Актуальные направления сверхпроводниковой спинтроники

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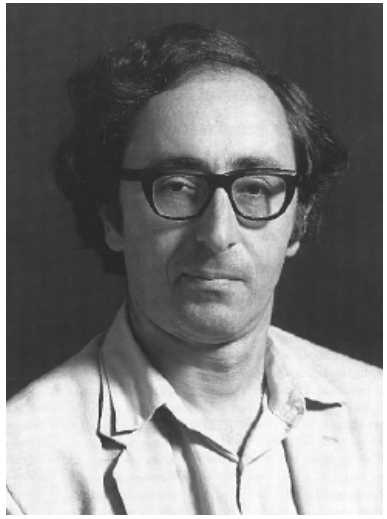
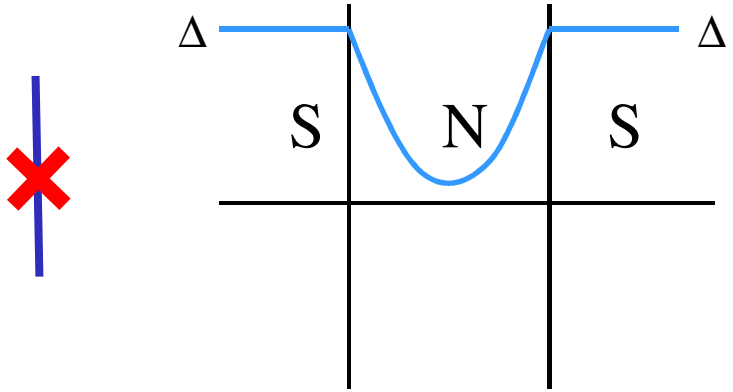
Сверхпроводящие наноструктуры
Криогенная электроника (RSFQ), Джозефсоника
Квантовая логика
Сверхпроводящая спинтроника

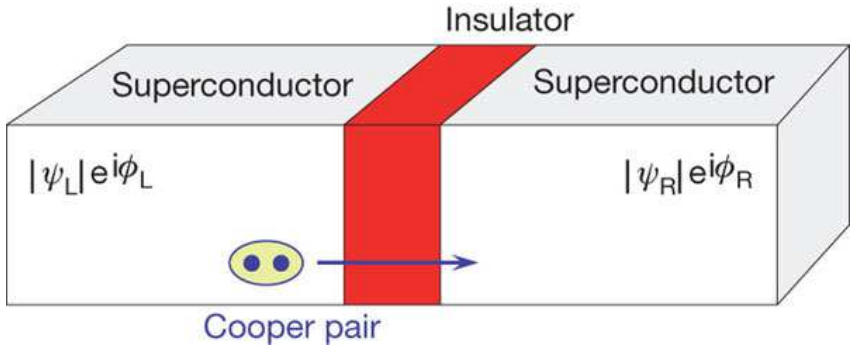
Эффект Джозефсона



Брайан Джозефсон
(Brian Josephson)
1962 г.

