Principles of superconducting (Josephson) electronics

Valeriy V. Ryazanov

Moscow Institute of Physics and Technology, Dolgoprudny
Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka

February 4, Skoltech
Review of materials and devices for nano- and optoelectronics
Term 3, 2020  Tuesday  Skoltech (16.00,  R3-C2-2009)

February 4, Valeriy Ryazanov (Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka). **Principles of superconducting (Josephson) electronics**

February 11, Nikolai Klenov (Lomonosov Moscow State University, Dukhov All-Russia Research Institute of Automatics) **Physical foundations of macroscopic quantum effects in superconducting electronics and spintronics**

February 18, Alexey Ustinov, (Karsruhe Institute of Technology, Germany, Russian Quantum Center, MISIS). **Dynamics of magnetic flux quanta**

February 25, Valery Koshelets, (Kotel'nikov Institute of Radio Engineering and Electronics RAS, Moscow) **Superconducting Low-noise Terahertz Receivers**

March 3. Igor Soloviev. (Lomonosov Moscow State University, Dukhov All-Russia Research Institute of Automatics). **Superconducting digital electronics**

March 10/11. Jukka Pekola (Aalto University, Helsinki, Finland) Josephson current standards, calorimetry and bolometry. (?)

March 17, 24 – **Seminars...**
Superconductivity
Magnetic flux quantization
Josephson junctions
SQUIDs
Magnetic flux quantization in superconductors

The superconducting flux quantum was predicted by London (1948) using a phenomenological semiclassical model.

Superconductivity is a macroscopic quantum phenomenon.

\[ \Psi = \left| \Psi \right| e^{i\theta} \]

is the single superconducting wave function described all condensed collective of Cooper electron pairs \((2e, 2m)\).

\[ \left| \Psi \right|^2 = n_s / 2 \]

\[ p = 2mv_s + 2eA \]

is the gauge-invariant momentum of Cooper pairs.

Meissner effect in bulk superconductor

\[ \hbar \nabla \theta = 2mv_s + 2eA \]

\[ \hbar \oint \nabla \theta \, dl = 2e \oint A \, dl = \oint \oint B \, dS \]

\[ 2\pi n = (2e/\hbar) \Phi = 2\pi \Phi/\Phi_0 \]

\[ \Phi = n\Phi_0 \]

Magnetic flux quantum

\[ \Phi_0 = \hbar/(2e) = 2.067833636 \times 10^{-15} \text{ Wb} \]

\[ (2.067833636 \times 10^{-7} \text{ G cm}^2) \]

The phase running \( \phi \) due to magnetic flux \( \Phi \):

\[ \phi = 2\pi \Phi/\Phi_0 \]
Magnetic flux quanta in type II superconductors and Josephson junctions

Meissner state destruction in type II superconductors

\[ V \sim \frac{dn}{dt} \sim \omega \sim \frac{d\phi}{dt} \]

\[ \phi = \theta_2 - \theta_1 \]

\[ 2eV = \hbar \omega = \hbar \frac{d\phi}{dt} \]

\[ V = \left[ \frac{\hbar}{2e} \right] \frac{d\phi}{dt} = \frac{\Phi_0}{2\pi} \frac{d\phi}{dt} \]

\[ I_s(\phi) = I_c \sin \phi \]

\[ I_s(\phi) = I_c \sin \phi \quad \text{Josephson equation} \quad I \]

\[ 2eV = \hbar \omega = \hbar \frac{d\phi}{dt} \quad \text{Josephson equations} \quad \text{II} \]
Superconducting quantum interferometer (dc-SQUID)

\[ \phi_{13} + \phi_{42} = \theta_3 - \theta_1 + \theta_2 - \theta_4 = (2e/h) \int A \, dl + (2e/h) \int A \, dl \]

\[ \theta_2 - \theta_1 + \theta_3 - \theta_4 = \varphi_a - \varphi_b = (2e/h) \oint A \, dl \]

