Cryogenic (superconducting) detectors for fundamental Physics experiments

PhD School in Experimental Physics - 31/05/2023

F. Paolucci

Quantum detection

quantum detection

quantum mechanical systems as sensors

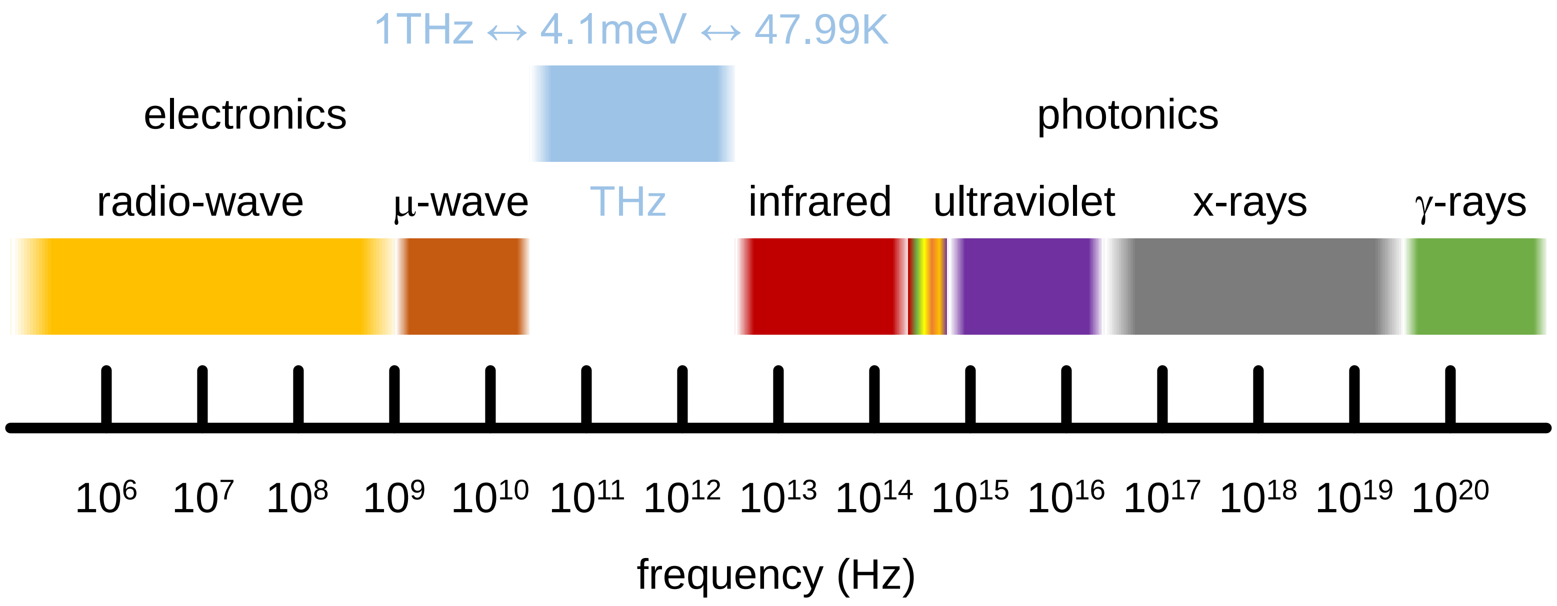
quantum objects
quantum coherence
quantum entanglement

revelation of quantum states

single photons
superconducting state
Bose-Einstein condensates
quantum Hall states
gravitational waves
single spins
qubits

Why GHz-THz?

GHz-THz detection



Physics:
time domain spectroscopy
frod dynamics of electrons,
holes and phonons

Chemistry:
chemical reactions,
combustion, pollution and
environment control

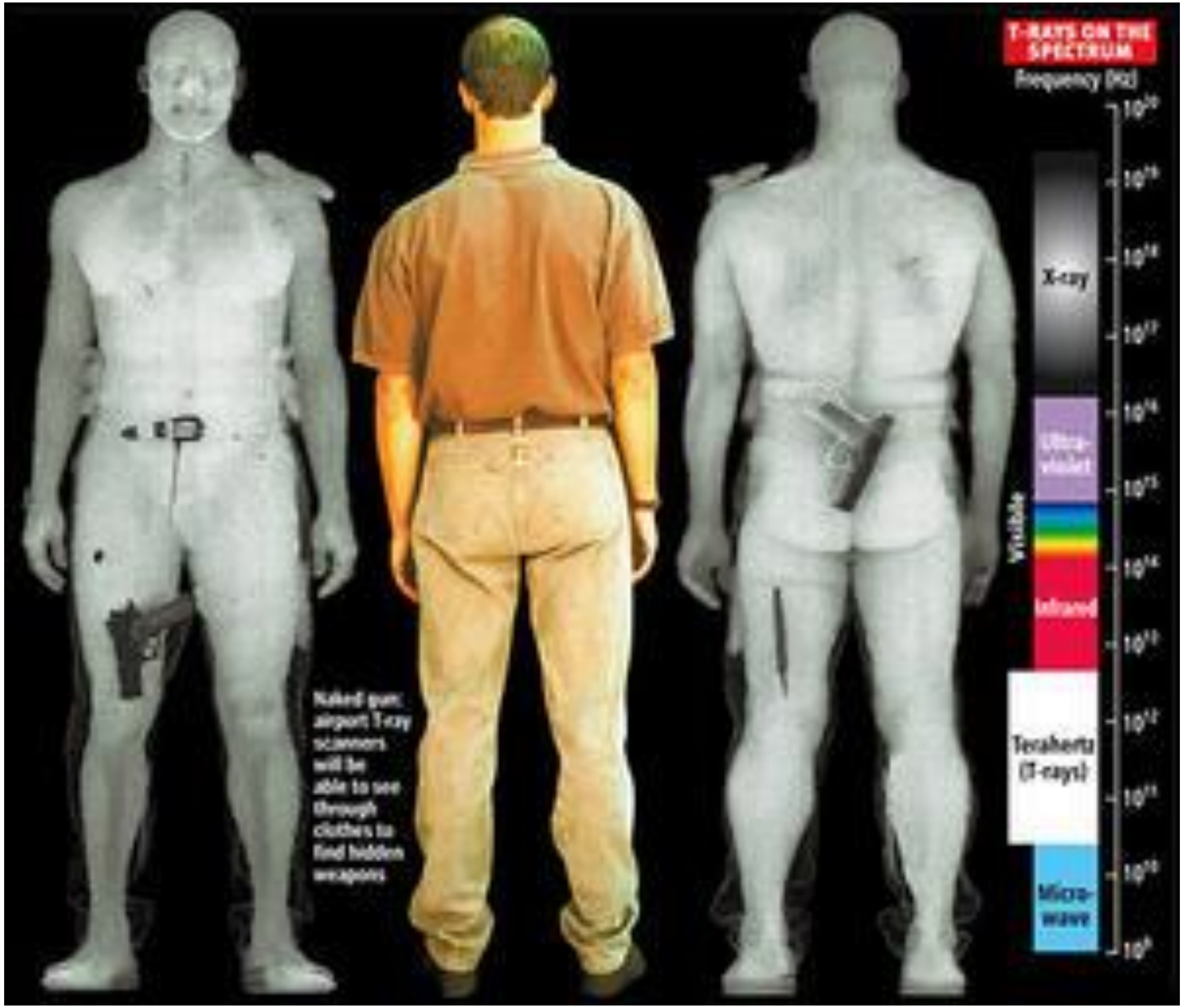
Astronomy:
atmospheric window,
detection of molecules,
atoms and ionized gas