Джозефсоновский переход





Уравнения Джозефсона

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

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

квант магнитного потока

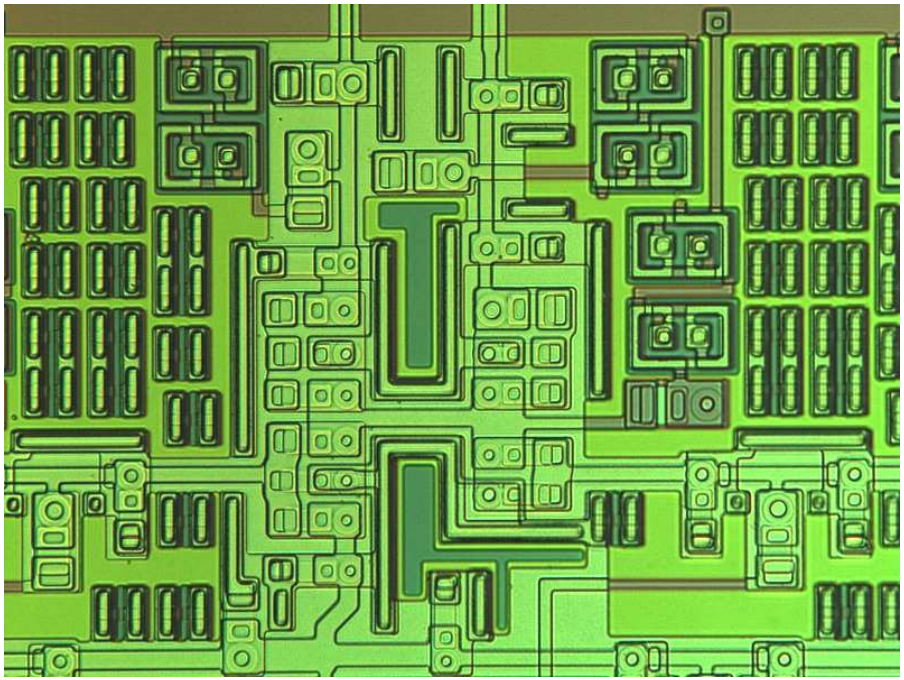
Компьютеры на сверхпроводниках

К. К. Лихарев

В. К. Семенов

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

сверхпроводящая цифровая логика



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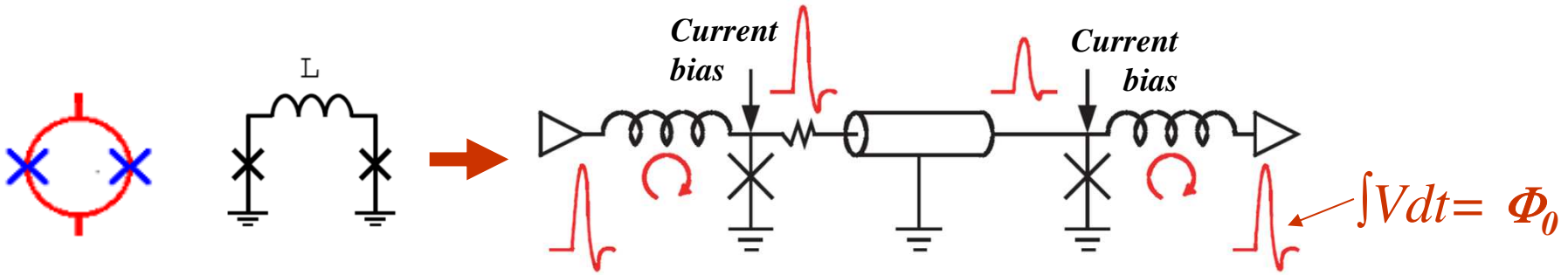
придумано в России

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

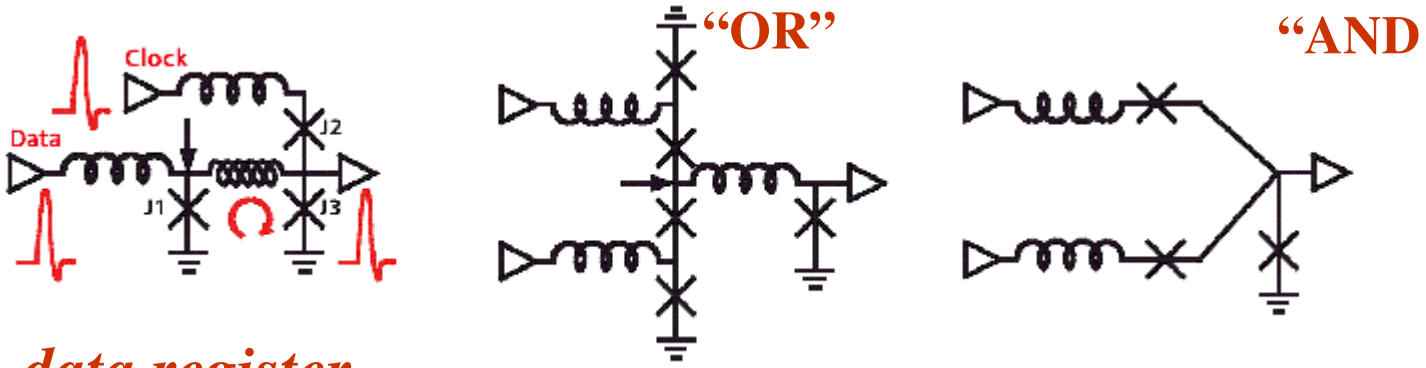
RSFQ-logic principles



$LI_c > \Phi_0$

$j_c \sim 1$ кА/см^2

Passive Josephson transmission line for picosecond SFQ-pulses



data register

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

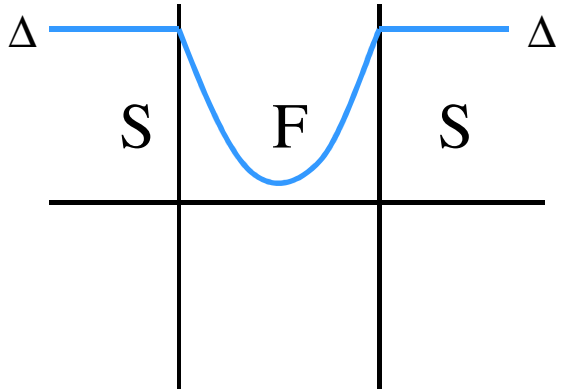
K.K. Likharev and V.K. Semenov, IEEE Trans. Appl. Supercond. 1, 3 (1991);

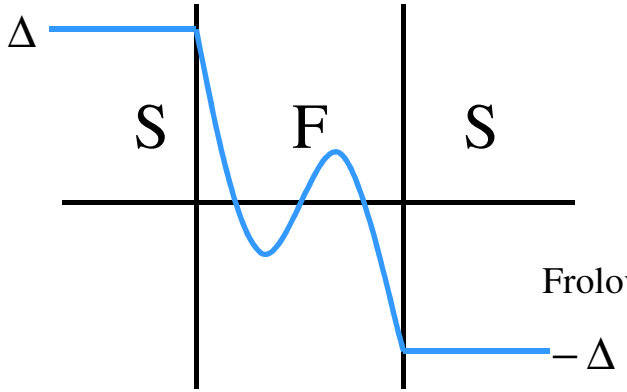
V.P. Koshelets, K.K. Likharev et al., IEEE Trans. Magn. 23, 755 (1987)

Пи – контакт (с ферромагнитной связью)

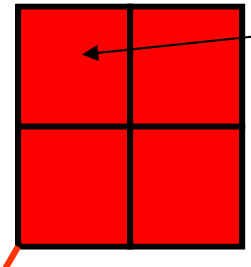
« 0 phase »

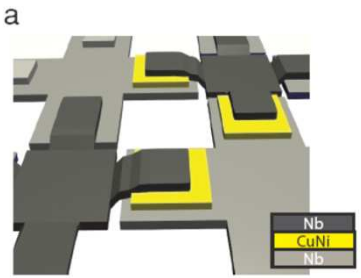
« π phase »

