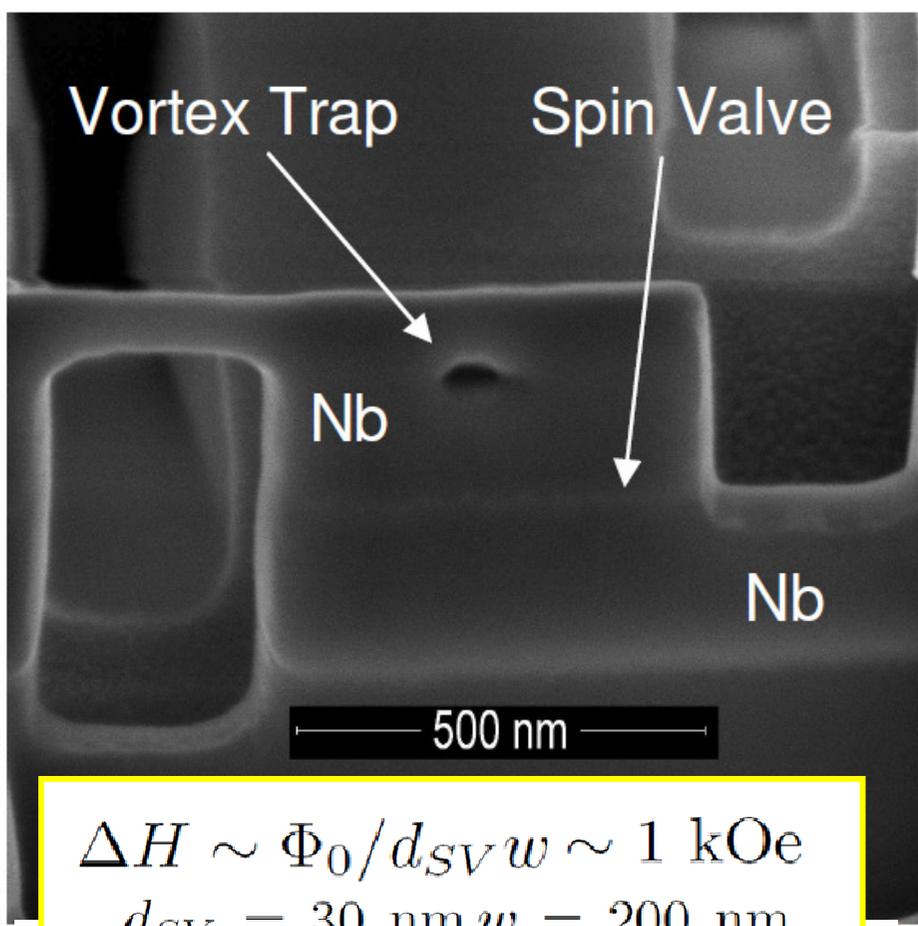
This can be utilized for creation of high density cryogenic random access memory.