\[ \varphi_a - \varphi_b = 2\pi \Phi/\Phi_0 \quad \varphi_a = \theta_2 - \theta_1; \quad \varphi_b = \theta_4 - \theta_2 \]

\[ I_a = I_c \sin \varphi_a; \quad I_b = I_c \sin \varphi_b; \quad I = I_c (\sin \varphi_a + \sin \varphi_b) \]

\[ \sin \varphi_a + \sin \varphi_b = 2 \sin[(\varphi_a + \varphi_b)/2] \cos[(\varphi_a - \varphi_b)/2]; \quad \varphi_a - \varphi_b = 2\pi \Phi/\Phi_0 \]

\[ I = 2I_c \cos(\pi \Phi/\Phi_0)\sin(\varphi_b + \pi \Phi/\Phi_0) \]

\[ \varphi_a = \varphi_b + 2\pi \Phi/\Phi_0 \]

Maximum of the current \( I \) is

\[ I_{\text{max}} = 2I_c |\cos(\pi \Phi/\Phi_0)| \]

SQUID is analog of light interference on double slit
Resistive-Capacitive Shunted Junction (RCSJ-model)

\[ I_J = I_c \sin \phi \] - “Josephson channel”

\[ I_n = V/R_n = [\Phi_0/(2\pi R_n)] \phi_t \] - “resistive channel”

\[ I_D = C dV/dt = [\Phi_0 C/(2\pi)] \phi_{tt} \] - “capacitive channel”

\[ E_J = I_c \Phi_0 / 2\pi \]

\[ \frac{\hbar}{(2e)} d\phi/dt = \Phi_0 / (2\pi) d\phi/dt \]

\[ E_J = I_c \Phi_0 / 2\pi \]

\[ \frac{\hbar}{(2e)} d\phi/dt = \Phi_0 / (2\pi) d\phi/dt \]

\[ I_I = I_c \sin \phi \]
Josephson weak links

\[ I_s(\varphi) = I_c \sin \varphi; \quad I < I_c; \]
\[ 2eV = \hbar \omega = \hbar d\varphi/dt; \quad I > I_c; \]
\[ V = \left[ \frac{\hbar}{2e} \right] d\varphi/dt = \left( \frac{\Phi_0}{2\pi} \right) d\varphi/dt \]
\[ \varphi = \theta_2 - \theta_1 \]

Different types of Josephson weak links

Josephson weak link is a region of suppressed superconductivity
Sensitive SQUID-magnetometer

Sensitivity with feedback better than $10^{-6} \Phi_0/\sqrt{\text{Hz}}$

$\Phi_0 = 2 \times 10^{-15} \text{ Wb (Vc)}$

Sensitivity to magnetic field better than $10^{-11} \text{ G}$

$I_{\text{max}} = 2I_c |\cos(\pi \Phi/\Phi_0)|$

Magnetic flux – voltage dependence (for $I \leq I_c$)

$V = \frac{2I_c}{(20 \mu \text{V/div})}$

Sample
Scanning SQUID-microscopy

Different magnetic structure visualization
Sensitive SQUID-picovoltmeter

Sensitivity better than $10^{-13}$ V

\[ R_{st} I_{st} = R_x I_x \]

SNS (SFS) junction I-V characteristics
Josephson junctions with ferromagnetic barrier
Josephson magnetic switches
Superconducting phase inverters
Problem of superconductivity/ferromagnetism coexistence

\[ \mu_B H_p = \sqrt{2(\Delta/g)} \]

\( \mu_B \) is Bohr magneton, \( \Delta \) is the energy gap of superconductor, \( g \) is Lande giromagnetic factor

S and F have antagonistic spin ordering!

Orbital and magnetic depairing.