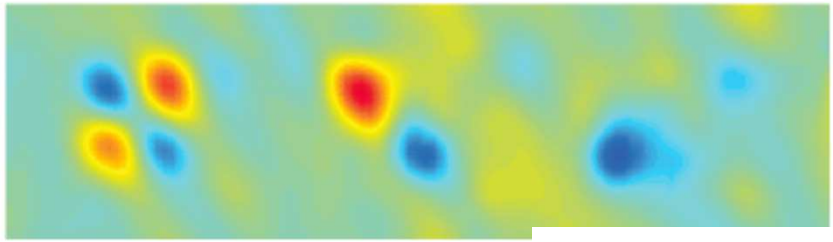


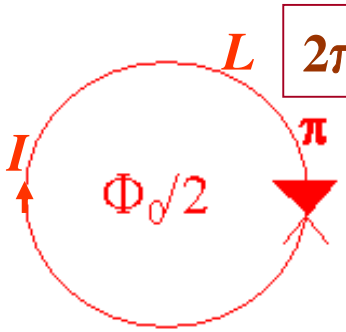


Frolov, et.al. Nature Physics 4, 32 (2008)







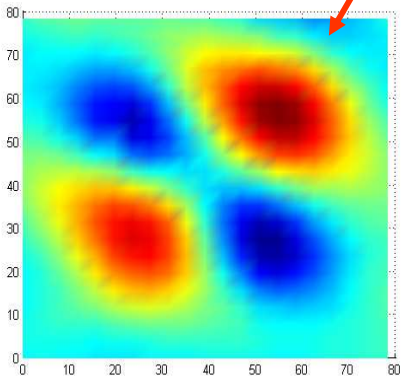


$2\pi LI_c > \Phi_0/2$

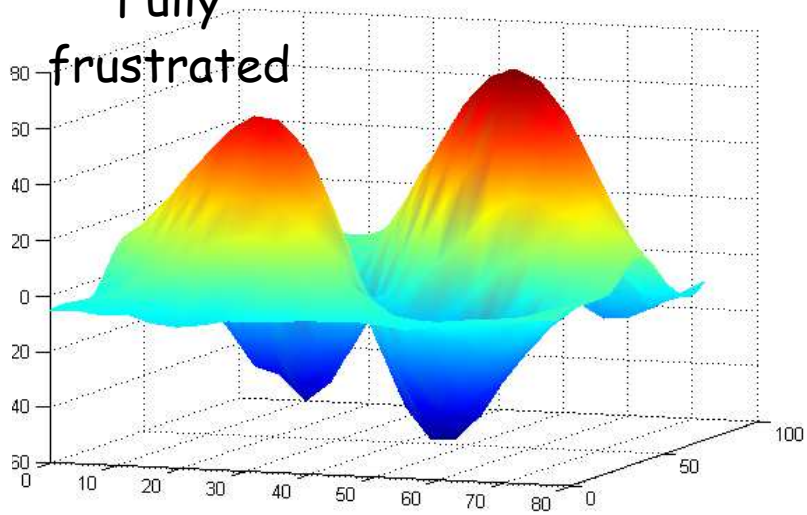
$\varphi = \pi =$

$2\pi\Phi/\Phi_0$

$\Phi = \Phi_0/2$



Fully frustrated



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.

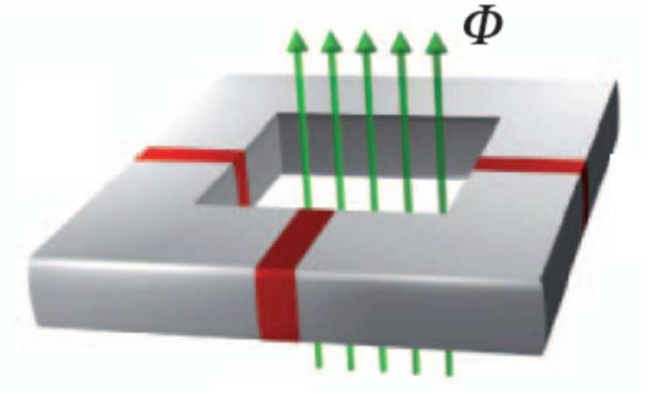
Phase two: to integrate those new technologies into small-scale working model of a superconducting computer.

C3 Program thrust will include:

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

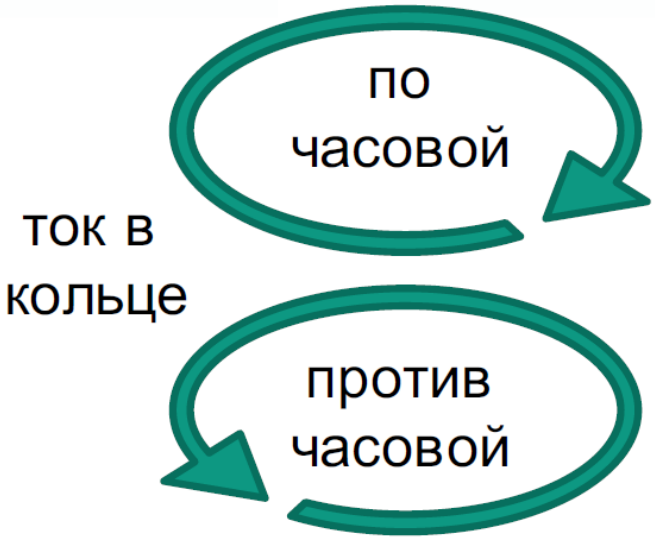
2.Logic, communications and systems: Development of advanced superconducting circuits and integration with memory and other components for demonstration of a limited superconducting computer system on which to measure performance metrics.