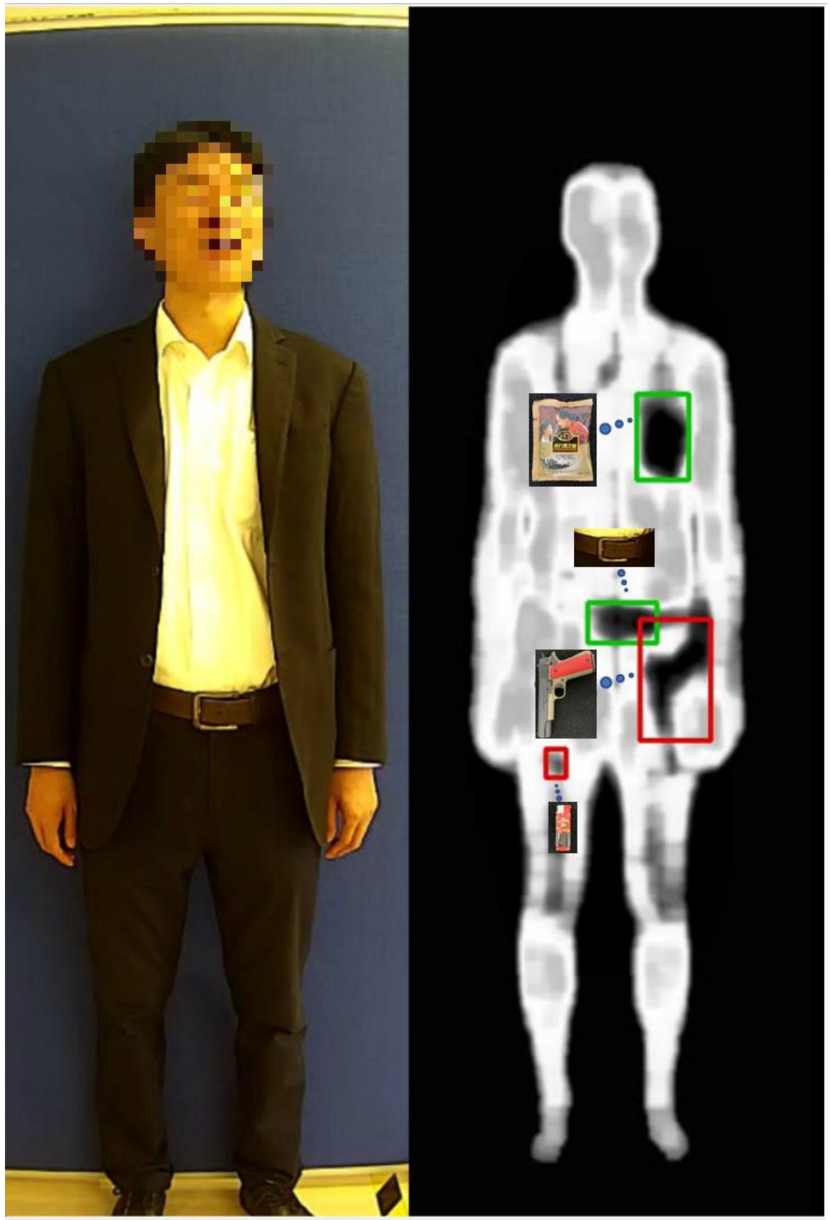
Medicine:
imaging of biological tissues

Material science:
inspection of materials,
devices and systems

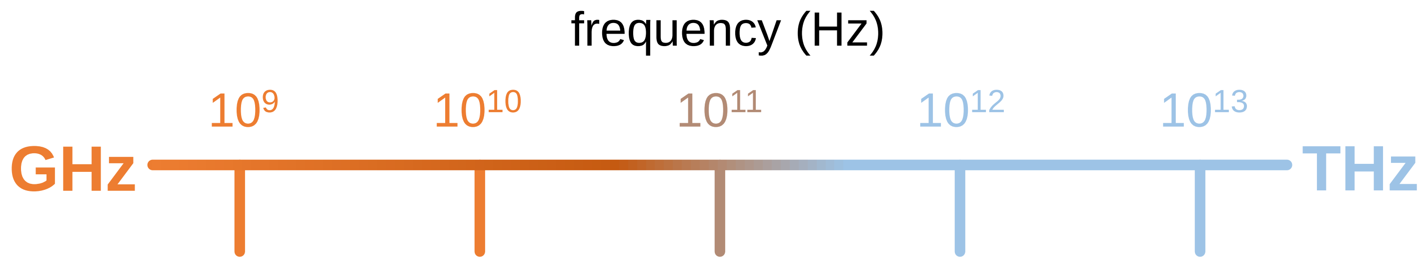
Security:
imaging of hidden objects,
drugs and explosives

GHz-THz detection





GHz-THz detection



bolometer

ALPS (1-30 GHz)

