Chapter 5

5. Josephson Effect

5.1 Josephson Equations

5.1.1 SIS Josephson Junction

5.1.2 Ambegaokar-Baratoff relation

5.2 Josephson Coupling Energy

5.2.1 Josephson Junction with applied current

5.3 Applications of the Josephson Effect

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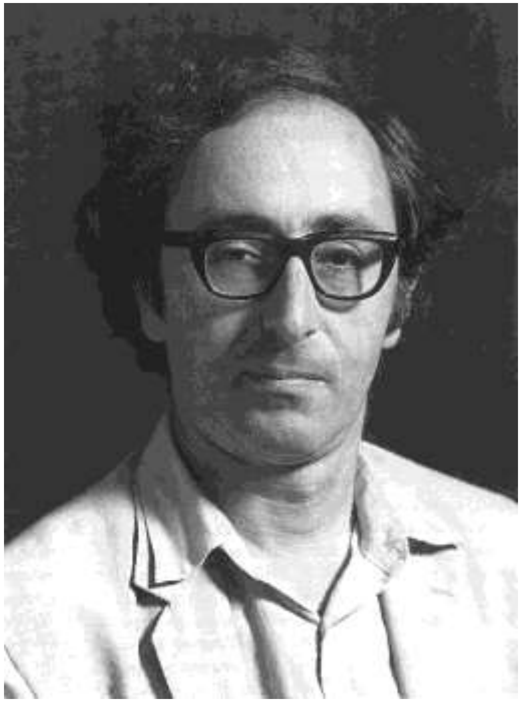
5 Josephson Effect



Brian David Josephson (born 1940)

What happens if we weakly couple two superconductors ?

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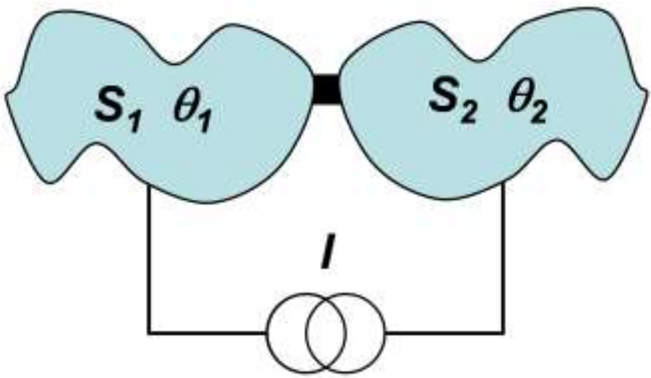
5.1 Josephson Effect (cf. 2.2.3)

- ***what happens if we weakly couple two superconductors?***

  - coupling by *tunneling barriers, point contacts, normal conducting layers, etc.*
  - do they form a bound state such as a molecule?
  - if yes, what is the binding energy?

- **B.D. Josephson** in 1962
  (nobel prize with Esaki and Giaever in 1973)



→ Cooper pairs can tunnel through thin insulating barrier

naive expectation:

- tunneling probability for pairs $\propto (|T|^2)^2$

  → extremely small $\approx (10^{-4})^2$

Josephson:

- tunneling probability for pairs $\propto |T|^2$
- coherent tunneling of pairs („*tunneling of macroscopic wave function*“)

→ ***finite supercurrent at zero applied voltage***

→ ***oscillation of supercurrent at constant applied voltage***

Josephson effects

→ ***finite binding energy of coupled SCs = Josephson coupling energy***

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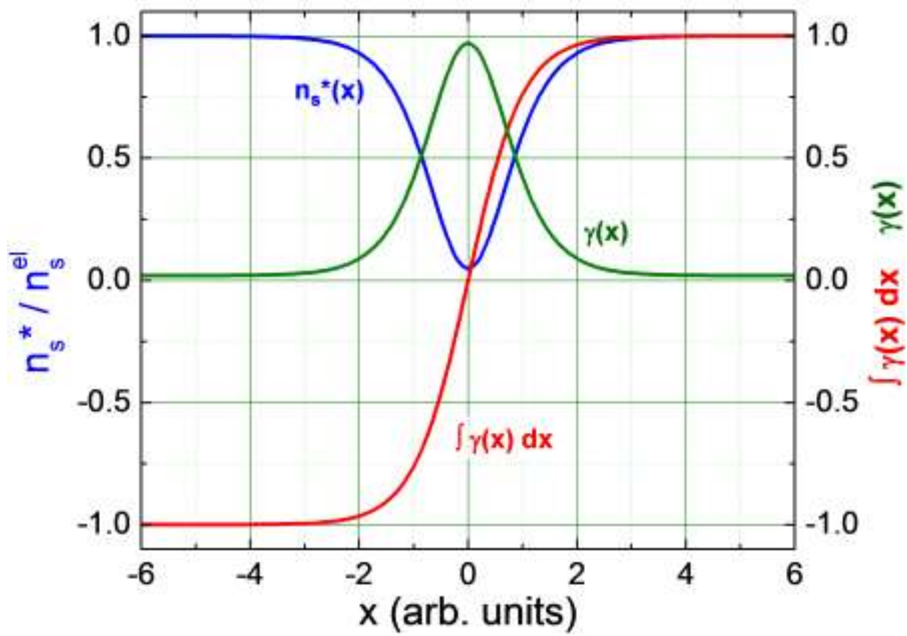
5.1 Josephson Effect (cf. 2.2.3)

- coupling is weak → supercurrent density is small → $|\Psi|^2 = n_s$ is not changed
- supercurrent density depends on gauge invariant phase gradient γ:

$$J_s(\mathbf{r},t) = \frac{q_s n_s \hbar}{m_s}\left[\nabla\theta(\mathbf{r},t) - \frac{2\pi}{\Phi_0}\mathbf{A}(\mathbf{r},t)\right] = \frac{q_s n_s \hbar}{m_s}\gamma(\mathbf{r},t)$$

- ***simplifying assumptions:***
  - current density is homogeneous
  - γ varies negligibly in electrodes
  - J_s same in electrodes and junction area
    → γ in superconducting electrodes much smaller than in insulator I



- ***then:***
  - replace gauge invariant phase gradient γ by ***gauge invariant phase difference***:

$$\varphi(\mathbf{r},t) = \int_1^2 \gamma(\mathbf{r},t) = \int_1^2 \left(\nabla\theta - \frac{2\pi}{\Phi_0}\mathbf{A}\right)\cdot d\mathbf{l}$$

$$= \theta_2(\mathbf{r},t) - \theta_1(\mathbf{r},t) - \frac{2\pi}{\Phi_0}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$$

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5.1 Josephson Effect (cf. 2.2.3)

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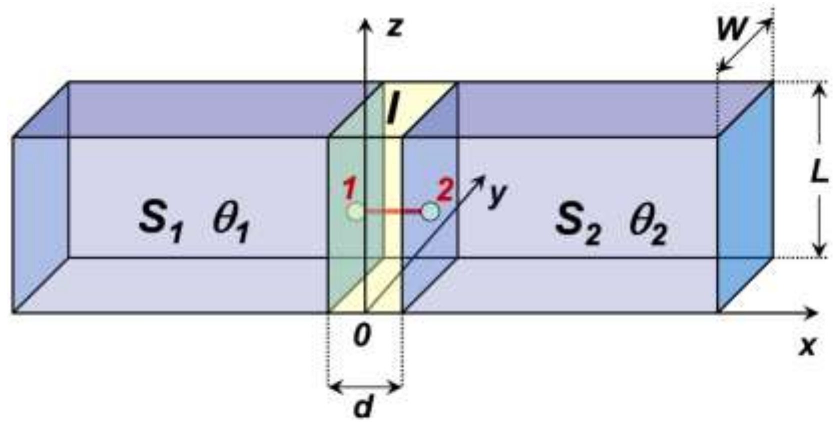
first Josephson equation:



- we *expect:*

$$J_s = J_s(\varphi)$$

$$J_s(\varphi) = J_s(\varphi + n2\pi)$$

- for $J_s = 0$: phase difference φ must be zero:

$$J_s(0) = J_s(n \cdot 2\pi) = 0$$

therefore:

$$\boxed{J_s(\varphi) = J_c \sin\varphi + \sum_{m=2}^{\infty} J_m \sin(m\varphi)}$$

J_c: critical/maximum Josephson current density

general formulation of 1st Josephson equation: ***current-phase relation***

- in most cases: keep only 1st term (especially for weak coupling):

1\. Josephson equation: $J_s(\varphi) = J_c \sin\varphi$

derived by Josephson for SIS junctions

supercurrent density varies **sinusoidally** with $\varphi = \theta_2 - \theta_1$ w/o ext. potentials