Paramagnetic limit \( H_p \) of superconductivity:

Non-uniform superconductivity by Larkin-Ovchinnikov-Fulde-Ferrel in magnetic superconductor

LOFF-state was not still observed reliably in magnetic superconductors!
Proximity effect in SF-structures

\[ \psi(x) = \psi_0 \exp(-kx) = \psi_0 \exp(-x/\xi_N) \]

\[ \tau \Delta E \sim \hbar \]

Pair-breaking time \( \tau \sim \hbar/k_B T \)

\[ \xi_N \sim (D \tau)^{1/2} \sim (\hbar D/k_B T)^{1/2} \]

\[ \psi(x) = \psi_0 \exp(-x/\xi_{F1}) \cos \left( \frac{x}{\xi_{F2}} \right) \]

\[ \tau \sim \hbar/E_{ex} \quad (E_{ex} >> k_B T) \]

\[ \xi_{F1} = 1/k_1 \sim (\hbar D/E_{ex})^{1/2} \]

Spatial oscillations of induced superconducting order parameter in a ferromagnet in close proximity to a superconductor

\[ Q \neq 0 \] is the center of the pair mass momentum

\[ \frac{p'^2}{2m} - \frac{p^2}{2m} = p_FQ/m = E_{ex}; \]

\[ Q \sim \frac{E_{ex}}{v_F} \]

\[ \Psi(x) = \Psi_0 \left( e^{i2Qx} + e^{-i2Qx} \right)/2 = \Psi_0 \cos(2Qx) \]

\[ k = k_1 + ik_2 \]

\[ \Psi(x) \sim \exp(-k_1x)\cos(-k_2x) \]
Recent fundamental observations on superconductor/ferromagnet (SF-) structures

- Observation of the supercurrent through a ferromagnet in superconductor-ferromagnet-superconductor (SFS-) junctions \((LS~ISSP~1999)\).

- Observation of nonuniform (“sign-reversal”) superconductivity close to a superconductor-ferromagnet (FS-) interface, realization of Josephson SFS \(\pi\)-junctions with inversion of superconducting phase. \((LS~ISSP~2001)\)

- Prediction and realization of FS-spin-valves and spin-switches.

- Observation of superconducting long-range spin-triplet component.

- Ferromagnetically assisted Cooper pair splitting.
Possible applications

- Josephson SFS (MJJ) junction like a novel memory element for superconducting and other digital electronics

- Josephson SFS $\pi$-junctions like superconducting phase invertors for superconducting digital and quantum (qubit) logics

- FS-spin-valves and spin-switches

- Spin-polarized supercurrents for spintronics
Distributed Josephson junctions
Magnetic field penetration

\( \varphi(x,y) \neq \text{const at the junction plane. } \ H \neq 0 \)

\( \lambda_J > \ll \lambda_L \)

\( \lambda_J >> d_m \cdot \lambda_L \)

\( d_m = 2\lambda_L + t_{ox} \) — “magnetic depth”

\( C \) contour: 1-2-3-4 (out of \( d_m \) region, supercurrent = 0), \( (2-4) = dx \).

\( h \ \nabla \theta = 2mv + 2eA \)  \( \text{Phase winding over path } 1-3 + 4-2 \) is only due to magnetic field:

\( h \int_{1}^{3} \nabla \theta \cdot dl + h \int_{2}^{4} \nabla \theta \cdot dl = 2e \int_{1}^{3} A \cdot dl + 2e \int_{2}^{4} A \cdot dl \approx 2e \Phi A dl = 2e \ d \Phi, \) where \( d \Phi = B d_m \ dx \)

\( \theta_3 - \theta_1 + \theta_2 - \theta_4 = \varphi(x+dx) - \varphi(x) = d\varphi = 2\pi d\Phi/\Phi_0 \)

\( d\varphi/dx = (2\pi/\Phi_0) d\Phi/dx \)

Magnetic induction in the junction: \( B(x) = (1/d_m) d\Phi/dx = [\Phi_0/(2\pi d_m)]d\varphi/dx \)
Critical current vs. magnetic flux in the short junctions ($L < 4\lambda_J$)

$$B = \left[ \Phi_0 / (2\pi d_m) \right] d\varphi/dx = \text{const} \quad \text{(uniformly at the short junctions)}$$

i.e. $\varphi(x)$ is linear $\rightarrow d\varphi/dx = (2\pi d_m / \Phi_0) B = \text{const}$

$$\varphi(x) = (2\pi d_m / \Phi_0) B \cdot x + C; \quad \text{where } C \text{ is an integration constant}$$