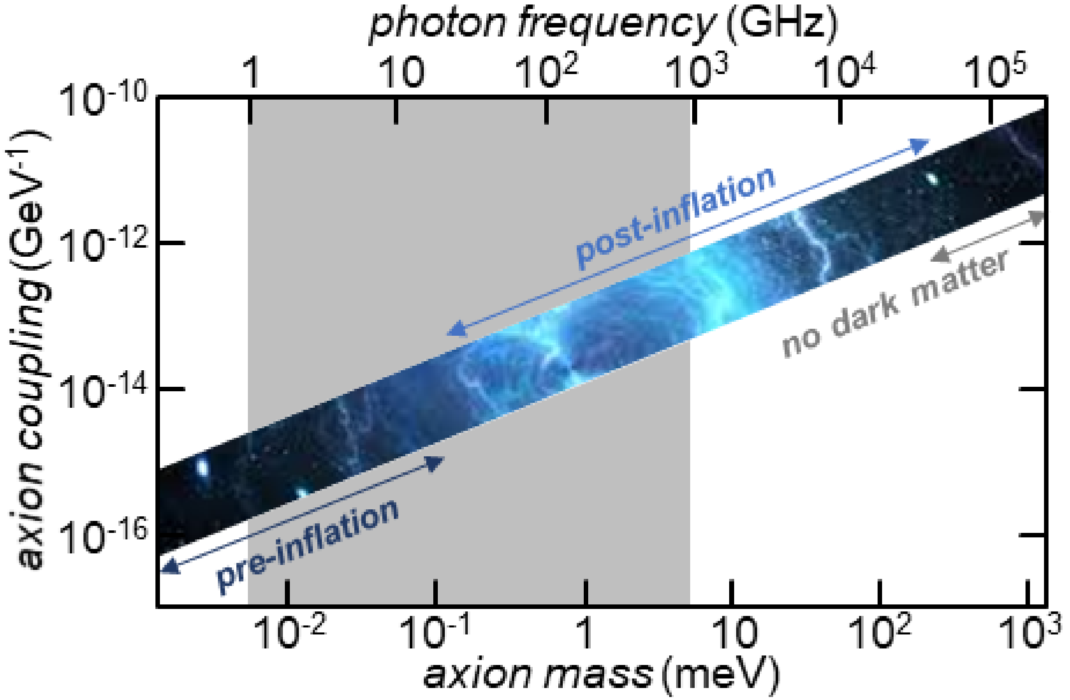
Medical Imaging (1-3 THz)

Cosmic Microwave Background (0.3-630 GHz)

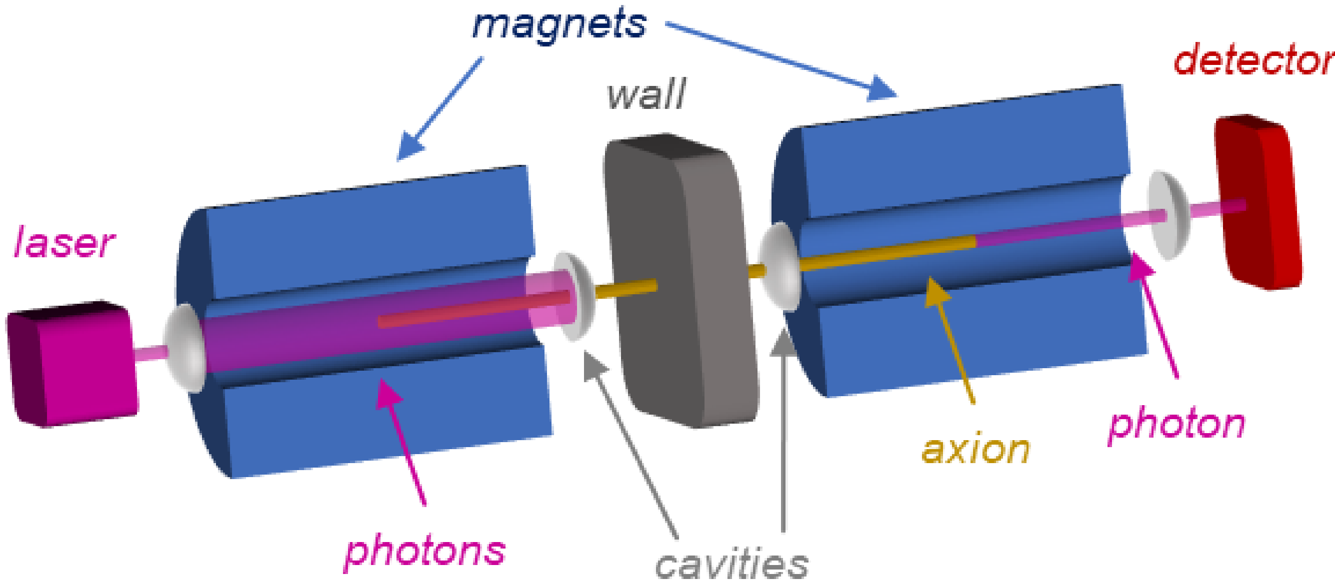
Drug and explosives search (1-3 THz)

Security Imaging (100-300 GHz)

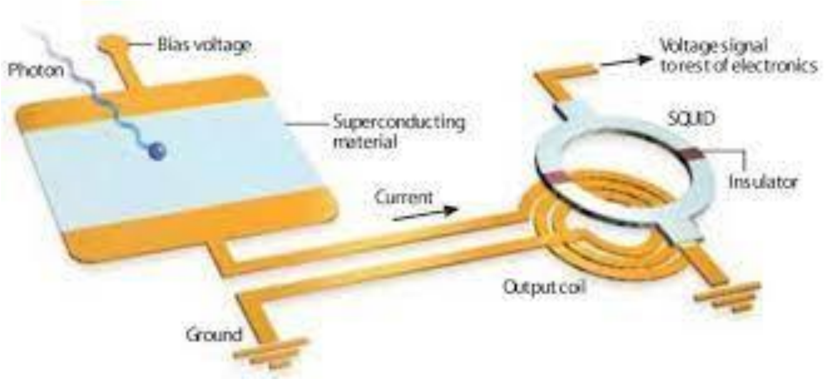
Phys. Rev. Lett. **78**, 2054 (1997)
Science **325**, 546 (2009)
Phys. Dark Univ. **12**, 37 (2016)
Phys. Rev. Applied **14**, 034055 (2020)
J. Appl. Phys. **128**, 194502 (2020)
Appl. Sci. **11**, 746 (2021)
Instruments **5**, 14 (2021)