I. AVRAM cell with a Josephson spin-valve readout



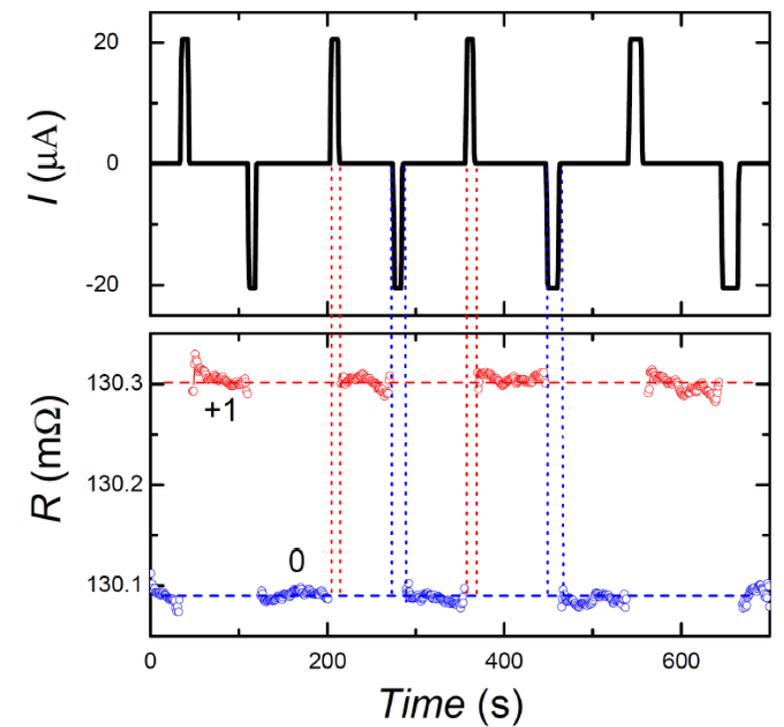
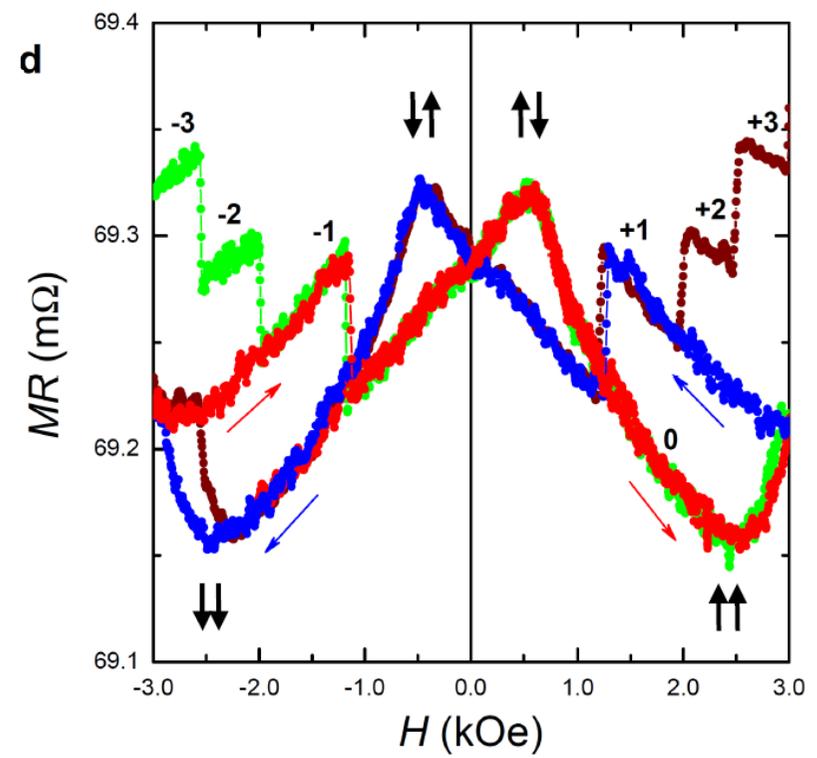
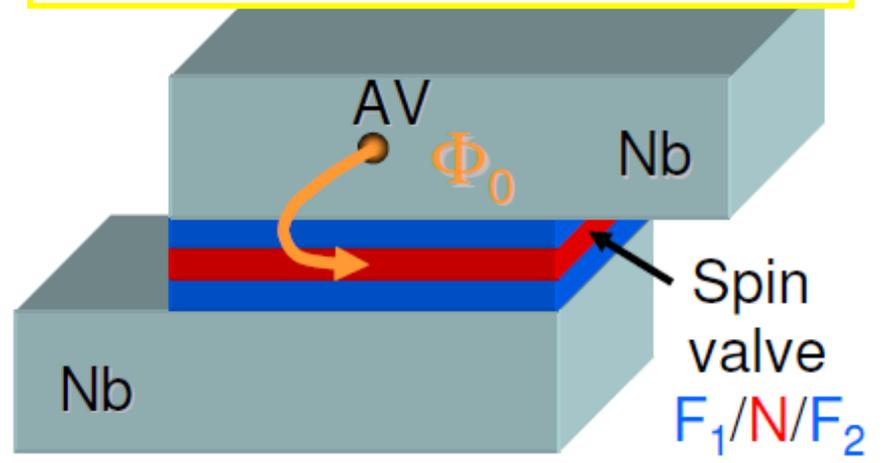
Iovan, A., Golod, T., and Krasnov, V.M., *Controllable generation of a spin-triplet supercurrent in a Josephson spin valve*, **Phys. Rev. B** 90, 134514 (2014).