- *generalization* to ***spatially inhomogeneous*** supercurrent density:

$$J_s(y, z, t) = J_c(y, z) \ \sin\varphi(y, z, t)$$

5.1 Josephson Effect (cf. 2.2.3)

- other argument why there are only sin contributions to Josephson current

$$\boxed{J_s(\varphi) = J_c \sin\varphi + \sum_{m=2}^{\infty} J_m \sin(m\varphi)}$$

⇨ ***time reversal symmetry***

- if we reverse time, the Josephson current should flow in opposite direction
  - $t \to -t, \;\; J_s \to -J_s$

- the time evolution of the macroscopic wave functions is $\propto \exp[i\theta(t)] = \exp[i\omega t]$
  - if we reverse time, we have

$$\varphi(t) = \theta_2(t) - \theta_1(t) \xrightarrow{t \to -t} \begin{aligned} \varphi(-t) &= \theta_2(-t) - \theta_1(-t) \\ &= -[\theta_2(t) - \theta_1(t)] \\ &= -\varphi(t) \end{aligned}$$

- if the Josephson effect stays unchanged under time reversal, we have to demand

$$J_s(\varphi) = -J_s(-\varphi)$$

⇨ satisfied only by sin-terms

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second Josephson equation:

- time derivative of the gauge invariant phase difference: $\varphi(\mathbf{r},t) = \theta_2(\mathbf{r},t) - \theta_1(\mathbf{r},t) - \frac{2\pi}{\Phi_0}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$

$$\frac{\partial\varphi}{\partial t} = \frac{\partial\theta_2}{\partial t} - \frac{\partial\theta_1}{\partial t} - \frac{2\pi}{\Phi_0}\frac{\partial}{\partial t}\int_1^2 \mathbf{A}(\mathbf{r},t)\cdot d\mathbf{l}$$

- substitution of the energy-phase relation $-\hbar\frac{\partial\theta}{\partial t} = \frac{1}{2n_s}\Lambda\mathbf{J}_s^2 + q_s\phi$ gives:

$$\frac{\partial\varphi}{\partial t} = -\frac{1}{\hbar}\left(\frac{\Lambda}{2n_s}\left[\mathbf{J}_s^2(2) - \mathbf{J}_s^2(1)\right] + q_s\left[\phi(2) - \phi(1)\right]\right) - \frac{2\pi}{\Phi_0}\frac{\partial}{\partial t}\int_1^2 \mathbf{A}\cdot d\mathbf{l}$$

- supercurrent density across the junction is *continuous* ($\mathbf{J}_s(1) = \mathbf{J}_s(2)$):

$$\frac{\partial\varphi}{\partial t} = \frac{2\pi}{\Phi_0}\int_1^2\left(-\nabla\phi - \frac{\partial\mathbf{A}}{\partial t}\right)\cdot d\mathbf{l}$$

(term in parentheses = electric field)

2. Josephson equation: $$\frac{\partial\varphi}{\partial t} = \frac{2\pi}{\Phi_0}\underbrace{\int_1^2 \mathbf{E}(\mathbf{r},t)\cdot d\mathbf{l}}_{\text{voltage drop}}$$

voltage – phase relation

5.1 Josephson Effect (cf. 2.2.3)

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- for a constant voltage across the junction: $$\frac{\partial \varphi}{\partial t} = \frac{2\pi}{\Phi_0} V$$ $$\varphi(t) = \varphi_0 + \frac{2\pi}{\Phi_0} V \cdot t$$
- I_s is oscillating at the Josephson frequency $f = V/\Phi_0$:

$$I_s(t) = I_c \sin \varphi(t) = I_c \sin\left(\frac{2\pi}{\Phi_0} V \cdot t\right)$$

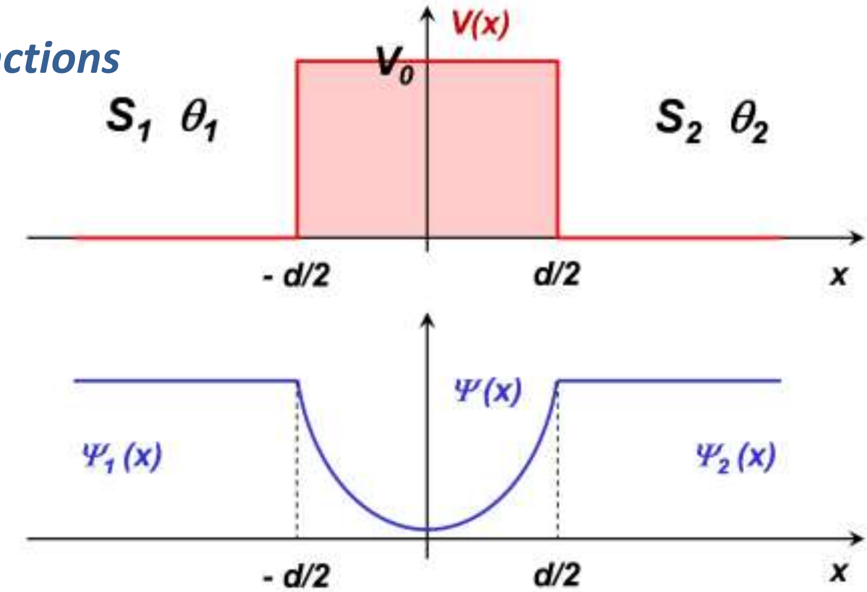
$$\frac{f}{V} = \frac{\omega}{2\pi V} = \frac{1}{\Phi_0} \simeq 483.597898(19)\ \frac{\mathrm{MHz}}{\mu\mathrm{V}}$$

→ ***voltage controlled oscillator***

- applications: - Josephson voltage standard
  - microwave sources
- derivation of Josephson equations for SIS junction from time-dependent Schrödigner equation:
  - ➢ see exercise sheet
  - ➢ see appendix G.4 in „Festkörperphysik“, 2. Auflage, R. Gross, A. Marx, de Gruyter (2014)

5.1.1 Special Topic:
Superconducting Tunnel Junctions

- ***Josephson effect in superconducting tunnel junctions***
  - *insulating* tunneling barrier, thickness *d*



- what determines the *maximum Josephson current density J_c* ?
  - calculation by ***wave matching method***

- *energy-phase relation:*

$$-\hbar\frac{\partial\theta}{\partial t} = \frac{1}{2n_s}\Lambda\mathbf{J}_s^2 + \cancel{q_s\phi + \mu}$$

$$-\hbar\frac{\partial\theta}{\partial t} = \frac{1}{2n_s}\Lambda\mathbf{J}_s^2 \quad\Rightarrow\quad \frac{\partial\theta}{\partial t} = -\frac{E_0}{\hbar}$$

E_0 = kinetic energy

→ time depedent macroscopic wave function: $\psi(\mathbf{r},t) = \psi(\mathbf{r})\,\mathrm{e}^{-\imath(E_0/\hbar)t}$

- wave function **within** barrier with height $V_0 > E_0$:

only **elastic** processes:
→ time evolution is the **same** outside and inside barrier
→ consider only **time independent** part
→ time independent Schrödinger(-like) equation for region of constant potential

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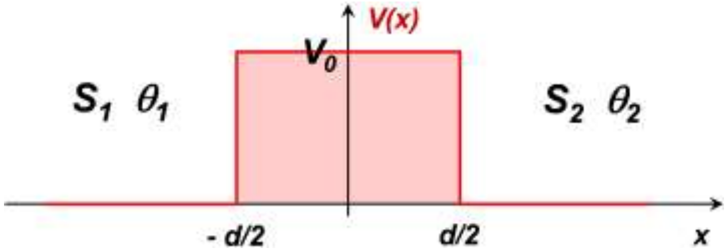
5.1.1 Josephson Effect

$$-\frac{\hbar^2}{2m^\star}\nabla^2\psi(\mathbf{r}) = (E_0 - V_0)\psi(\mathbf{r})$$



- ***assumption***:
  homogeneous barrier and supercurrent flow → **1D problem**

- ***solutions***:
  - in superconductors $\psi_{1,2} = \sqrt{n_{1,2}}\, \mathrm{e}^{\imath\theta_{1,2}}$
  - in insulator: sum of decaying and growing exponentials $\psi(x) = A\cosh(\kappa x) + B\sinh(\kappa x)$
  - characteristic decay constant: $\kappa = \sqrt{\frac{2m_s(V_0 - E_0)}{\hbar^2}}$

barrier properties

- coefficients A and B are determined by the boundary conditions at $x = \pm d/2$:

$$\psi(-d/2) = \sqrt{n_1}\, \mathrm{e}^{\imath\theta_1}$$
$$\psi(+d/2) = \sqrt{n_2}\, \mathrm{e}^{\imath\theta_2}$$