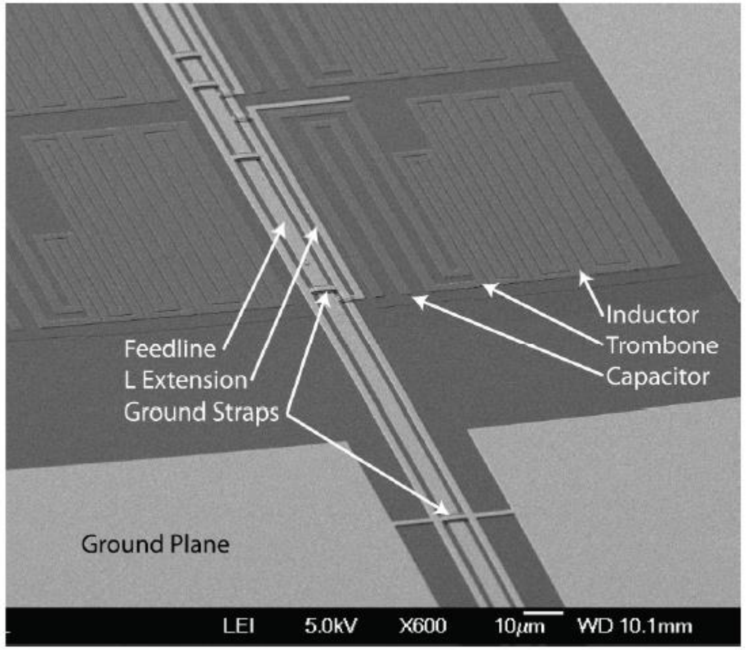
calorimeter

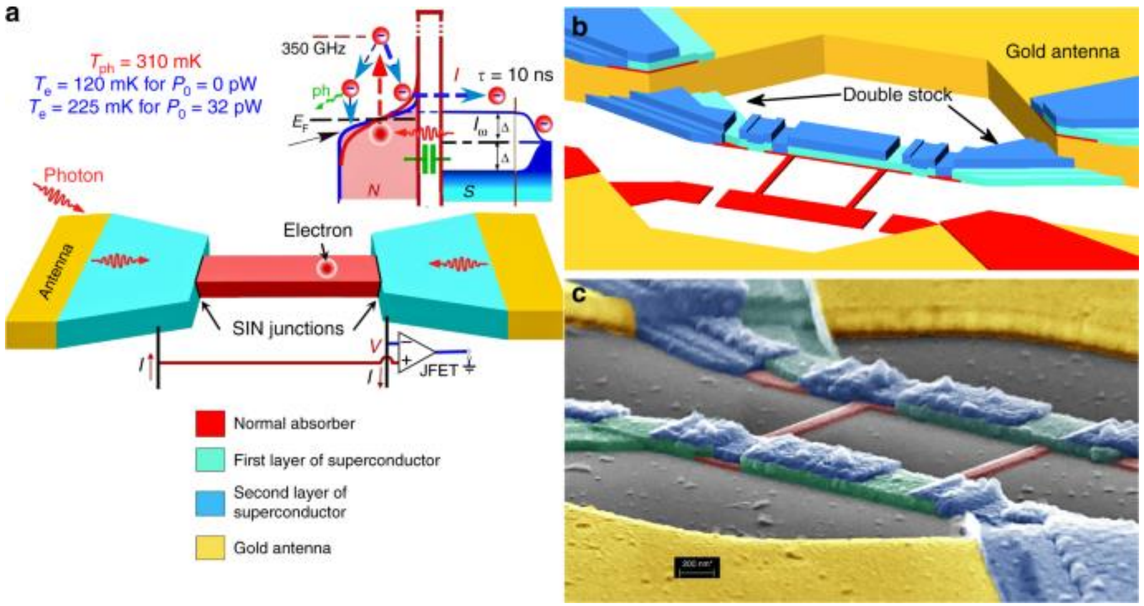


Superconducting detectors



Transition-edge sensor (TES)
Applied Physics Letters **66**, 1998-2000 (1995)





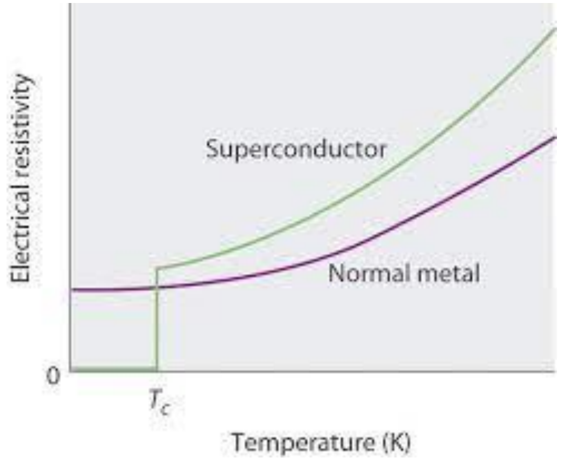
Kinetic inductance detector (KID)
Proc. SPIE 9914, 99140N (2016)
Commun. Phys. **2**, 124 (2019)

Cold electron bolometer (CEB)
Commun Phys **2**, 104 (2019)

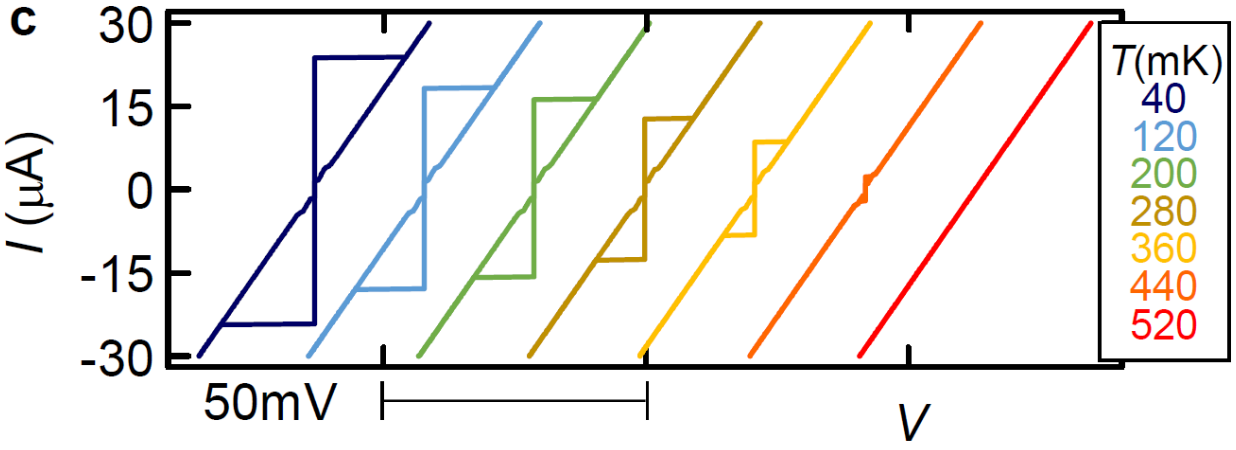
Introduction to superconductivity

Experimental evidences

- Zero-resistance under a certain temperature (critical temperature, T_C)