I. Offset of Josephson spin-valve by stray fields from AV



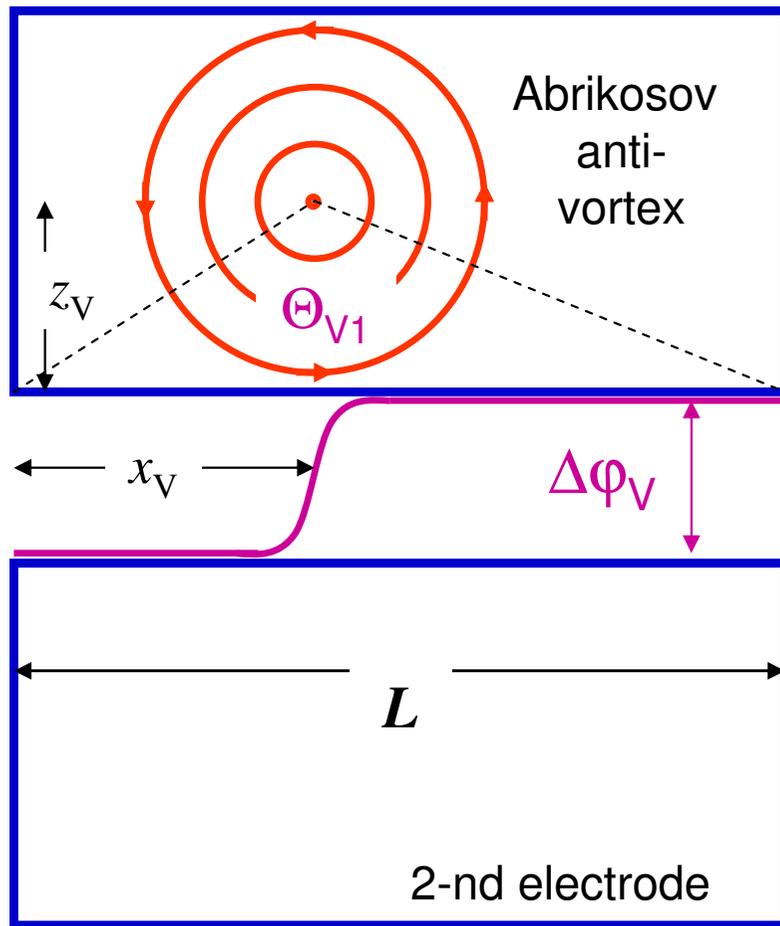
$$\Delta H \sim \Phi_0 / d_{SV} w \sim 1 \text{ kOe}$$