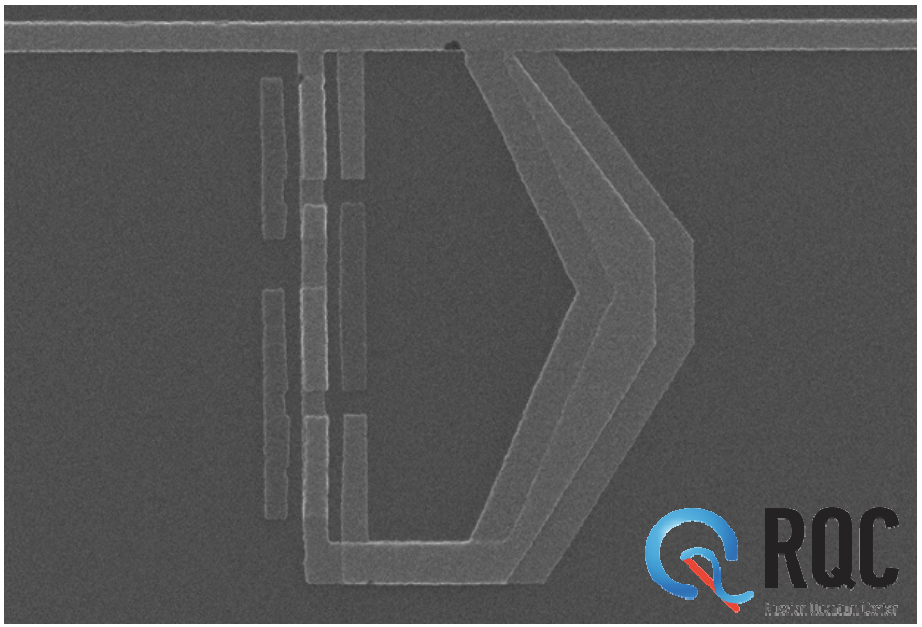
Сверхпроводниковый кубит



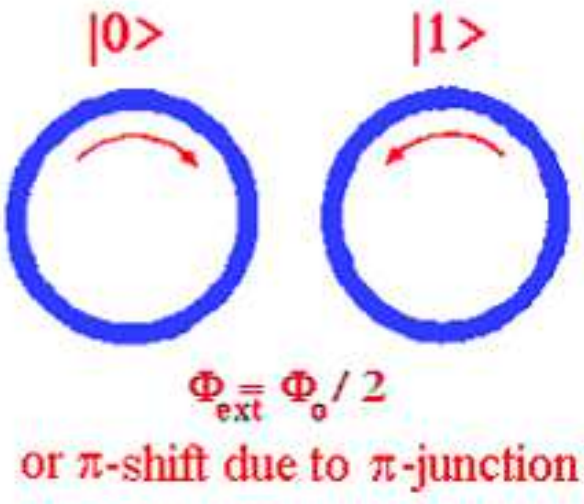
кубит – это **кольцо из сверхпроводника** с одним или несколькими джозефсоновскими переходами

с точки зрения квантовой механики, кубит – это рукотворная модель атома, с состояниями $|0\rangle$ и $|1\rangle$





Сверхпроводящий кубит (тихий)



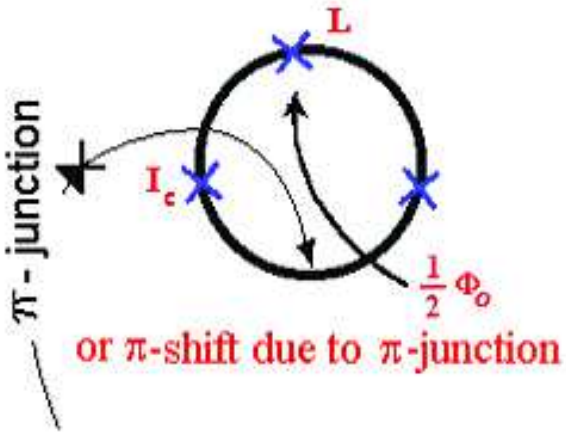
классический бит (бит)

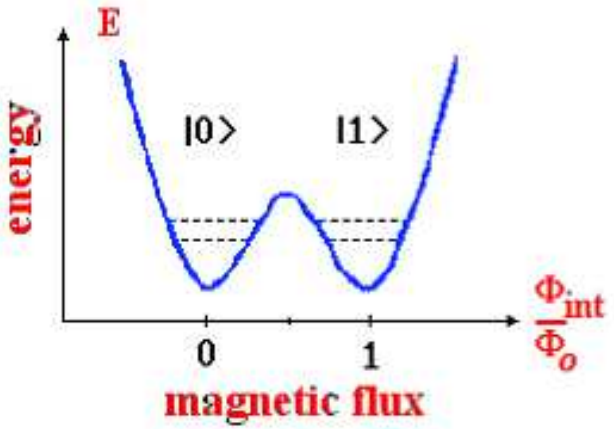
$$|\Psi\rangle = |0\rangle, \quad |\Psi\rangle = |1\rangle$$