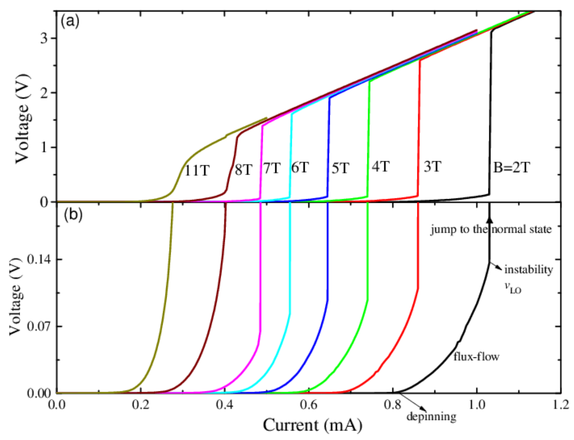


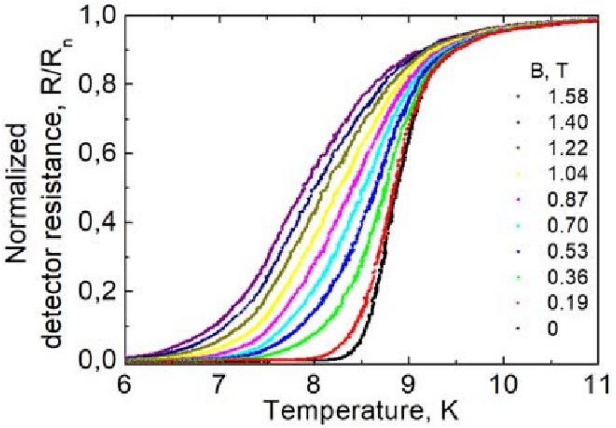
- Maximum current [critical current, $I_C(T)$] for dissipationless transport



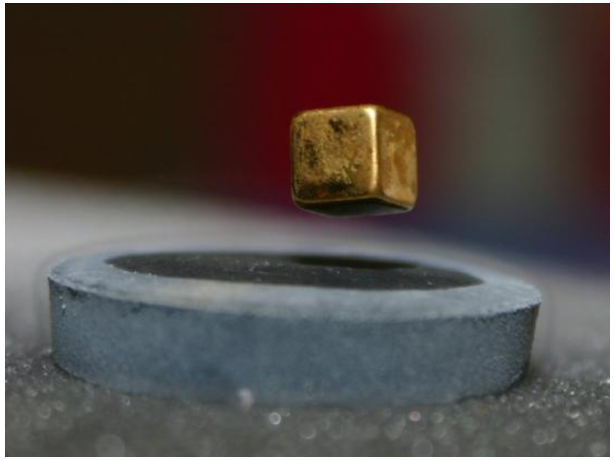
Experimental evidences

- Maximum magnetic field [critical field, $H_C(T)$] for superconductivity



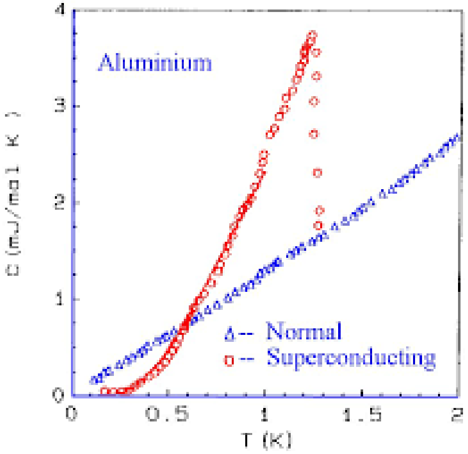


- Expulsion of the magnetic field for H<$H_C(T)$: perfect diamagnetism



Experimental evidences

- Peak of the electronic specific heat at T_C



<u>Superconductivity cannot be described only by perfect conductance</u>

Experimental evidences

- 35 superconducting elements with T_C from 12 mK (W) to 9.3 K (Nb)

- Good metals are not superconductors (Cu, Ag, Au, Pt)

- Many alloys are superconductors

(NbTi, PbBi) also when constitutents are **<u>NOT</u>** SC (CuS)

- Ceramic materials are superconductors

- Iron based superconductors

(also magnetic)

Superconducting elements with their transition temp & Critical field

Material	T_c (K)	H_{cf}(G at 0 K)	Material	T_c (K)	H_{cf}(G at 0 K)
Ti	0.39	100	La	6.0	1100
V	5.38	1420	Hf	0.12	-
Zr	0.546	47	Ta	4.483	830
Nb	9.5	1980	W	0.012	1.07
Mo	0.92	95	Re	1.4	198
Tc	7.77	1410	Os	0.655	65
Ru	0.51	70	Ir	0.14	19
Rh	0.003	0.049	Hg	4.153	412
Cd	0.56	30	Tl	2.39	171
In	3.404	293	Pb	7.193	803
Sn	3.722	309	Th	1.368	1.62

C. Kittel

How is it possible?