$$d_{SV} = 30 \text{ nm } w = 200 \text{ nm}$$

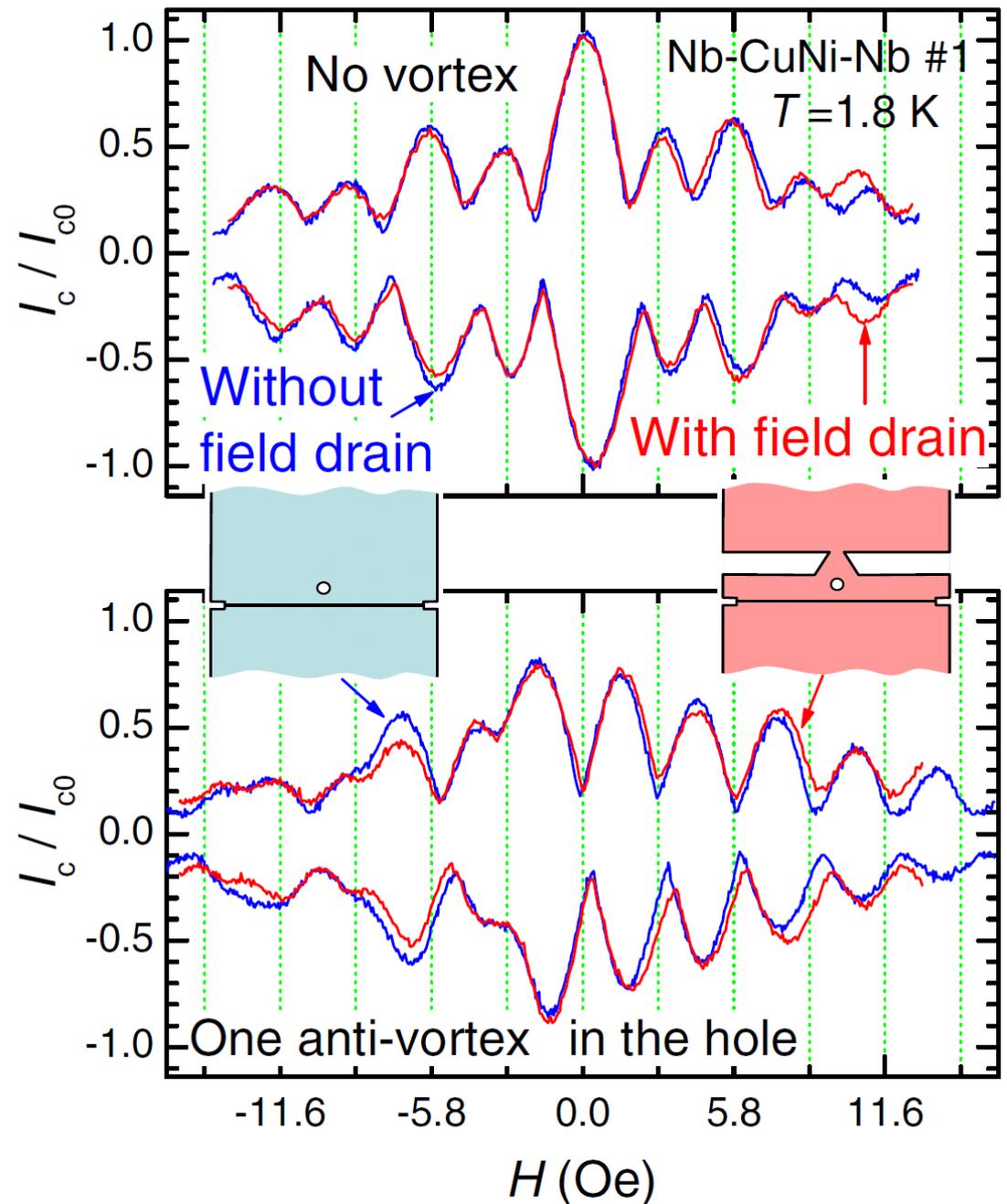