**Supercurrent distribution:** $j_s(x) = j_c \sin[(2\pi x / a_v) + C]$, where $a_v = \Phi_0 / (B d_m)$

**Total current over the junction:**

$$I_s = \int_{-L/2}^{L/2} j_s(x) \sin[(2\pi x / a_v) + C] \, dx = -(a_v / 2\pi) j_c \cos[(2\pi x / a_v) + C]$$

$$\cos(\alpha + \beta) = \cos \alpha \cos \beta - \sin \alpha \sin \beta \quad \text{and} \quad \cos(2\pi x / a_v) \cos C \bigg|_{-L/2}^{L/2} = 0$$

$$I_s = j_c L (a_v / \pi L) \sin(\pi L / a_v) \sin C = I_c \left[ \sin(\pi L / a_v) / (\pi L / a_v) \right] \sin C$$

Supercurrent $I_s$ through the junction can change only due to the phase difference $C$: $\left| \sin C \right| \leq 1$

**Critical current $I_{\text{max}}$:**

$$I_{\text{max}} = I_c \left| \sin(\pi L / a_v) / (\pi L / a_v) \right| = I_c \left| \sin(\pi \Phi / \Phi_0) / (\pi \Phi / \Phi_0) \right|$$

where $I_c = j_c L$, $L / a_v = \Phi / \Phi_0$, $\Phi = B L d_m$

**Fraunhofer pattern**
Magneto-hysteretic behavior of the critical current
Magnetic Josephson Memory with Fast Reading

Weak ferromagnetic alloys (10-20 nm)
Cu$_{1-x}$Ni$_x$, Pd$_{1-x}$Fe$_x$

$\text{Cu}_{1-x}\text{Ni}_x$, $x=0.53-0.59$, $T_{\text{Curie}}=30-150$ K;

Pd$_{1-x}$Fe$_x$, $x=0.01$, $T_{\text{Curie}}=15$ K

$I_{\text{max}} = I_c \left| \frac{\sin(\pi \Phi / \Phi_0)}{\pi \Phi / \Phi_0} \right|$  

Critical current, mA

Magnetic field, Oe

Very weak and soft ferromagnet

non-volatile switchable Magnetic Josephson junctions (MJJs) programmable using small field
Josephson magnetometry

\[ I_c = I_{c0} \sin(\pi \Phi/\Phi_0)/(\pi \Phi/\Phi_0), \]

\[ \Phi = H(d_F + 2\lambda_L) + 4\pi M d_F, \]

\[ \Phi_{\text{min}} = \Phi_0 n, \quad \Phi_{\text{max}} = \Phi_0 (n+1/2) \]

\[ M_{\text{sat}} \sim 10^{-15} \text{ Am}^2 \]

SFS without a tunnel layer

\[ V_c \sim 3 \text{nV} \]

Switching rate \( \sim 1 \text{MHz} \)

\[ f \sim V_c / \Phi_0 \]
Magnetic Josephson Memory with Fast Reading

SIsFS junction with thin s-layer $d_s = 15$ nm; $\xi_S < d_s << \lambda$

SIs tunnel junction “feels” F-layer remagnetization
Theoretical model of SIsFS structures

S.V. Bakurskiy, N.V. Klenov, I.I. Soloviev, V.V. Bol'ginov, V.V. Ryazanov, I.V. Vernik, O.A. Mukhanov, M.Yu. Kupriyanov, and A.A. Golubov.