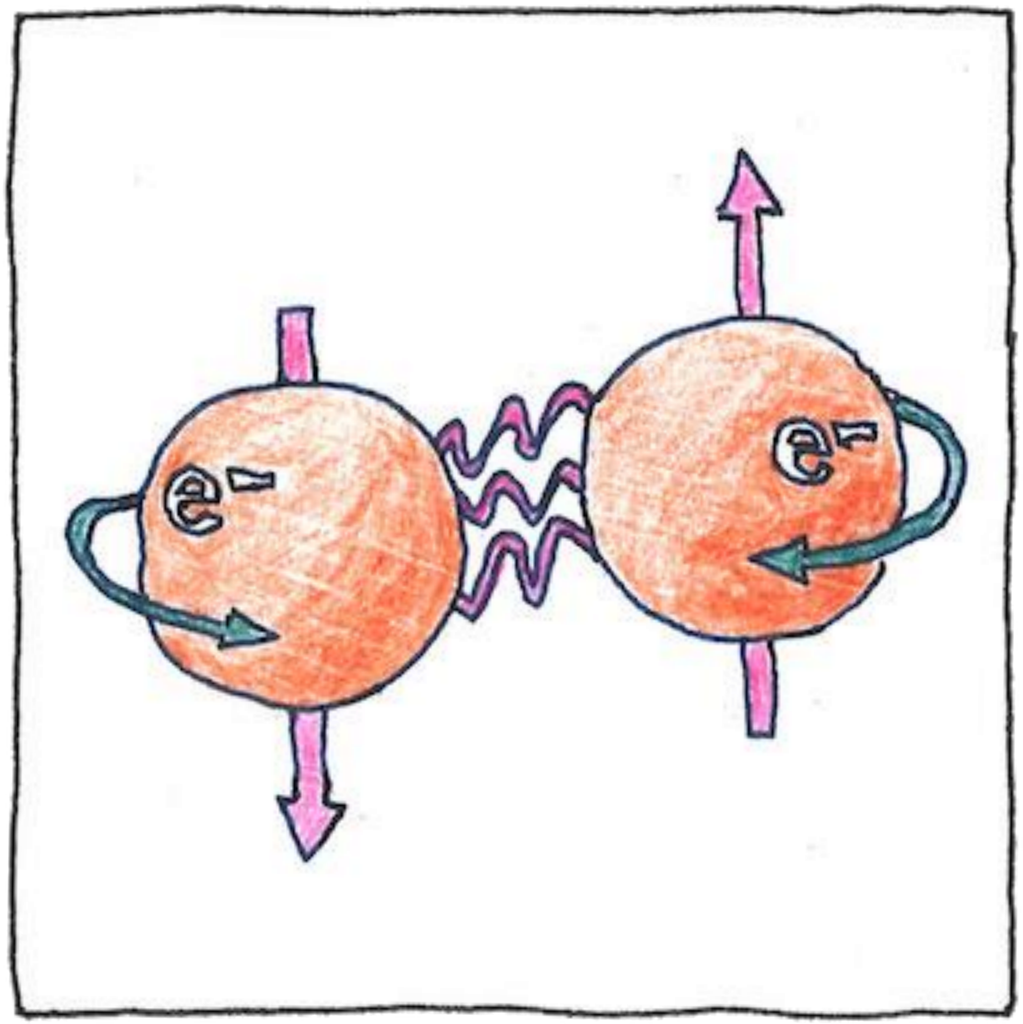
Two *almost equivalent* theories: **BCS** (micro) and **GL** (phenomenological)

The ground state of a metal is unstable to the creation of a couple of electrons: **Cooper pair**

Small attractive potential needed

This state has a lower energy than a metal

All CPs have same energy: condensate



How is it possible?

$\psi(\vec{r})$: wavefunction as complex order parameter

$|\psi(\vec{r})|^2 = n_s(\vec{r})$ number of superconducting electrons

$\psi(\vec{r}) = \sqrt{n_s(\vec{r})}e^{i\varphi(\vec{r})}$

$$f_S - f_n = +\alpha|\psi(\vec{r})|^2 + \frac{\beta}{2}|\psi(\vec{r})|^4$$ free energy

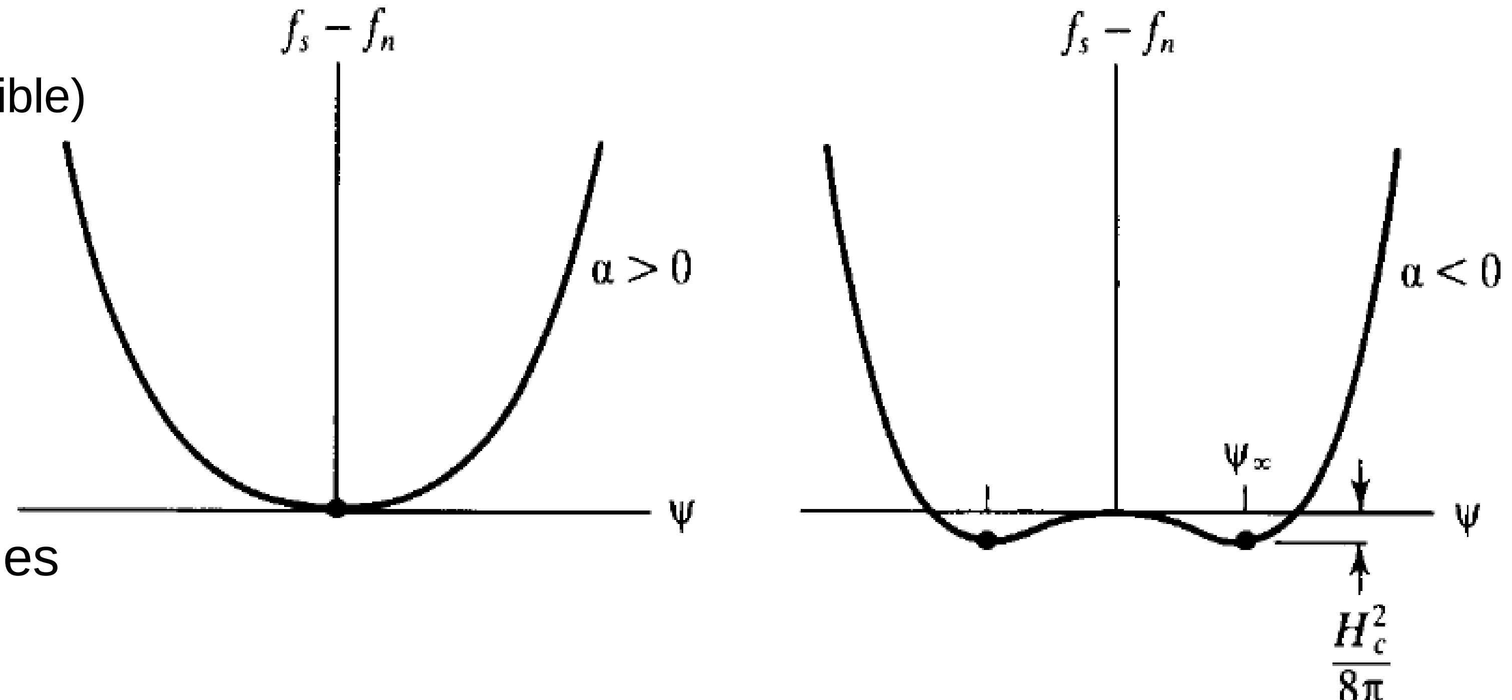
$\beta > 0$ otherwise $|\psi(\vec{r})|^2 = n_S(\vec{r}) \to \infty$ (impossible)

α changes sign at the transition

$$|\psi_\infty|^2 = n_S = -\frac{\alpha}{\beta}$$

bulk value far from interfaces and impurities (minimum of free energy)

normal state superconducting state



How is it possible?