Detection of the AV phase shift by a Josephson junction

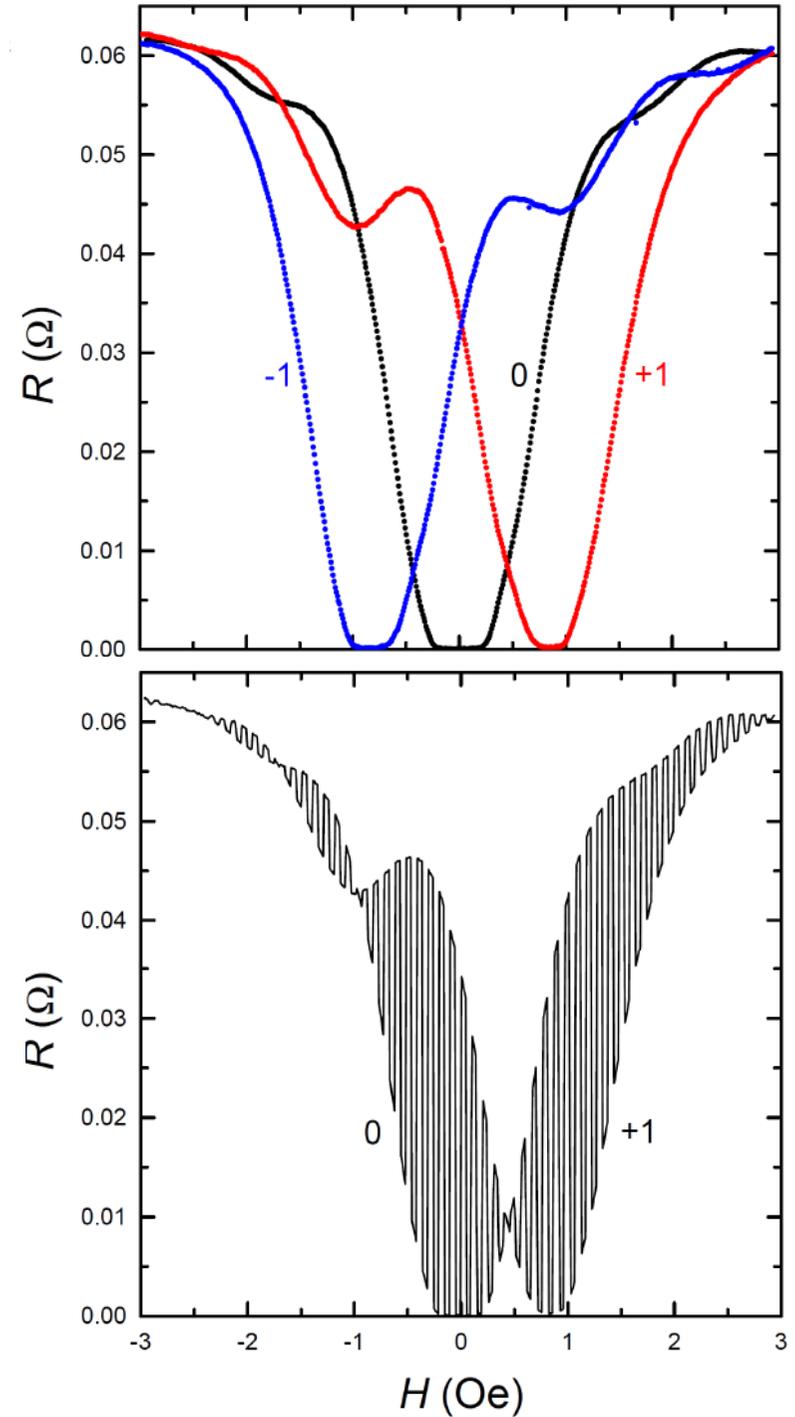
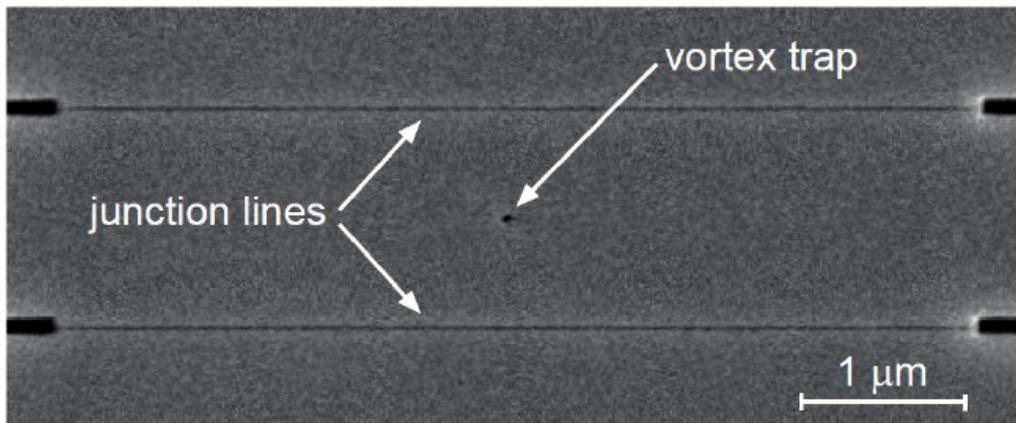