$n_{1,2}$, $\theta_{1,2}$: Cooper pair density and wave function phase at the boundaries $x = \pm\, d/2$

$$\sqrt{n_1}\, \mathrm{e}^{\imath\theta_1} = A\cosh(\kappa d/2) - B\sinh(\kappa d/2)$$
$$\sqrt{n_2}\, \mathrm{e}^{\imath\theta_2} = A\cosh(\kappa d/2) + B\sinh(\kappa d/2)$$

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5.1.1 Josephson Effect

- solving for A and B: $A = \frac{\sqrt{n_1}\, e^{\imath\theta_1} + \sqrt{n_2}\, e^{\imath\theta_2}}{2\cosh(\kappa d/2)}$ $\quad B = -\frac{\sqrt{n_1}\, e^{\imath\theta_1} - \sqrt{n_2}\, e^{\imath\theta_2}}{2\sinh(\kappa d/2)}$

- supercurrent density: $\mathbf{J}_s = \frac{q_s}{m_s} \Re\left\{\psi^\star \left(\frac{\hbar}{\imath}\nabla\right) \psi\right\} = \frac{\hbar q_s}{m_s} \Im\{\psi^\star \nabla \psi\}$

- substituting the coefficients A and B: $\quad \Rightarrow \quad \mathbf{J}_s = \frac{q_s}{m_s}\kappa\hbar \;\Im\{A^\star B\}$

$$\mathbf{J}_s = \mathbf{J}_c \;\sin(\theta_2 - \theta_1)$$

current-phase relation

→ ***maximum Josephson current density J_c:***

$$\mathbf{J}_c = -\frac{q_s}{m_s}\kappa\hbar \frac{\sqrt{n_1 n_2}}{\underbrace{2\sinh(\kappa d/2)\cosh(\kappa d/2)}_{=\sinh(2\kappa d)}} = -\frac{q_s\hbar\kappa}{m_s}\frac{\sqrt{n_1 n_2}}{\sinh(2\kappa d)}$$

- ***real junctions:***
  $V_0 \approx$ few eV $\Rightarrow 1/\kappa < 1$ nm, d few nm $\Rightarrow \kappa d \ll 1$, then: $\quad \sinh(2\kappa d) \simeq \frac{1}{2}\exp(2\kappa d)$

- maximum Josephson current **decays exponentially** with increasing barrier thickness *d*:

$$\mathbf{J}_c = -\frac{q_s\hbar\kappa}{m_s}\, 2\sqrt{n_1 n_2}\;\exp(-2\kappa d)$$

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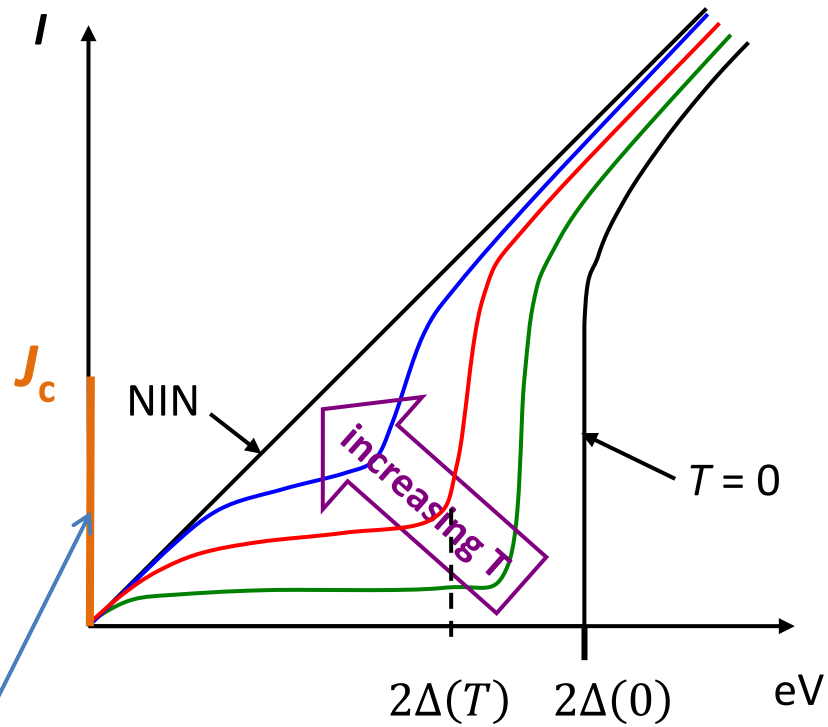
5.1.2 Ambegaokar-Baratoff Relation

- quasiparticle tunneling:
  - current-voltage characteristics



at $eV \gg 2\Delta(T)$

$$\mathbf{J}_{\mathrm{qp}} \propto \frac{1}{R_n A} \cdot \exp(-2\kappa d)$$

R_n = normal resistance
resistance of NIN
tunnel junctions

- Cooper pair tunneling: $$\mathbf{J}_c = \frac{e\hbar\kappa}{m} 2\sqrt{n_1 n_2} \exp(-2\kappa d)$$

- $V > 0$: time average of supercurrent vanishes: $\langle J_c \sin\frac{2eV}{\hbar}t\rangle = 0$

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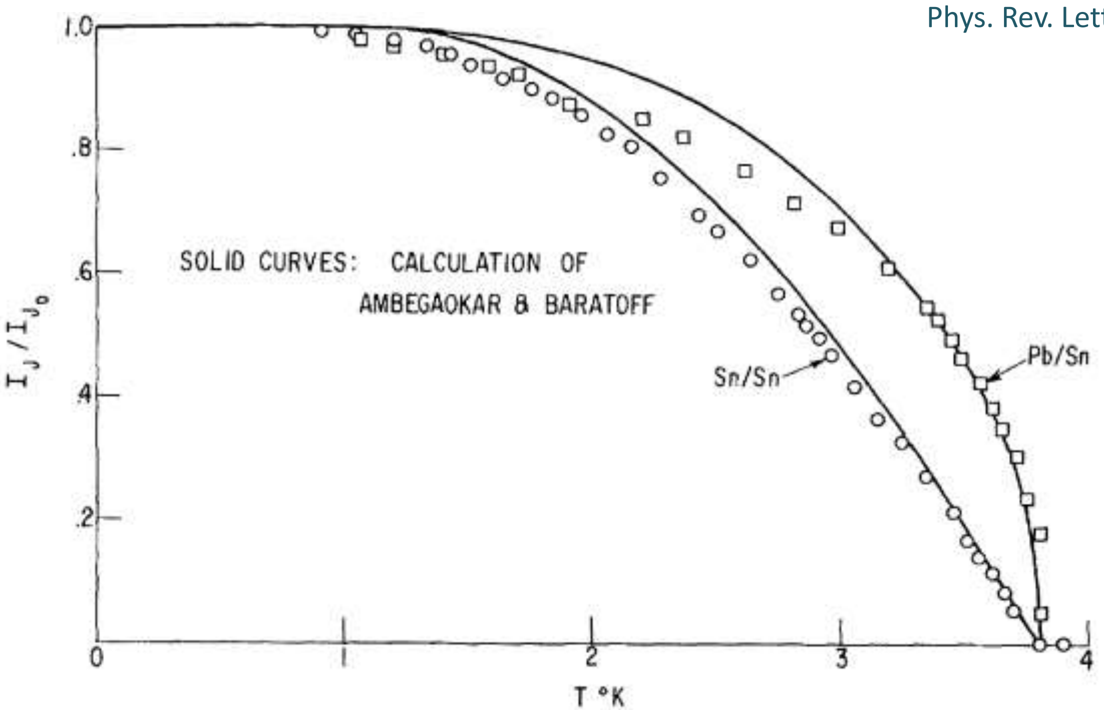
- ratio of J_c and $J_{qp}(eV \gg 2\Delta) = const$ ➔ $J_c R_n A = I_c R_n A = I_c R_n = const$
- exact calculation yields Ambegaokar-Baratoff relation:

$$\boxed{I_c R_n = \frac{\pi}{2e}\Delta(T) \cdot \tanh\left(\frac{\Delta(T)}{2k_B T}\right)}$$

V. Ambegaokar, A. Baratoff, *Tunneling Between Superconductors*, Phys. Rev. Lett. **10**, 486-489 (1963).



M.D. Fiske, Rev. Mod. Phys. **36**, 221–222 Temperature and Magnetic Field Dependences of the Josephson Tunneling Current