$\psi(\vec{r})$: wavefunction as complex order parameter

$|\psi(\vec{r})|^2 = n_s(\vec{r})$ number of superconducting electrons

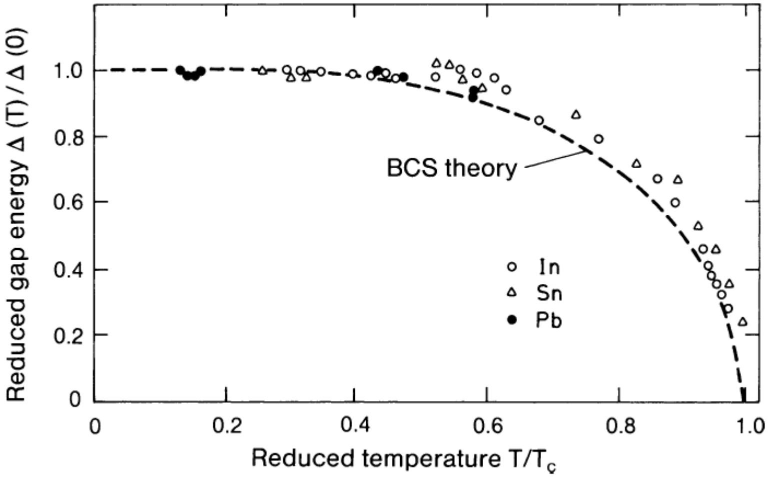
$$\psi(\vec{r}) = \sqrt{n_s(\vec{r})}e^{i\varphi(\vec{r})}$$

Coherence length [dimension of $\psi(\vec{r})$]

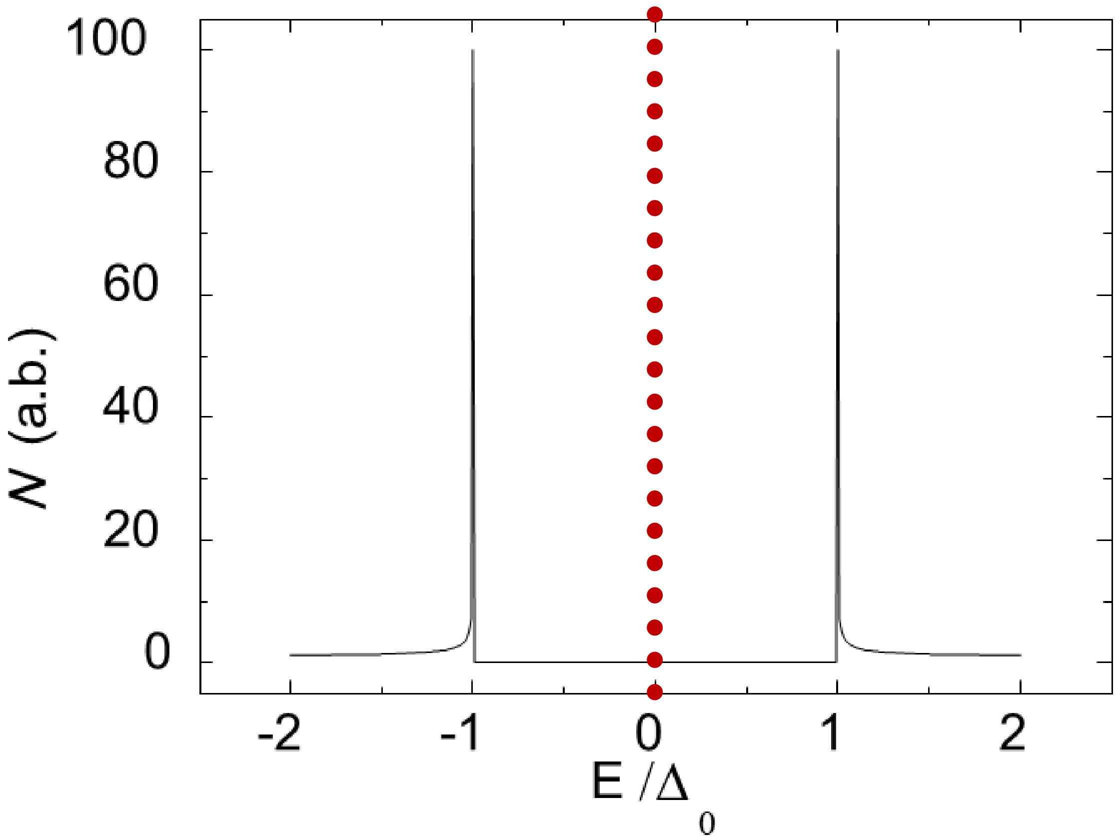
$$\xi_0 = \sqrt{\frac{\hbar}{\rho N_F e^2 \Delta_0}}$$

Penetration depth of magnetic field

$$\lambda_L = \sqrt{\frac{\hbar\rho}{\pi\mu_0\Delta_0}}$$



$$\frac{D_S(E_{\boldsymbol{K}})}{D_N(E_{\boldsymbol{K}})} == \left|\mathrm{Re}\left[\frac{E_{\boldsymbol{K}}}{\sqrt{{E_{\boldsymbol{K}}}^2 - \Delta(T)^2}}\right]\right|$$



Superconductivity - Remarks

$e^* = 2e$

$m^* = 2m_0$ — no corrections as in metals (no influence of phonons or band structure)

$n_S = \frac{1}{2}n$ — conservation of charge

$|\psi_\infty|^2 = n_S$

superconducting quantum detection

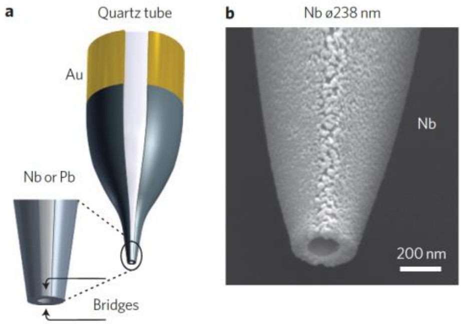
superconducting detectors

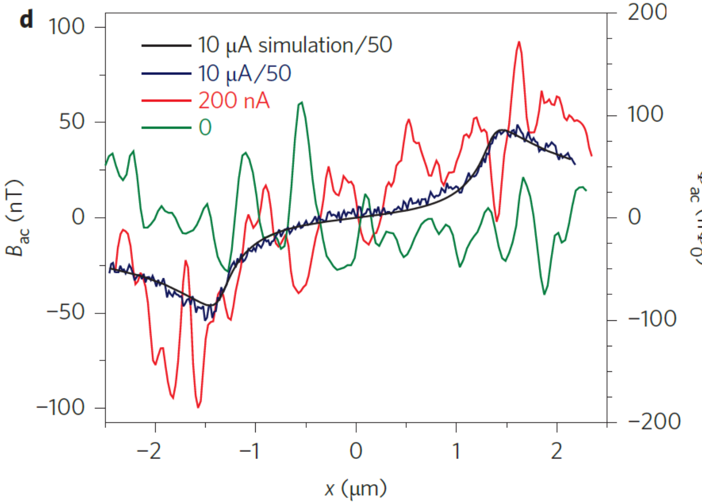
magnetometers (SQUID, SQUIPT)
thermometers (SIN)
photons (STJ, TES, KID, SNS, SNSPD, CEB)
phonons (TES)