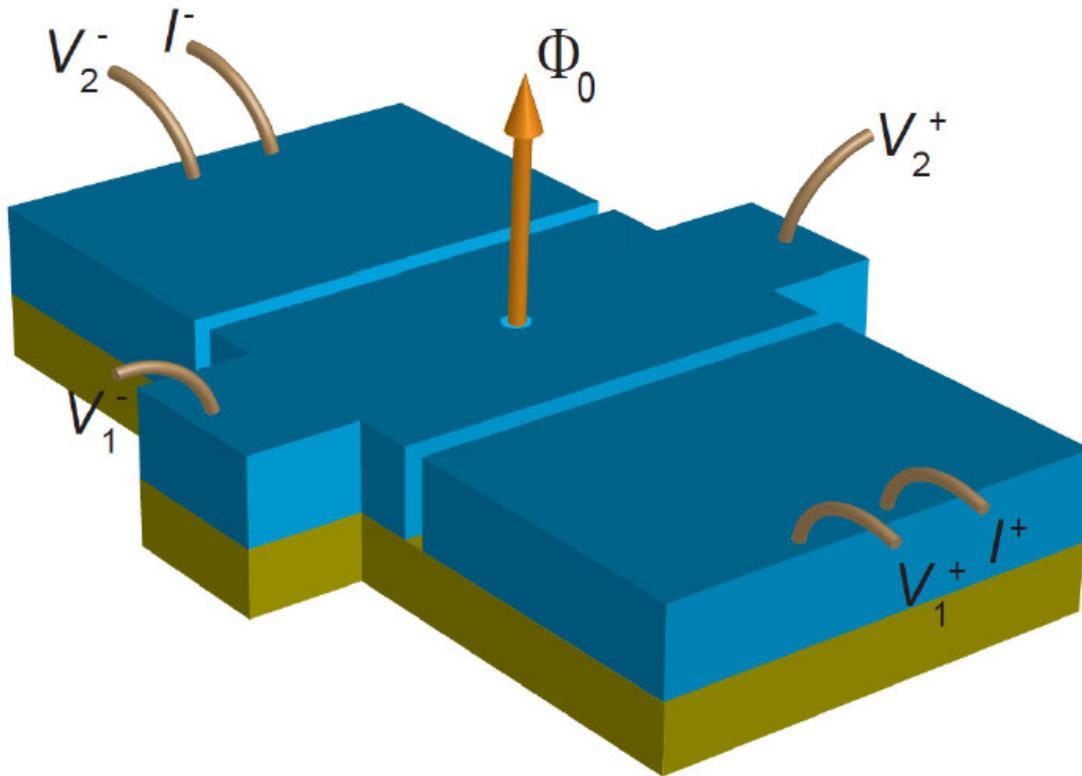
Controllable switching into a 0- π state