волновая функция квантового бита

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

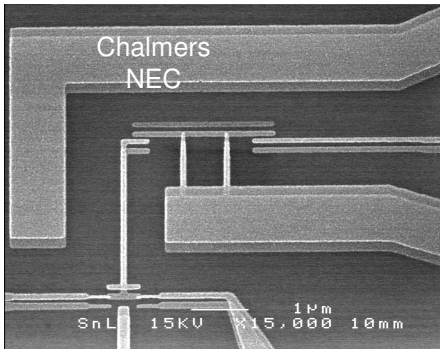
суперпозиция состояний -> параллелизм



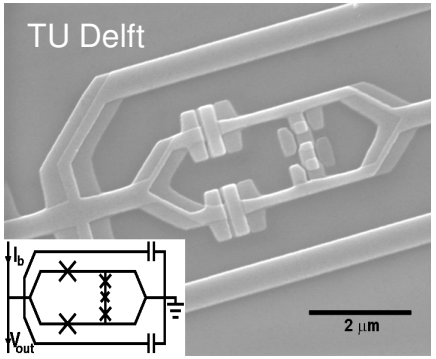


Superconducting qubits

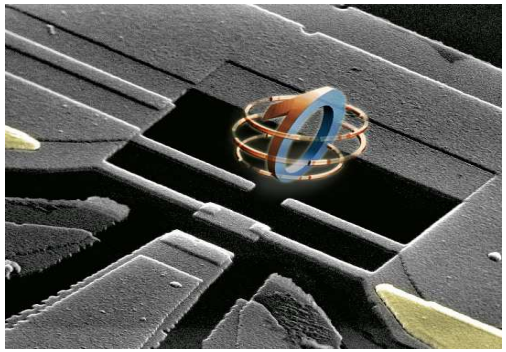
charge 1999



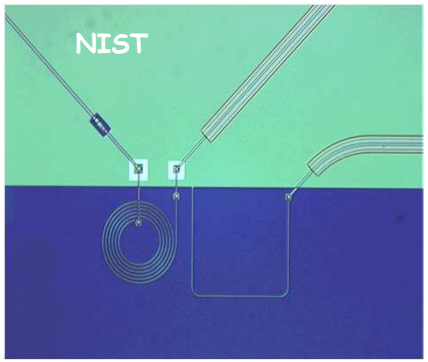
flux 2002