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5.1 Summary

Macroscopic wave function Ψ:

describes ensemble of macroscopic number of superconducting pairs

$|\Psi|^2$ describes density of superconducting pairs

Current density in a superconductor:

$$\mathbf{J}_s = \frac{\hbar n_s q_s}{m_s}\left\{\nabla\theta(\mathbf{r},t) - \frac{q_s}{\hbar}\mathbf{A}(\mathbf{r},t)\right\} = \frac{\hbar n_s q_s}{m_s}\left\{\nabla\theta(\mathbf{r},t) - \frac{2\pi}{\Phi_0}\mathbf{A}(\mathbf{r},t)\right\}$$

Gauge invariant phase gradient:

$$\gamma(\mathbf{r},t) = \nabla\theta(\mathbf{r},t) - \frac{q_s}{\hbar}\mathbf{A}(\mathbf{r},t) = \nabla\theta(\mathbf{r},t) - \frac{2\pi}{\Phi_0}\mathbf{A}(\mathbf{r},t)$$

Phenomenological London equations:

$$\frac{\partial}{\partial t}(\Lambda \mathbf{J}_s) = \mathbf{E} \qquad \nabla \times (\Lambda \mathbf{J}_s) = -\mathbf{B} \qquad (\Lambda = m_s/n_s {q_s}^2 = \mu_0 \lambda_L^2)$$

flux/fluxoid quantization: $$\oint_C (\Lambda \mathbf{J}_s)\cdot d\mathbf{l} + \int_S \mathbf{B}\cdot d\mathbf{s} = n\,\Phi_0$$

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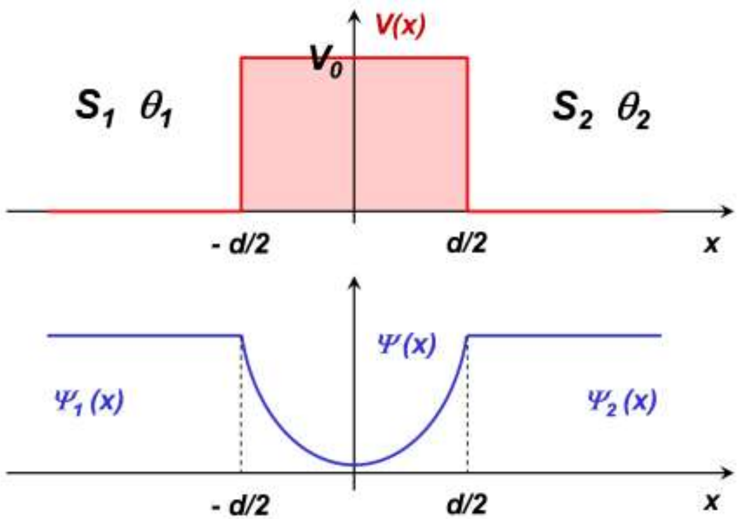
5.1 Summary

Josephson equations:

$$\mathbf{J}_s(\mathbf{r},t) = \mathbf{J}_c(\mathbf{r},t)\sin\varphi(\mathbf{r},t)$$

$$\frac{\partial\varphi}{\partial t} = \frac{2eV}{\hbar} = \frac{2\pi}{\Phi_0}V \qquad (\omega/2\pi = 483.6\,\mathrm{GHz/mV})$$

maximum Josephson current density J_c:
wave matching method



$$\mathbf{J}_s = \mathbf{J}_c\ \sin(\theta_2 - \theta_1)$$

$$\mathbf{J}_c = -\frac{q_s\hbar\kappa}{m_s}\,2\sqrt{n_1 n_2}\,\exp(-2\kappa d)$$

tunneling current of unpaired electrons (quasiparticles, cf. chapter 4.4.2):

$$\mathbf{J}_q = f(V)\ \cdot\ \exp(-2\kappa d)$$

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5.2 Josephson Coupling Energy

- the two weakly coupled superconductors form "***molecule***" analogous to H_2 molecule
  → what is the ***binding energy*** of this molecule ?

- consider a JJ with initial current & phase difference equal to zero
  then: ***increase junction current from zero to finite value***
  - phase difference has to change
  - voltage-phase relation: finite junction voltage
  - external source has to supply energy (to accelerate the superelectrons)
  - stored in kinetic energy of moving superelectrons
  - integral of the supplied power *I·V* to increase current to $I(\varphi) = I_c \sin\varphi$ (voltage during increase of current):

$$E_J = \int_0^{t_0} I_s V \, dt = \int_0^{t_0} (I_c \sin\widetilde{\varphi}) \left(\frac{\Phi_0}{2\pi} \frac{d\widetilde{\varphi}}{dt} \right) dt$$

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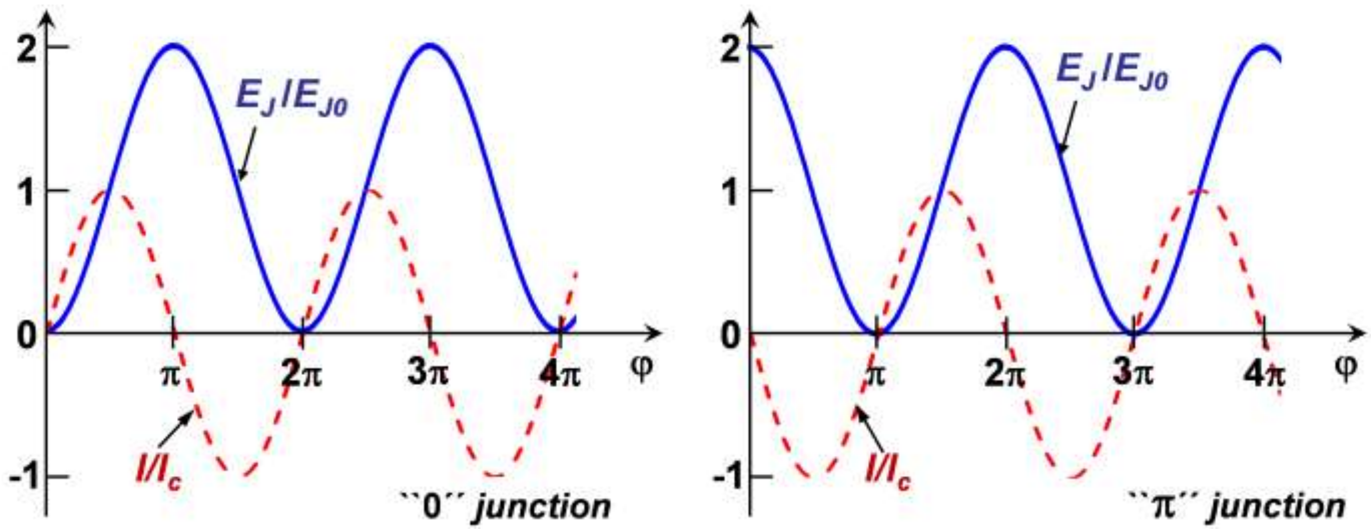
5.2 Josephson Coupling Energy

with $\varphi(0) = 0$ and $\varphi(t_0) = \varphi$: $$E_J = \frac{\Phi_0 I_c}{2\pi} \int_0^{\varphi} \sin\tilde{\varphi}\, d\tilde{\varphi}$$

integration: $$E_J = \frac{\Phi_0 I_c}{2\pi}\left(1 - \cos\varphi\right) = E_{J0}\left(1 - \cos\varphi\right)$$

Josephson coupling energy



- **order of magnitude:**
  - typically: $I_c \sim 1\ \mathrm{mA} \;\Rightarrow\; E_{J0} \simeq 3 \times 10^{-19}\ \mathrm{J}$
  - corresponds to thermal energy $k_B T$ for $T \simeq 20\,000\ \mathrm{K}$
  - junction with very small critical current: $I_c \simeq 1\ \mu A \;\Rightarrow$ thermal energy $\simeq k_B \times 20\ \mathrm{K}$