Golod, T., Rydh, A., and Krasnov, V. M.,
Detection of the Phase Shift from a Single Abrikosov Vortex,
Phys. Rev. Lett. **104**, 227003 (2010).

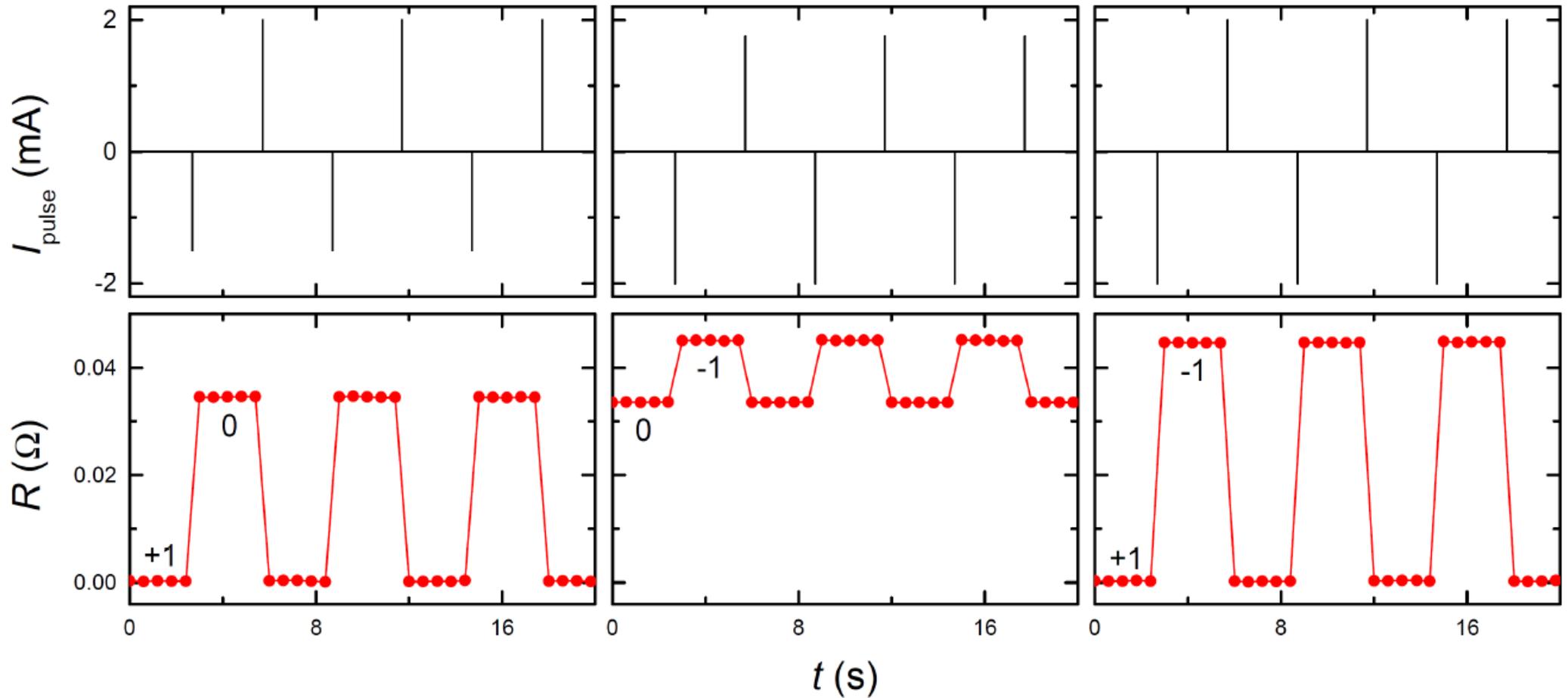


I. AVRAM cell with a planar Josephson junction readout



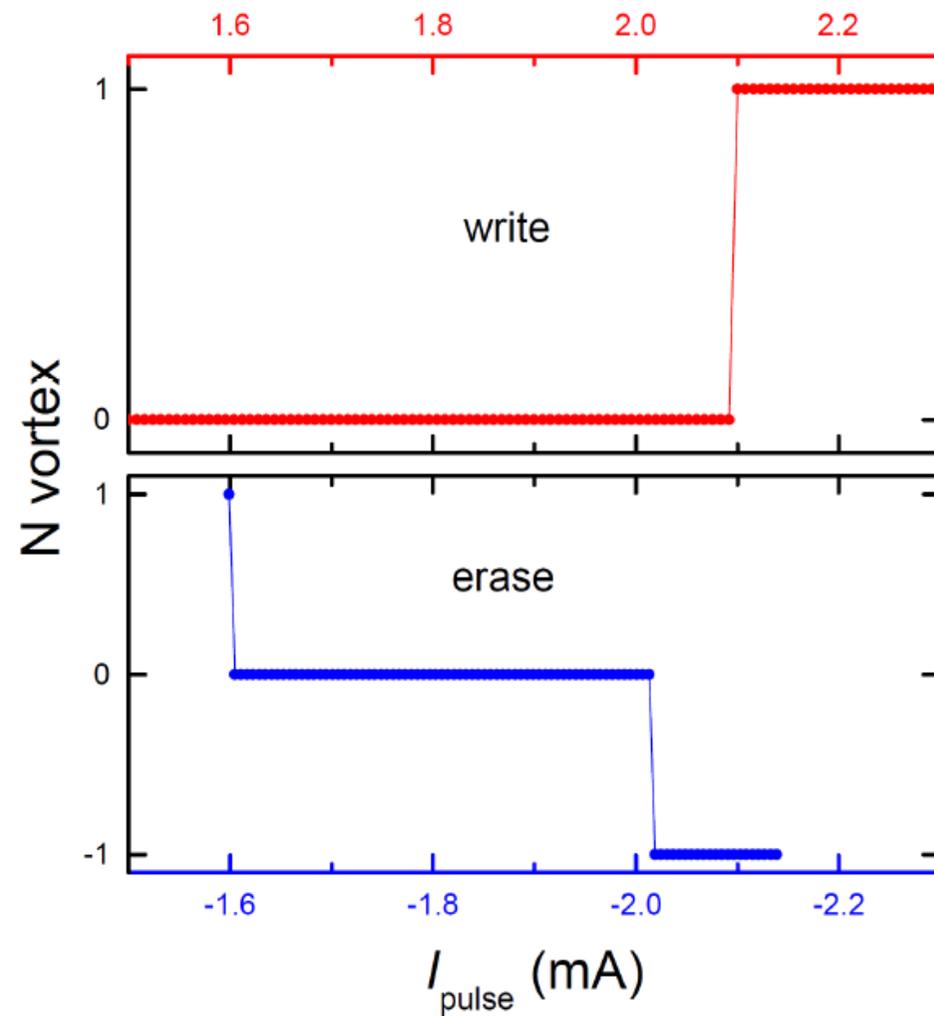