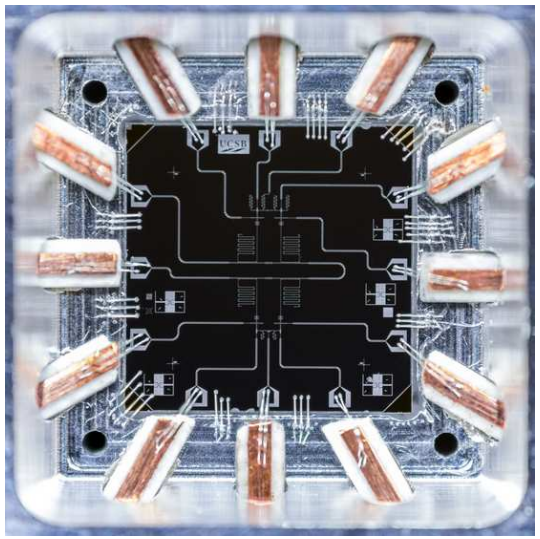


Charge-flux 2004

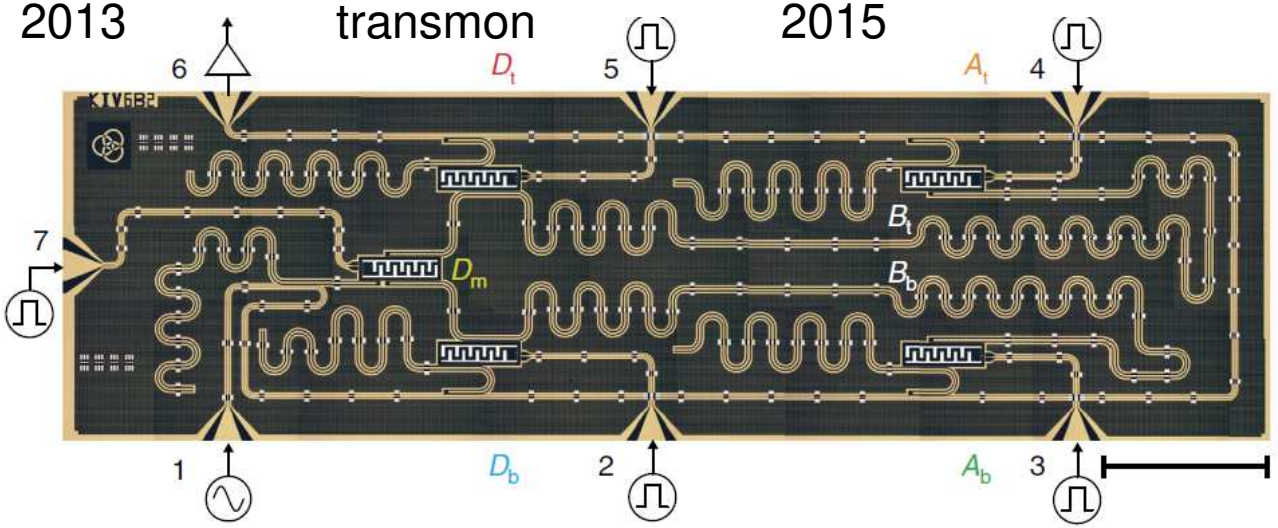


phase 2004

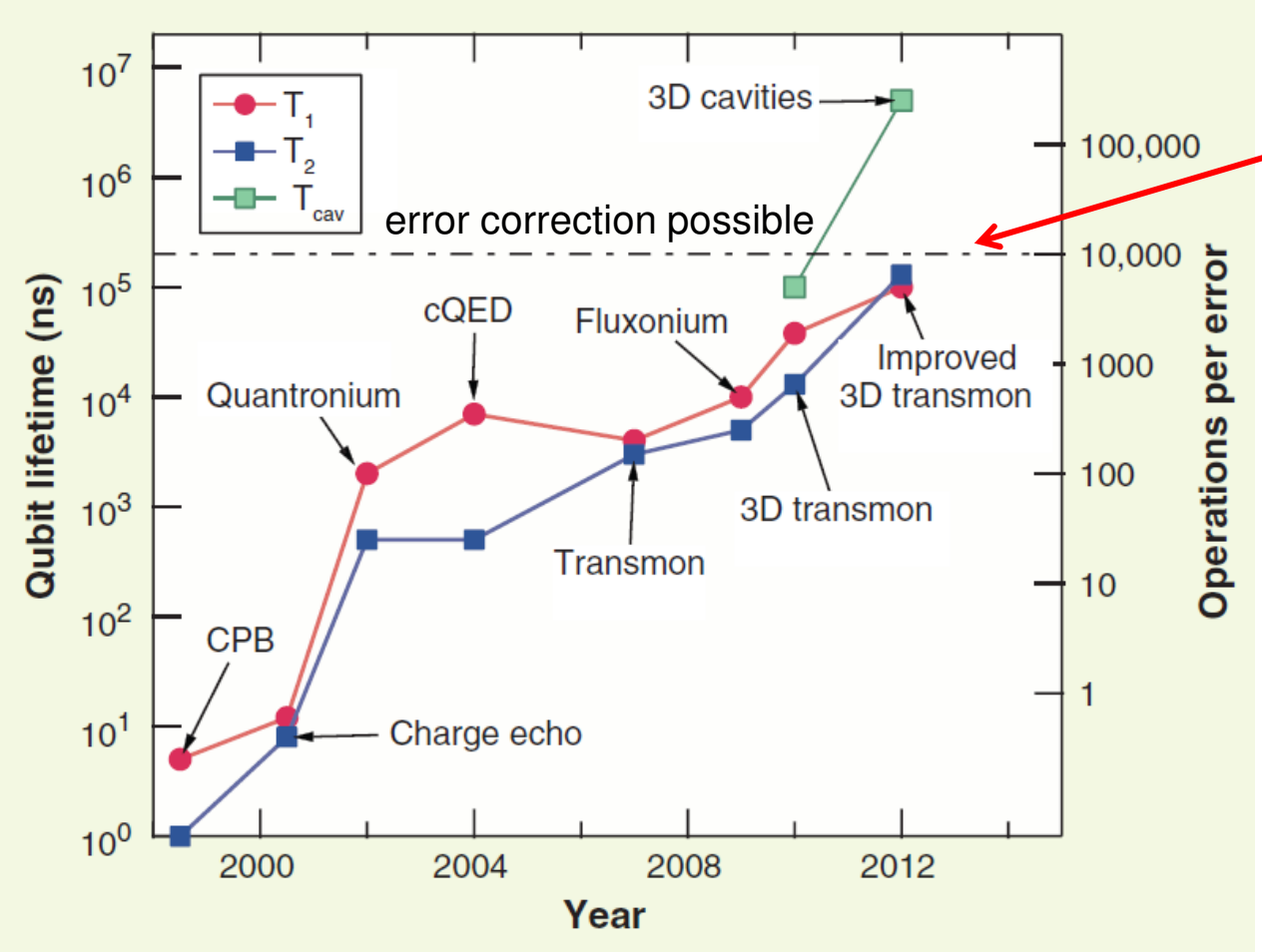




2013 transmon 2015



Decoherence time: «Moore's law» for superconducting qubits



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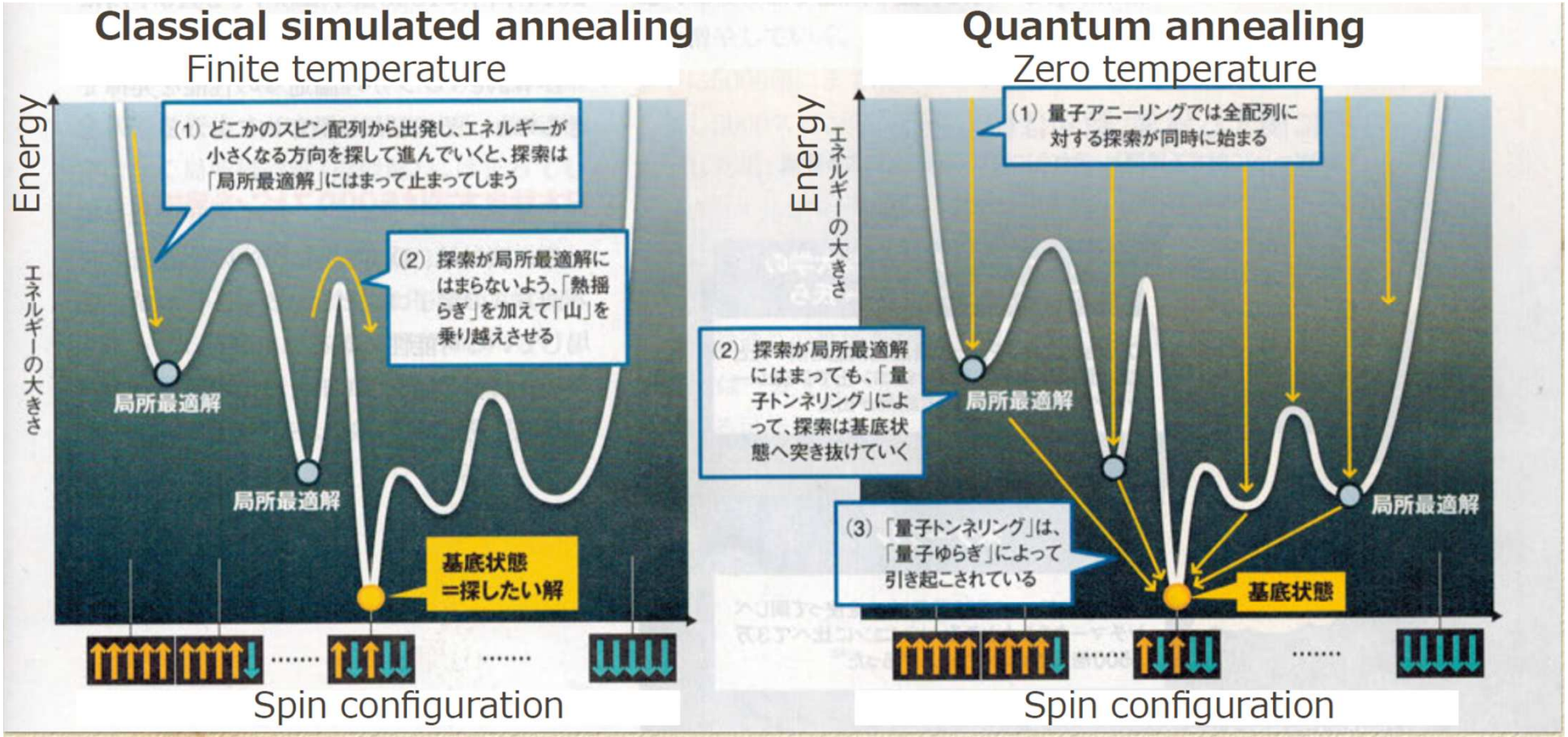
Error correction Efficiency level