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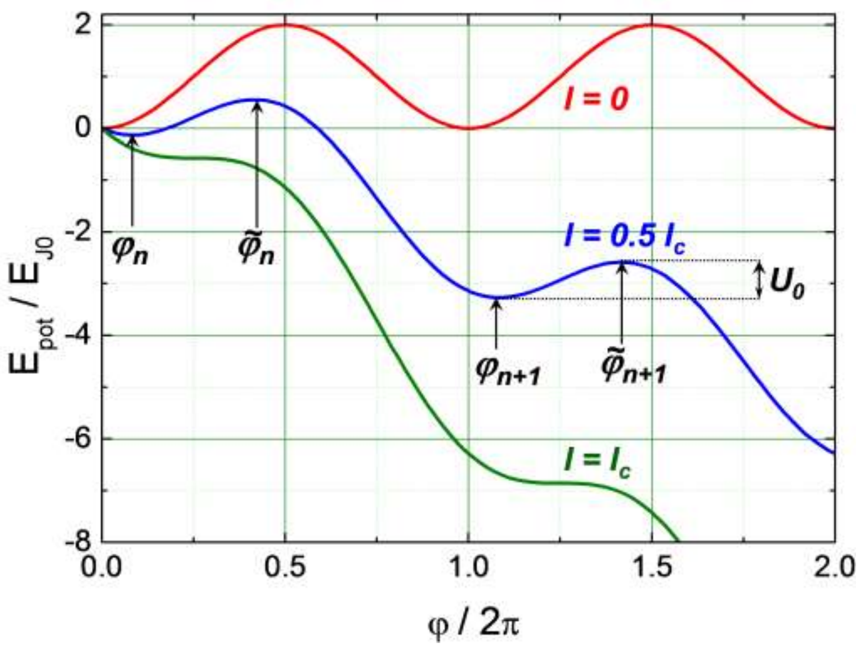
5.2.1 Josephson Junction with Applied Current

- analysis of **stability** of (junction + current source) – system:
  potential energy E_{pot} of the system under action of external force: $E_J - F \cdot x$
  E_J: intrinsic free energy of the subsystem junction
  F: generalized force $(F = I)$
  x: generalized coordinate $\Rightarrow$ $F \cdot \partial x / \partial t$ = power flowing into subsystem ($I \cdot V$):

$$x = \int V\, dt = \frac{\hbar}{2e}\varphi + c = \frac{\Phi_0}{2\pi}\varphi + c$$

→ ***potential energy***:

$$E_{\mathrm{pot}}(\varphi) = E_J(\varphi) - I\left(\frac{\Phi_0}{2\pi}\varphi + c\right) = E_{J0}\left[1 - \cos\varphi - \frac{I}{I_c}\varphi\right] + \tilde{c}$$



tilted washboard potential
stable minima φ_n, unstable maxima $\tilde{\varphi}_n$,
states for different n: equivalent

- junction dynamics: motion of φ in tilted washboard potential (not discussed here)

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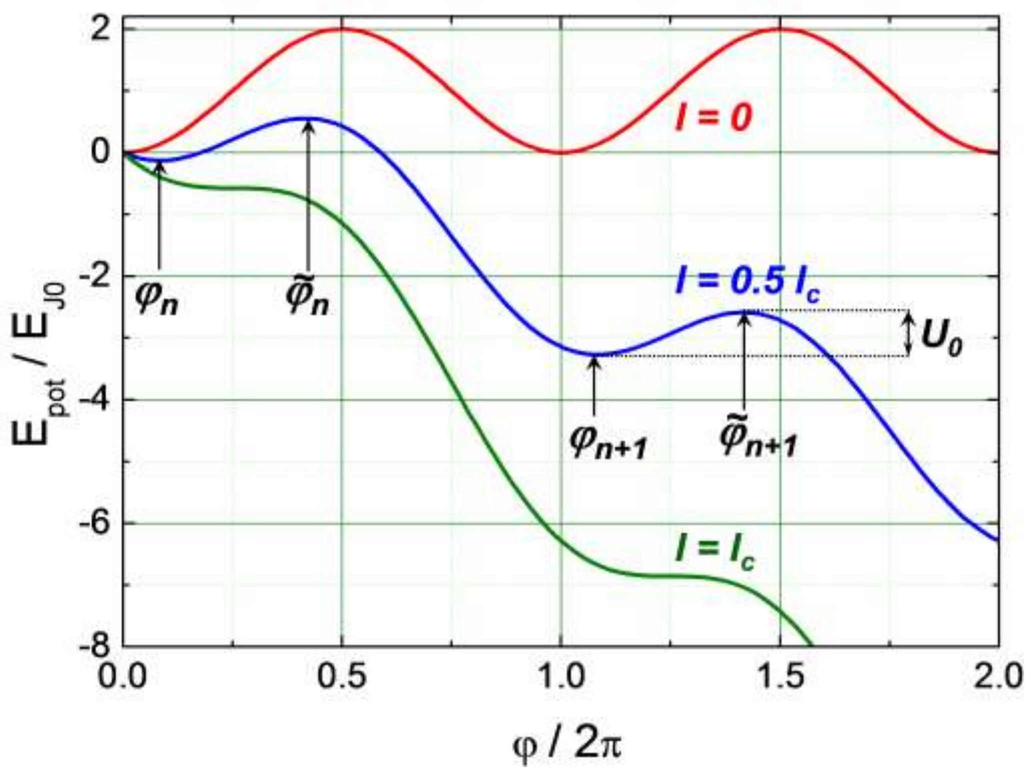
5.2.1 Josephson Junction with Applied Current

$-I_c < I < I_c$ $\Rightarrow$ ***constant phase difference***: $\varphi = \varphi_n = \arcsin\left(\frac{I}{I_c}\right) + 2\pi n$

→ zero junction voltage:
zero voltage state / ordinary (S) state $\varphi = \tilde{\varphi}_n = \pi - \arcsin\left(\frac{I}{I_c}\right) + 2\pi n$



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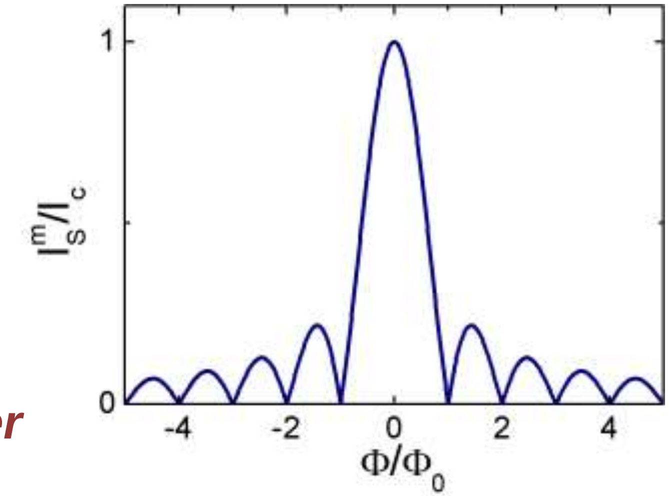
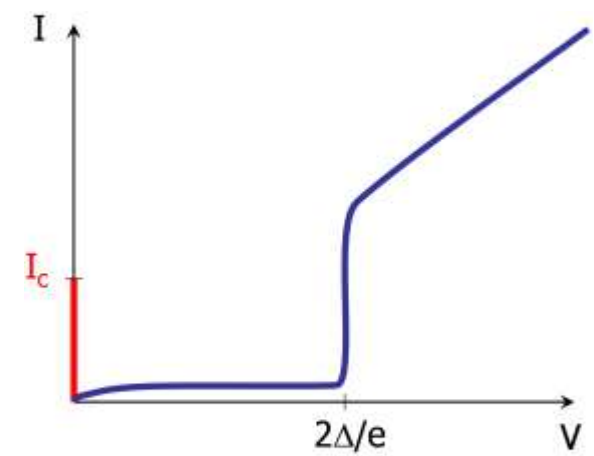
5.3 Applications of the Josephson Effect

large number of applications in **analog** and **digital** electronics

➔ detailed discussion in lecture *„Applied Superconductivity“*

- $I_s^m = I_s^m(B)$:
  → ***magnetic field sensors (SQUIDs)***
- $\beta_C \gg 1$
  → **bistability**: zero/voltage state
  → ***switching devices, Josephson computer***
- 2nd Josephson equation
  → ***VCO, voltage standard***
- **nonlinear** IVC
  → ***mixers up to THz, oscillators***
- **macroscopic quantum** behavior
  → ***superconducting qubits***