Oscillating superconductivity and Josephson $\pi$-junction


Imaging spontaneous flux in arrays of \( \pi \)-junctions


\[\Phi_0/2\]

\[\Phi = \pi = 2\pi\Phi/\Phi_0\]

\[\Phi = \Phi_0/2\]

Checkerboard frustrated

Fully frustrated
2. Demonstration of SFS $\pi$-shifters ($I_{c\pi} >> I_{cJ}$)

Realization of the complementary cell-\(\Pi\)

Physical compatibility of SFS and SIS JJs was proven

In collaboration with M.I. Khabipov, D.V. Balashov, A B Zorin, PTB, Germany (2010)
Superconducting digital electronics

Started in Russia in 1985:
RSFQ –logic (Rapid Single Flux Quantum logic)

**Fast digital electronics** 20 GHz - 700 GHz (Nb)
**Ultra-low power, can be used for reversible computing**

Based on storage of the magnetic flux quanta \( \Phi_0 = \frac{\hbar}{2e} = 2.07 \times 10^{-15} \) Вб

- JJ-based memory for Random Access Memories (RAM) exists, but it has low density, low capacity, cannot be easily pipelined, not energy-efficient

- Large cell sizes needed to keep the flux quantum is the second problem of the superconducting logic
The circuits demonstrated correct functionality with the operation parameter ranges of ± 20%.
Integrated SFS+SFQ circuit of T-flip-flop

in collaboration with M. Khabipov, D. Balashov, A. B. Zorin,
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
In this cell, a large inductance required for the fluxon storage is replaced by a $\pi$-junction operated as a passive phase shifter.
Josephson junctions in “quantum limit”
Superconducting qubits
Nanotechnology at ISSP

- Different technique of thin film sputtering
- Optical and electron lithography
- Focused ion beam technique
- Chemical nanostructuring
- Ion and Reactive ion etching
Shadow evaporation technique

Shadow evaporation at two angles
Base pressure $10^{-10}$ mbar

Shadow evaporation at three angles

Sample fabrication by means of electron beam lithography and shadow evaporation
Josephson junction energy

\[ \begin{align*} 
I_s (\phi) &= I_c \sin \phi & \text{Josephson equation I} \\
2eV &= \hbar \omega = \hbar d\phi/dt & \text{Josephson equations II} \\
\phi &= \theta_2 - \theta_1 ; \quad V = [\hbar/(2e)]d\phi/dt = (2\pi/\Phi_0)d\phi/dt \\
\end{align*} \]

\[ E_{coup} = \int_{0}^{t} I_s V dt = \frac{\hbar}{2e} \int_{0}^{\phi} I_c \sin \phi \frac{d\phi}{dt} dt = \frac{\hbar I_c}{2e} \int_{0}^{\phi} \sin \phi d\phi = E_J (1 - \cos \phi) \]

where

\[ E_J = \frac{\hbar I_c}{2e} = \frac{\Phi_0 I_c}{2\pi} \]

\[ E_b = \int_{0}^{t} IV dt = \frac{\hbar}{2e} I \int_{0}^{\phi} \frac{d\phi}{dt} dt = \frac{\Phi_0}{2\pi} I \phi \]

\[ E = E_{coup} - E_b = E_J [(1 - \cos \phi) - \frac{I}{I_c} \phi] \]

“Tilted washboard” potentials with minima at \( \phi \) satisfying \( I = I_c \sin \phi \) (stationary states)
“Equation of motion” for Josephson tunnel junction. Analogy with a pendulum.

Resistive-Capacitive Shunted Junction (RCSJ-model)

\[ I_j = I_c \sin \varphi \]  - “Josephson channel”
\[ I_n = \frac{V}{R_n} = [\Phi_0 / (2\pi R_n)] \varphi_t \]  - “resistive channel”
\[ I_D = C \frac{dV}{dt} = [\Phi_0 C / (2\pi)] \varphi_{tt} \]  - “capacitive channel”
\[ I_c \sin \varphi + [\Phi_0 / (2\pi R_n)] \varphi_t + [\Phi_0 C / (2\pi)] \varphi_{tt} = I_e \]

\[ [\hbar / (2e)]^2 C \varphi_{tt} + [\hbar / (2e)]^2 R_n^{-1} \varphi_t + E_J \sin \varphi = E_J \left( \frac{I_e}{I_c} \right) \]