M. H. Devoret and R. J. Schoelkopf, *Science* **339**, 1169 (2013)

Квантовый отжиг



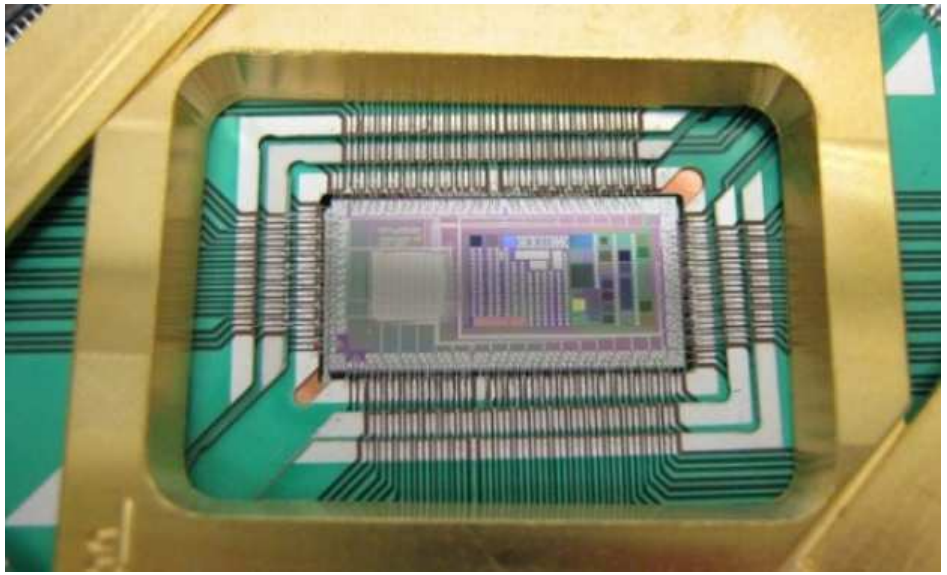
Starting from one configuration

Escaped by thermal activation

Starting from ALL possible configurations

Escaped by quantum tunneling

«Квантовый компьютер» компании D-Wave



adiabatic quantum annealer

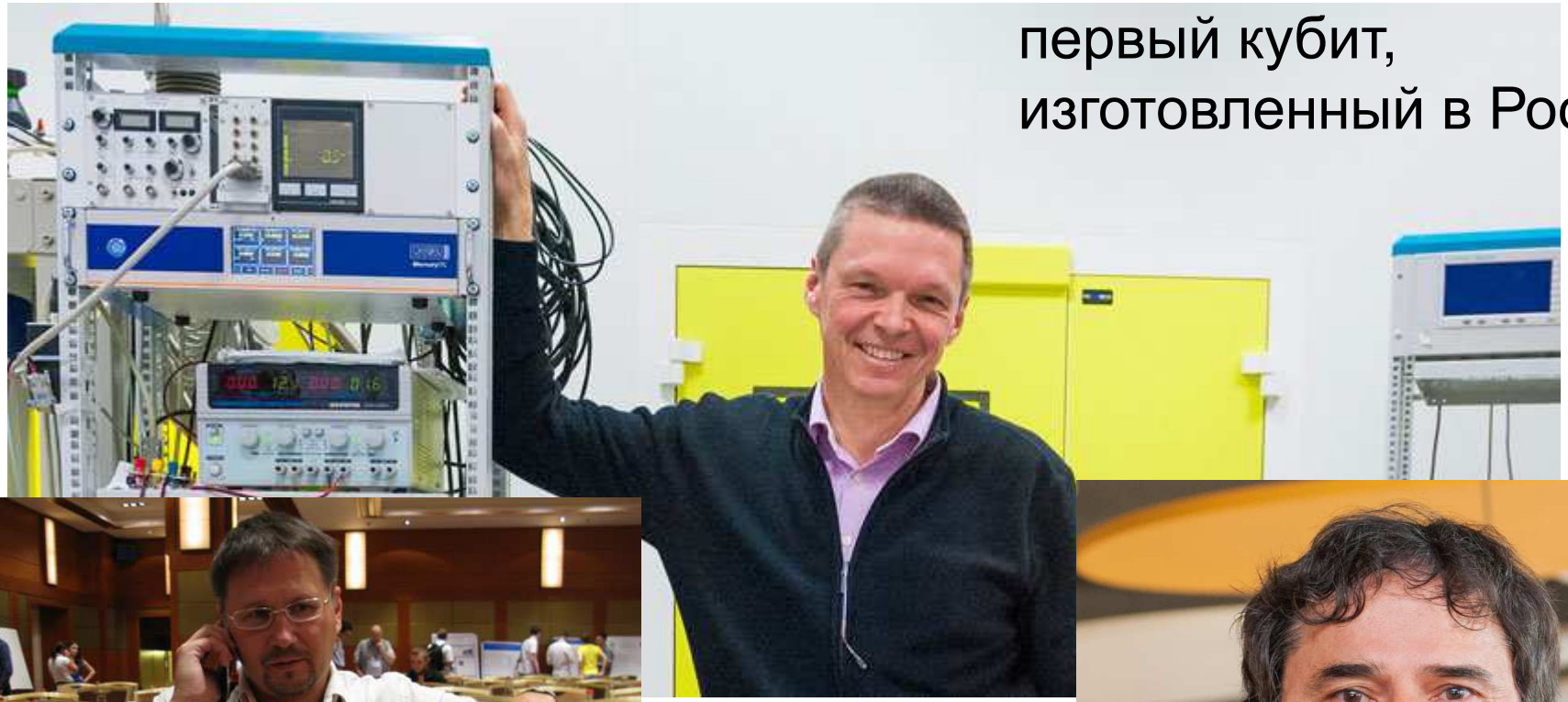
«Квантовый компьютер» D-Wave купили Lockheed Martin, NASA, Google, и др.

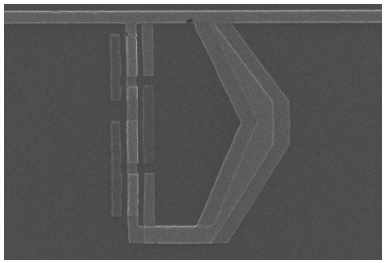
QQ competition

- In December 2017, Microsoft unveiled a complete quantum development kit, including a new computer language, Q#, developed specifically for quantum applications.