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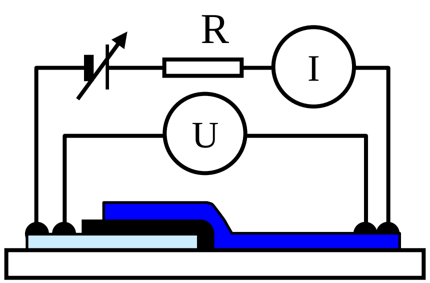
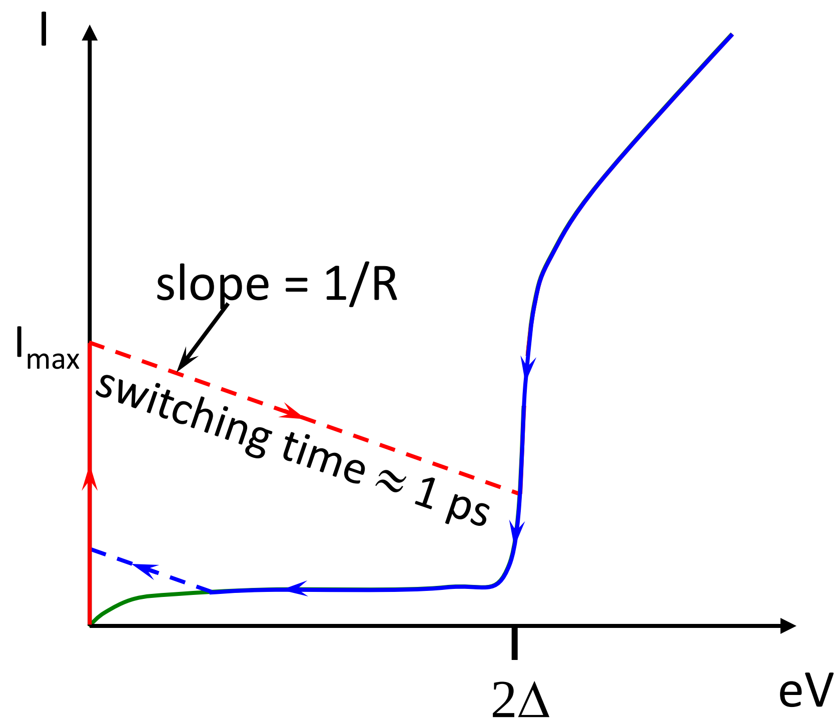
- $V = 0$: Josephson current
- $V \neq 0$: quasiparticle current





- hysteresis:

  fast switching device

  very low power consumption

  ⇒ Josephson digital electronics

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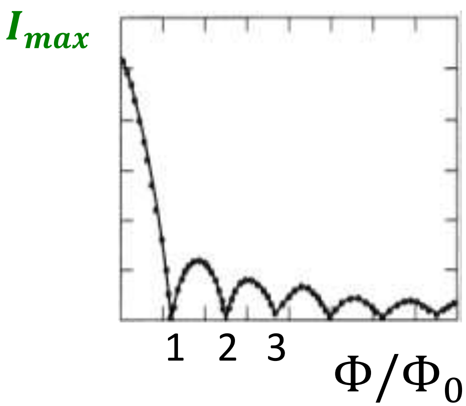
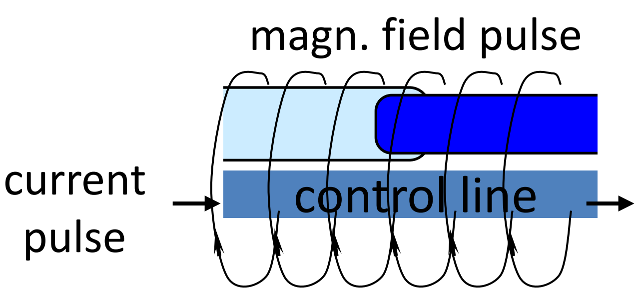
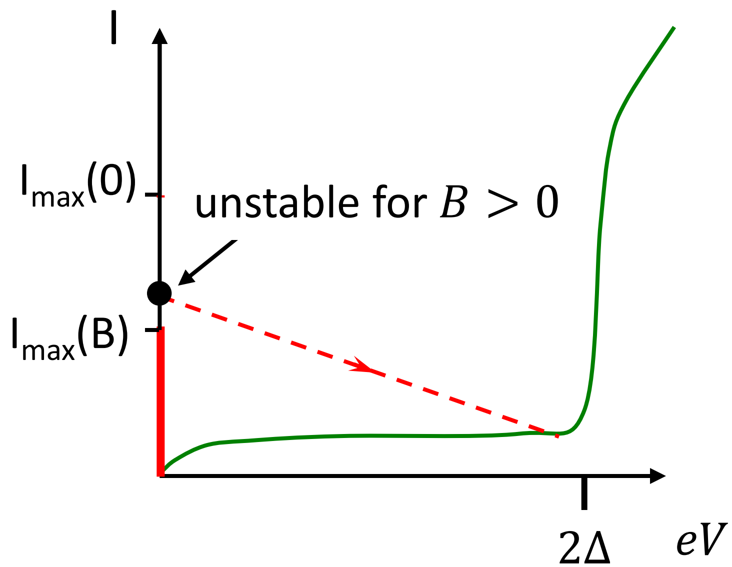
principle of switching element:

- magnetic field dependence of the maximum Josephson current







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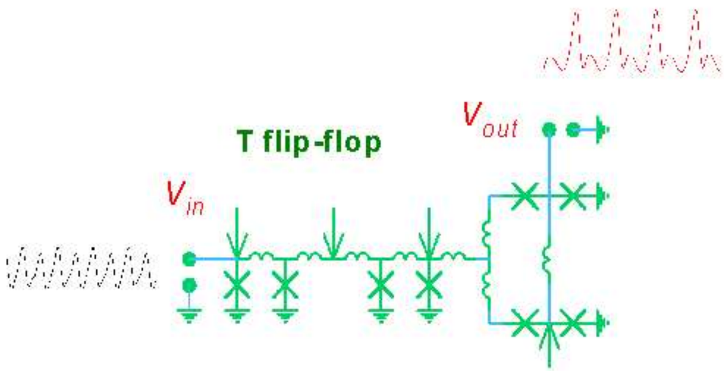
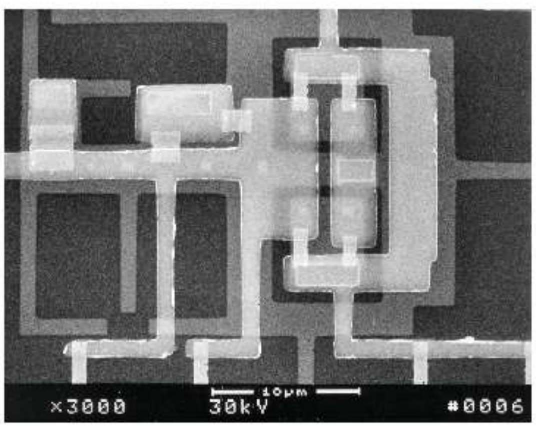
5.3 Applications of the Josephson Effect

World's fastest digital IC - operates to 750 GHz

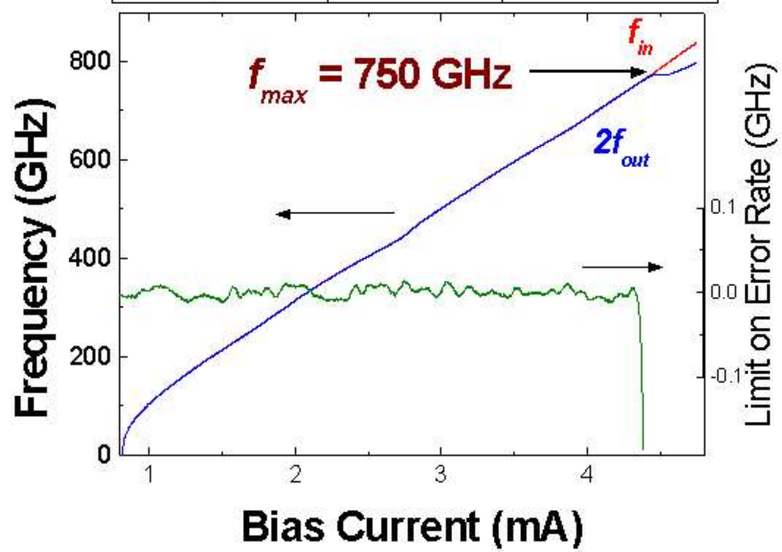
http://insti.physics.sunysb.edu/physics/news_fast_ic.htm





Dividers

	RSFQ	Semi-conductor
Frequency	750 GHz	60 GHz
Power Dissipation	1.5 μW	0.5 W



for details see: http://gamayun.physics.sunysb.edu/RSFQ/

- problem: integration of large number of JJs (> 10^5) with high yield and small parameter spead

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5.3 Applications of the Josephson Effect