**The pendulum motion equation**
\[ J \varphi_{tt} + \eta \varphi_t + mg l \sin \varphi = M \]

- **Phase angle** \( \varphi \)
- **Phase difference** \( \varphi \)
- **Moment of inertia** \( J = m l^2 \) \( \rightarrow \) \([\hbar / (2e)]^2 C\)
- **Viscosity coefficient** \( \eta \) \( \rightarrow \) \([\hbar / (2e)]^2 R_n^{-1}\)
- **Restoring moment** \( (mg \sin \varphi) l \) \( \rightarrow \) \( E_J \sin \varphi \)
- **Applied torque moment** \( T \) \( \rightarrow \) \( E_J \left( \frac{I_e}{I_c} \right) \)
Submicron tunnel junctions in normal state

Submicron-scale tunnel junction with small enough capacitance $C$. Single electron Coulomb (charging) energy $E_C = e^2/(2C)$ is large. $Q$ is charge and $E_c = Q^2/(2C) = CV^2/2$ is energy of this capacitor. Discharge of the capacitor is not favorable for some value $Q$: new energy $E'_c = (Q - |e|)^2/(2C)$ becomes larger for $0 < Q < |e|/2$!

Coulomb blockade of tunneling for $V$: ($V = Q/C$)

$$0 < V < |e|/(2C)$$

The increase of the differential resistance around zero bias is called the **Coulomb blockade**.

Limitation on $T$ and $R$:

$E_C > kT$ (thermal fluctuations), $C < 10^{-15}$ F, $T > 1$ K

$1/R_T + 1/R_e < 1/R_Q$ (quantum fluctuations)

$R_Q = h/(4e^2) \sim 6$ kΩ is the quantum resistance

$$Q/e = VC/e$$
**Josephson junction in quantum limit**

“Quantum Josephson junction” is a submicron-scale tunnel junction with small enough capacitance $C \to 0$.

By analogy with “Quantum pendulum”: when $m \to 0$ null oscillations arise, because $\Delta \varphi \Delta M \sim \hbar$. ($\varphi=0 \Rightarrow M=0$ without oscillations!)

$$M= J \, \varphi_t \text{ is angular momentum.}$$

**Josephson junction angular momentum is**

$$M= J \, \varphi_t = [\hbar / (2e)]^2 C \varphi_t = [\hbar / (2e)] C \, Q = Q \cdot [\hbar / (2e)]$$

$$\Delta \varphi \Delta Q \sim 2e \quad \text{or} \quad \Delta \varphi \Delta n \sim 1$$

where $Q$ is the junction (capacitor) charge, $n = Q / (2e)$ is excess Cooper pairs.

Quantum Josephson junctions have large Coulomb energy $E_C \sim E_J$ due to small capacitance: $E_C = (2e)^2 / (2C)$

(Tunnel junctions with sizes smaller than $0.3 \times 0.3 \, \mu m^2$, $C \sim 10^{-15} F$)

Thus total energy of the quantum Josephson junction is

$$E = (2e)^2 / (2C) + E_J (1 - \cos \varphi) - [\Phi_0 / (2\pi)] I \varphi$$
Thermal and quantum fluctuations of the critical current

The resistive state is observed at $I_c^* < I_c = (2e/\hbar)E_J$ due to thermal activation through the barrier $U_0(I)$.

The rate of the thermo-activated decay is

$$\omega_T = \omega(I) \exp\left(-\frac{U_0(I)}{kT}\right)$$

where $\omega(I) = \omega_p[1 - (I/I_c)^2]^{1/4}$; $\omega_p = (L_JC)^{-1/2}$.

and $U_0(I) = (4\sqrt{2/3}) E_J[1 - (I/I_c)]^{3/2}$

Quantum decay for “quantum” Josephson junctions (from ground state)

$$\omega_Q = a_q \omega(I) \exp(-\alpha \frac{U_0(I)}{\hbar \omega(I)})$$

$kT \rightarrow \hbar \omega(I)$, the null oscillation energy
\( \beta_L \)-parameter, energy of superconducting ring with Josephson junction

\[ \Phi = \Phi_e - LI \]
\[ LI^2/2 = (\Phi - \Phi_e)^2/2L \]