- In early 2018, Google announced Bristlecone, a quantum processor based on a 72-qubit array, that might, one day, form the cornerstone of a quantum computer that could tackle real-world problems.
- Recently D-wave announced plans to start rolling out quantum power to a cloud computing platform. Now they have about 2000 qubits computer, working on quantum annealing.

Исследования в России

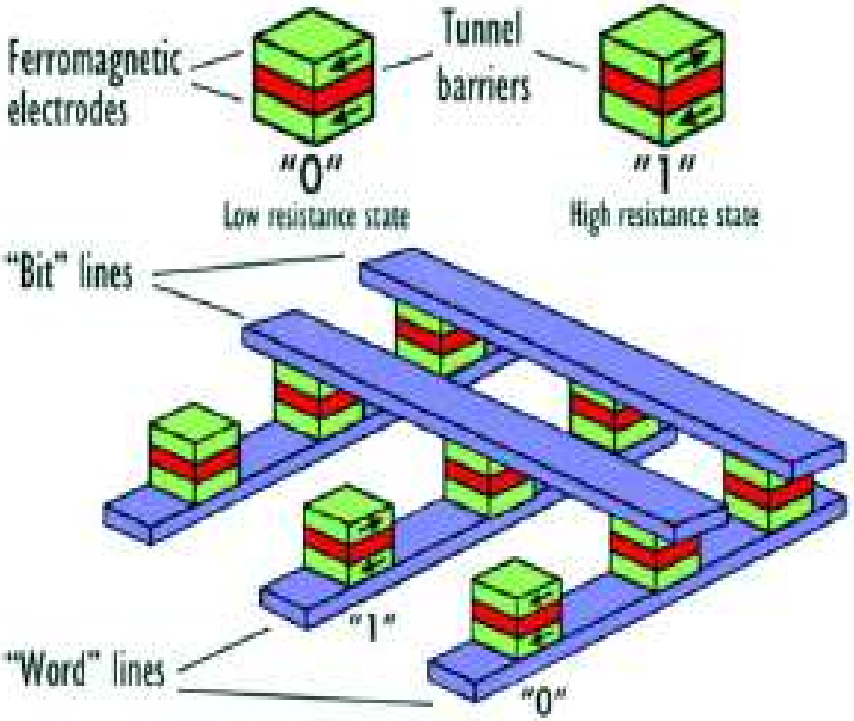
май 2015 г.
первый кубит,
изготовленный в России





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

Спасибо за внимание!