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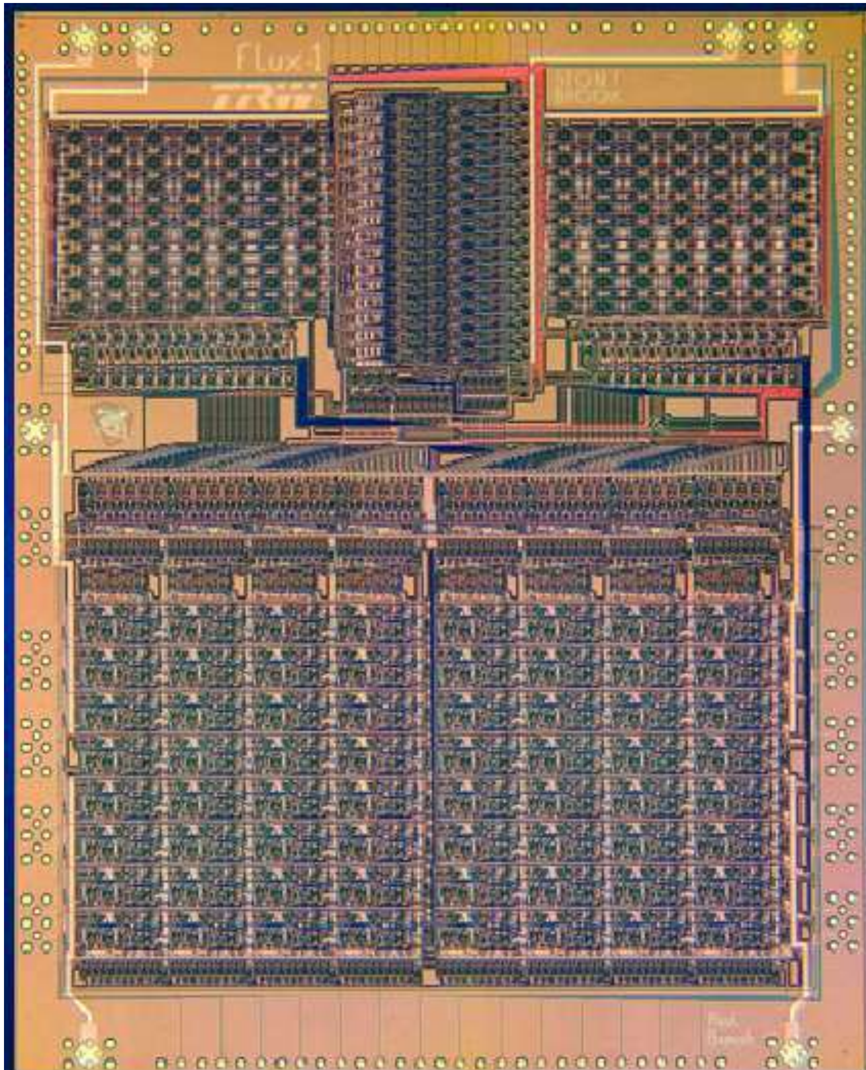


Stony Brook

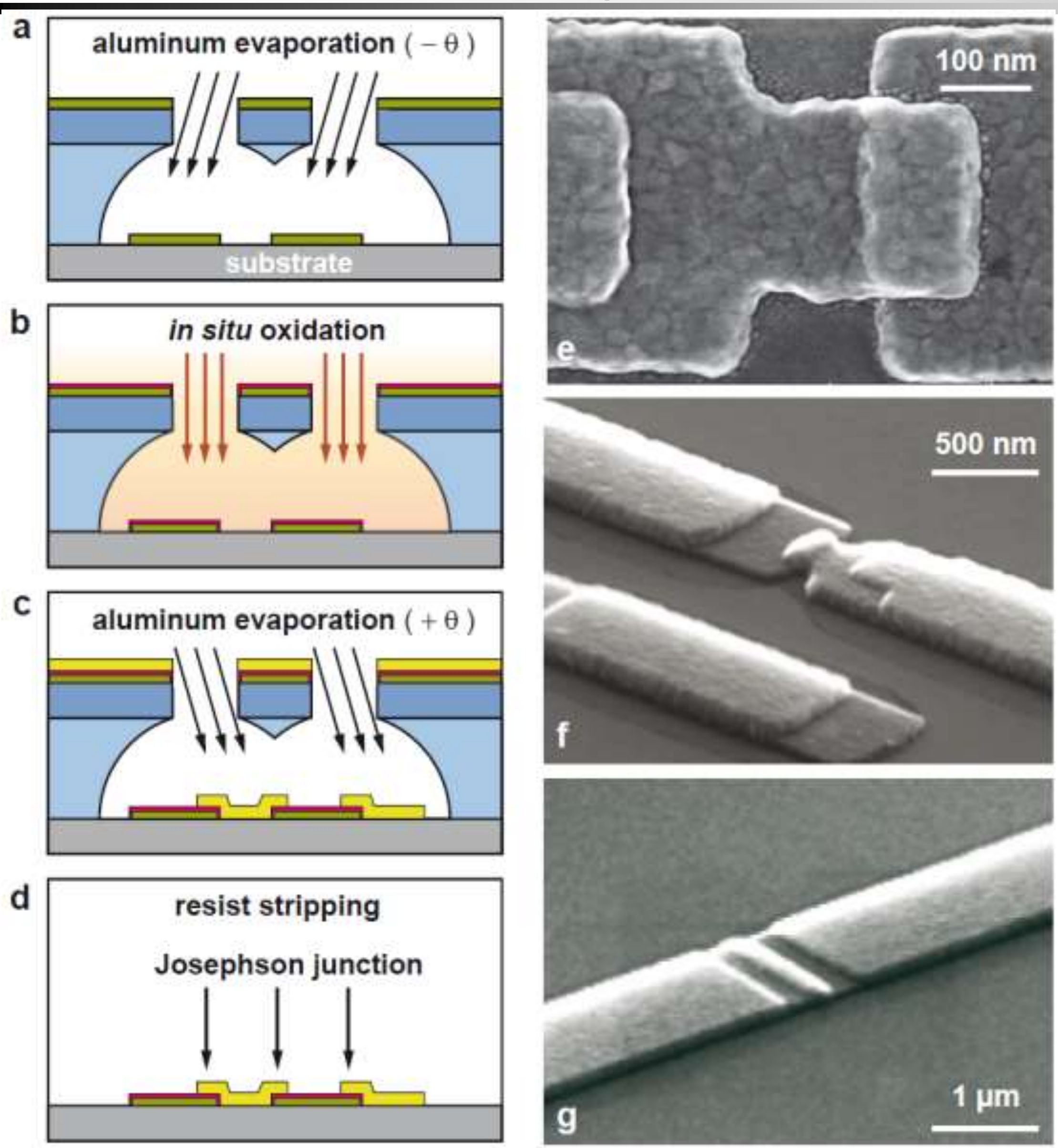
FLUX-1

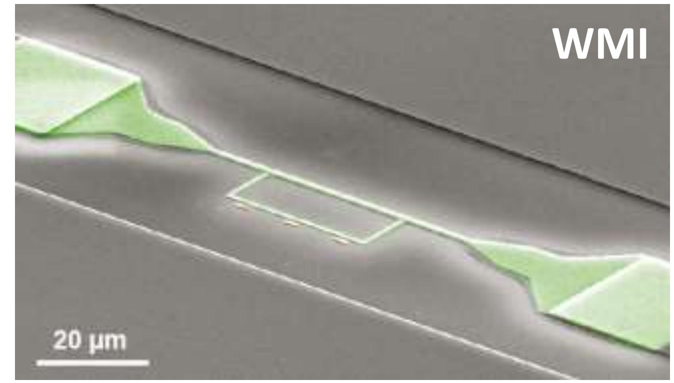
- the first RSFQ MPU
- 8 bit ALU array
- 16 word instruction memory
- 70,000 JJs
- 14 mW
- 20-22 GHz @ *F* = 2.0 um
  (⇒ 120-140 GHz @ 0.3 um)
- TRW's 4-metal process