\( \varphi = 2\pi \Phi/\Phi_0 \); \( \varphi_e = 2\pi \Phi_e/\Phi_0 \)

**Dimensionless potential** (normalized to \( E_J \)):

\[ U(\varphi) = 1 - \cos \varphi + li^2/2 = 1 - \cos \varphi + (\varphi - \varphi_e)^2/2l, \]

where dimensionless ring inductance:

\[ l = \beta_L \frac{2\pi LI_c}{\Phi_0}, \quad i = I/I_c \]

\( \beta_L > 1 \), barriers exist
\( \beta_L < 1 \), no barriers
Superconducting flux qubit

Digital bit

Quantum bit

π-junction

or π-shift due to π-junction

Energy

magnetic flux

qubit operation
Qubit is an artificial atom

Qubit states on Bloch sphere
Microwave manipulations on qubit states

Qubit controlled by magnetic field is a superconducting ring with several Josephson junctions. An artificial 2-level atom with \(|0\rangle\) and \(|1\rangle\) states

Classical bit

\(\begin{align*}
0 \\
1
\end{align*}\)

Qubit wave function

\(|\Psi\rangle = \alpha |0\rangle + \beta |1\rangle\)

Superposition of these two states

Bloch sphere

Microwave pulses with controlled amplitude, duration and phase

Two-level atom

\(\begin{align*}
\hbar \omega_q & \quad |1\rangle \\
& \quad |0\rangle
\end{align*}\)
Phase qubit: Rabi flopping

Anharmonic potential - only two levels are involved
Phase qubit with integrated SFS $\pi$-junction

in collaboration with Alexey Ustinov’s group, Karlsruhe Inst. of Technology, Germany

Here the $\pi$-junction always remains at the zero-voltage state.

SIS – junction and readout dc-SQUID fabricated by VTT, Finland

$\pi$ – junction integrated afterwards in Chernogolovka
Experimental data: Rabi oscillations

Phase qubit with a $\pi$-junction

Conventional phase qubit

\[ \Phi_0 / 2 \]
Flux qubit with SFS $\pi$-junction

- the resonator dispersive shift due to coupling to a qubit

Flux qubit shunted by large capacitance

C_{sh} \sim 20 \text{ fF}; \alpha=0.52; j_c=0.5 \text{ kA/cm}^2; I_c=0.4 \mu\text{A}

T_2 = 1.3 \text{ мкс}

\tau_1 = 1.25 \pm 0.06 \mu\text{s}

|\Delta\omega_{12}| = 5.216 \pm 0.006 \text{ MHz}
3D-transmons

The coherence time $T_2 = 5 \, \mu s$

Devoret & Schoelkopf, Science 339, 1169 (2013)
The coherence time
$T_1 = 11.5 \mu s$

The coherence time
$T_2 = 7 \mu s$
MULTIQUBIT SPECTRA (2-XMON-QUBIT SYSTEM)
THREE-QUBIT SYSTEM (2 XMONS AND ‘COUPLER’)

The coherence time for each qubit
\[ T_2 \sim 3 \text{ мкс} \]

\[ H_{\text{int}} = J \hat{\sigma}_x^1 \hat{\sigma}_x^2 \]

\[ J \sim 20-30 \text{ MHz} \]

<table>
<thead>
<tr>
<th>1-qubit spectrum</th>
<th>2-qubit spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2J )</td>
<td>( 4J )</td>
</tr>
</tbody>
</table>
Grover search algorithm
Grover search algorithm realization

The blue columns is statistics of the states at 10000 launches for sequential storage in each of the "cells":
|0> = |00>, |1> = |01>, |2> = |10> и |3> = |11>.

The red columns is a hypothetical result for an ideal (error-free) quantum computer.

The black dotted line is a 50% probability (the limit for a classic computer with a single access to the "Oracle"). Measured probabilities of correct state search: |00> – 58%, |01> – 57%, |10> – 53%, |1> / |11> - 57%.