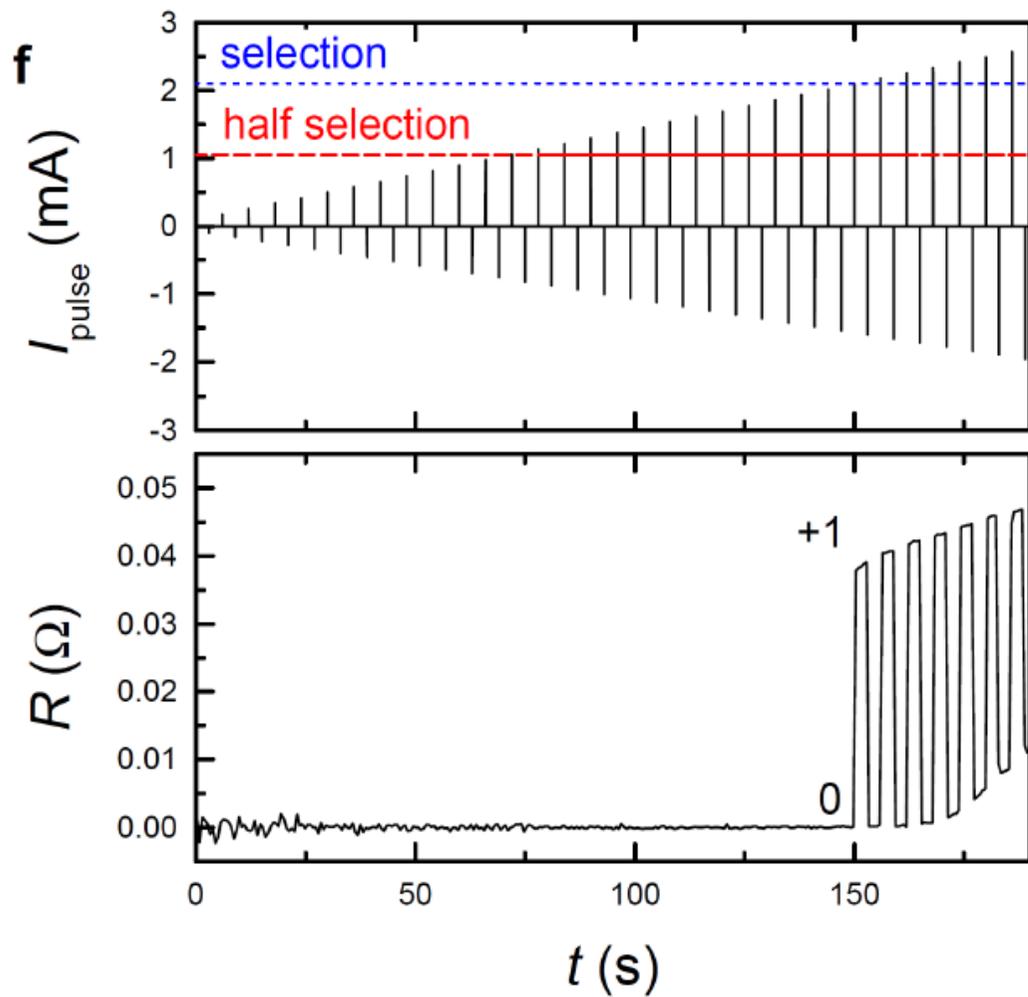
Writing / Erasing vortices by current pulses

Switching back-and-forth from 0 to 0- π state



Note infinite magnetoresistance ($R_{\text{max}}-R_{\text{min}}/R_{\text{min}}$) of the device !

Half-selection stability



High endurance write/erase operation