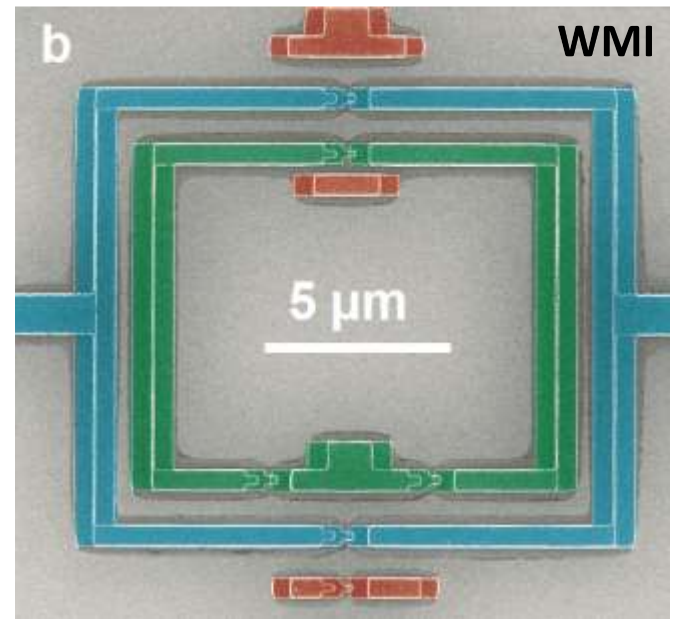
http://pavel.physics.sunysb.edu/RSFQ/

5.3 Applications of the Josephson Effect

superconducting quantum bits



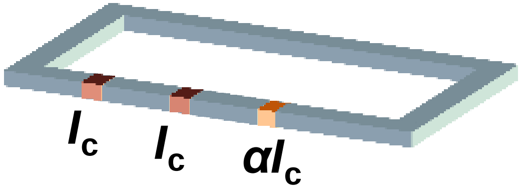


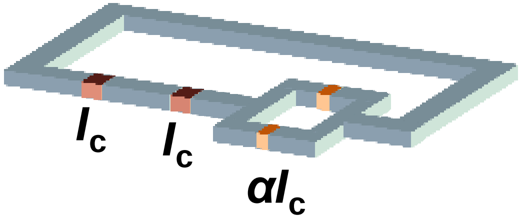


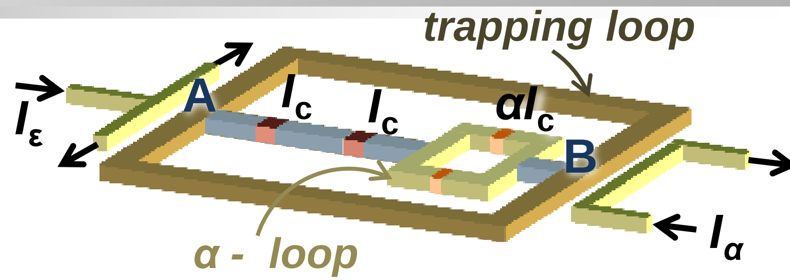
F. Deppe *et al.*, *PRB 76, 214503 (2007)*
T. Niemczyk et al., *SUST 22, 034009 (2009)*

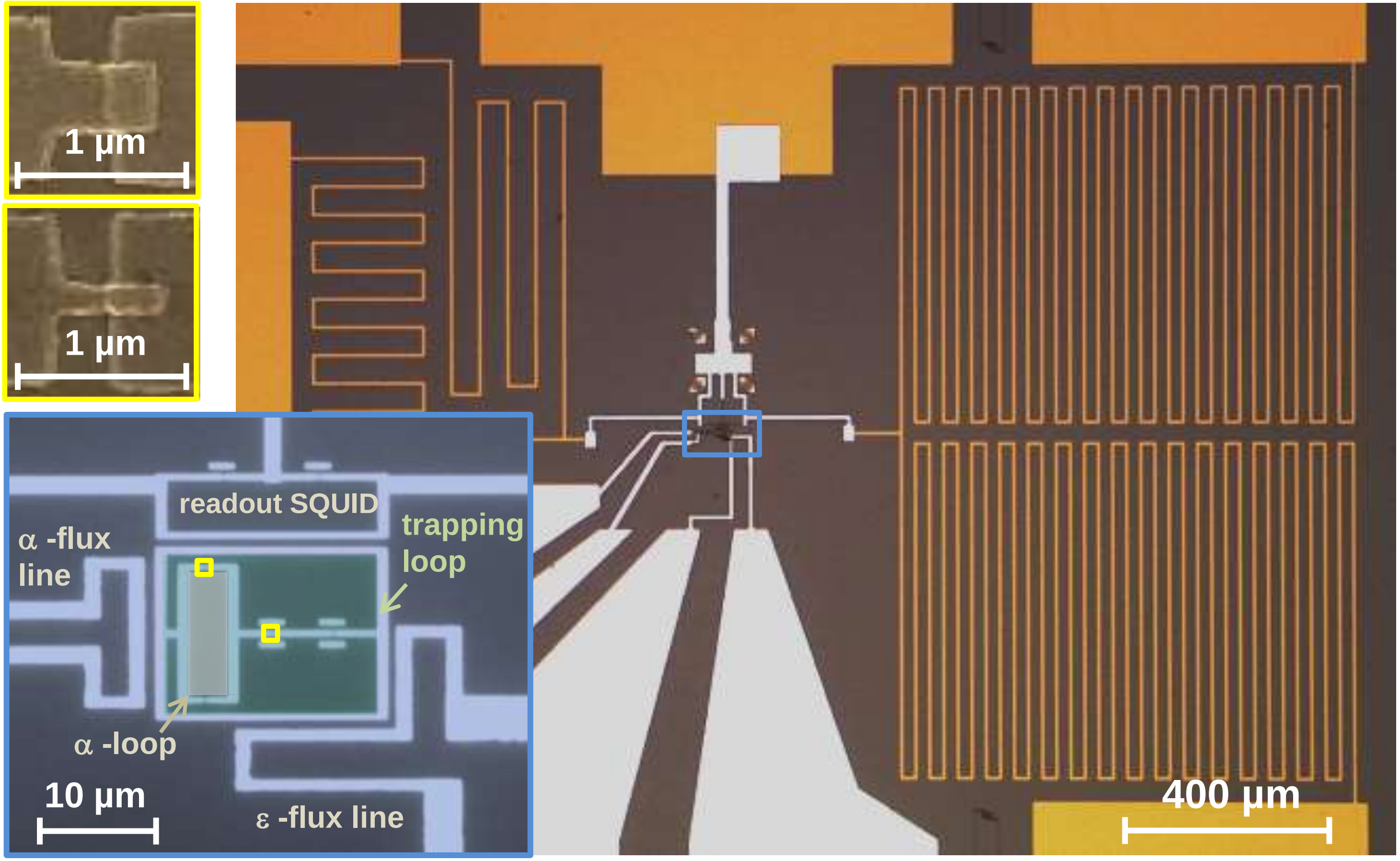
superconducting flux quantum bits fabricated at WMI

superconducting quantum bits









superconducting quantum circuits fabricated at WMI

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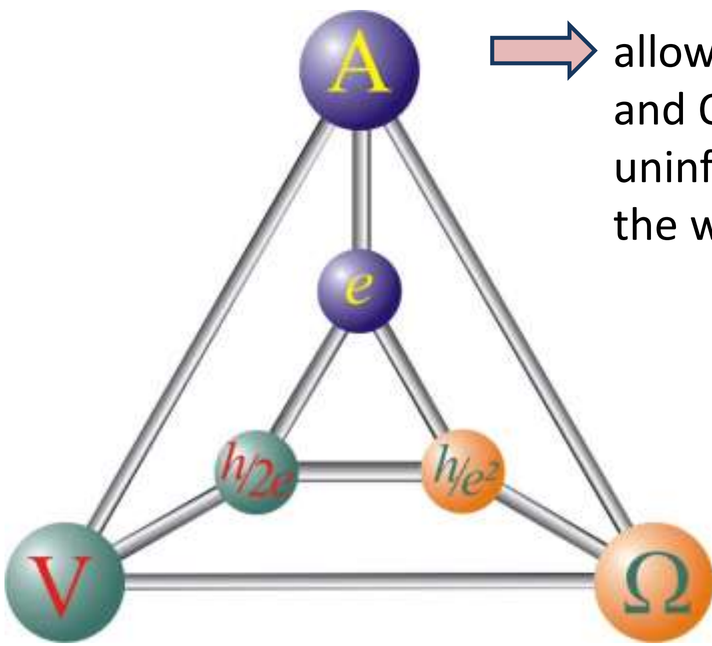
precise definition of the electrical voltage, current and the resistance by using fundamental quantum effects:

- ***Josephson effect***: $V = \frac{h}{2e} \cdot f = \Phi_0 \cdot f$ (relation between voltage and time/frequency by flux quantum)
- ***Single electron pump***: $I = e \cdot f$ (relation between current and time by charge quantum)
- ***Quantum Hall effect***: $V = \frac{h}{e^2} \cdot I = R_K \cdot I$ (relation between voltage and current by quantum resistance, unit = 1 Klitzing)



➔ allows the reproduction of the physical units Volt, Ampère and Ohm with a very high precision and largely uninfluenced by environmental parameters at any place in the world

realization of the Ampère by single electron pump not realized so far at sufficient precision
➔ would allow an important experimental test of the consistency of the relations between the fundamental constants illustrated in the "***electrical triangle***"

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