revelation of superconductivity

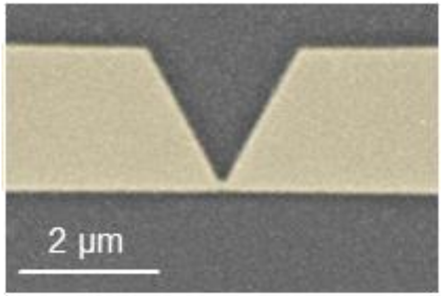
tunnel spectroscopy
critical current
critical field
critical temperature

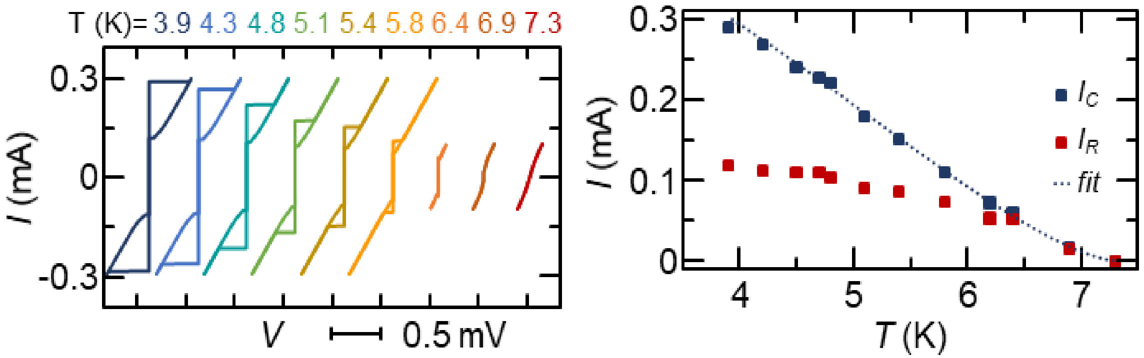
Nat. Nanotech. **8**, 639 (2013)





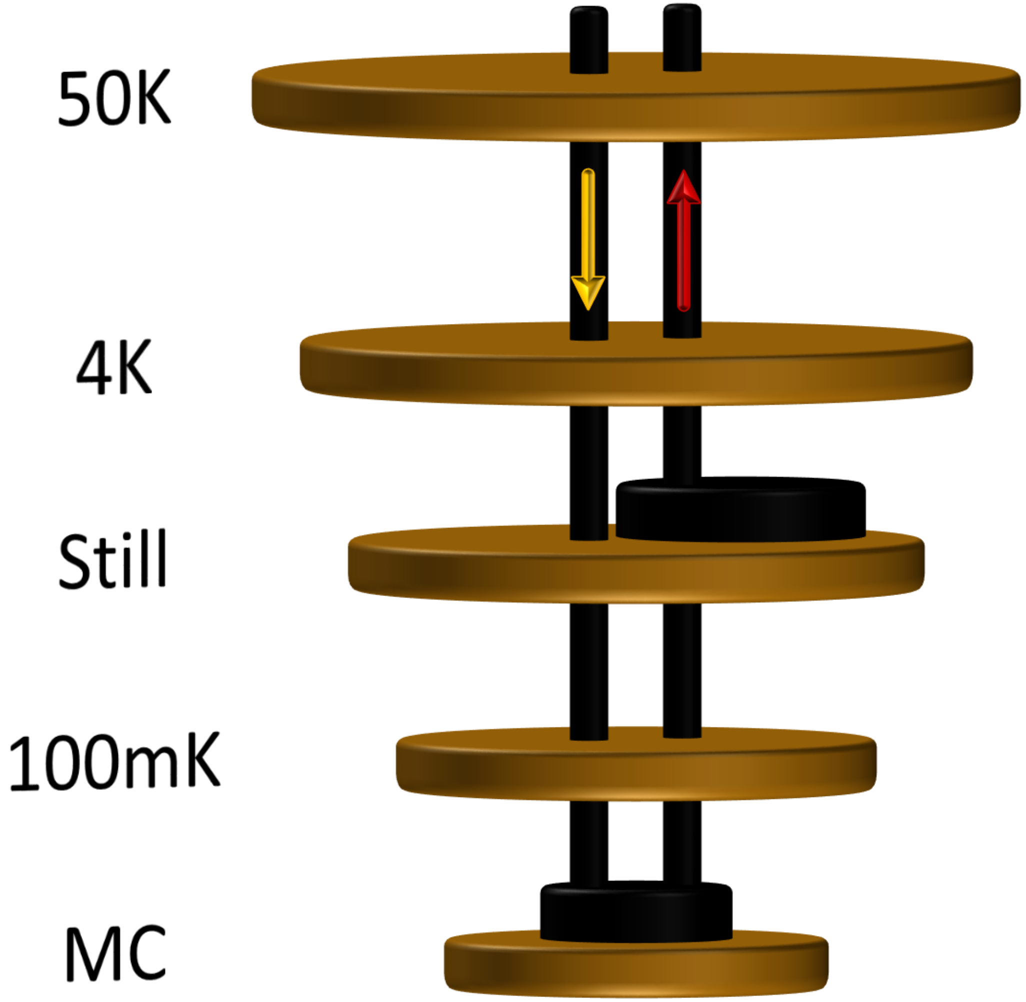
Nano Lett. **21**, 10309 (2021)





Cryogenics

Measurements at cryogenic temperatures



Cooling of 50K plate and 4K plate with:

- Liquid Helium
- Cryocooler

Cooling of Still, 100mK, MC with:
Mixture He^3-He^4

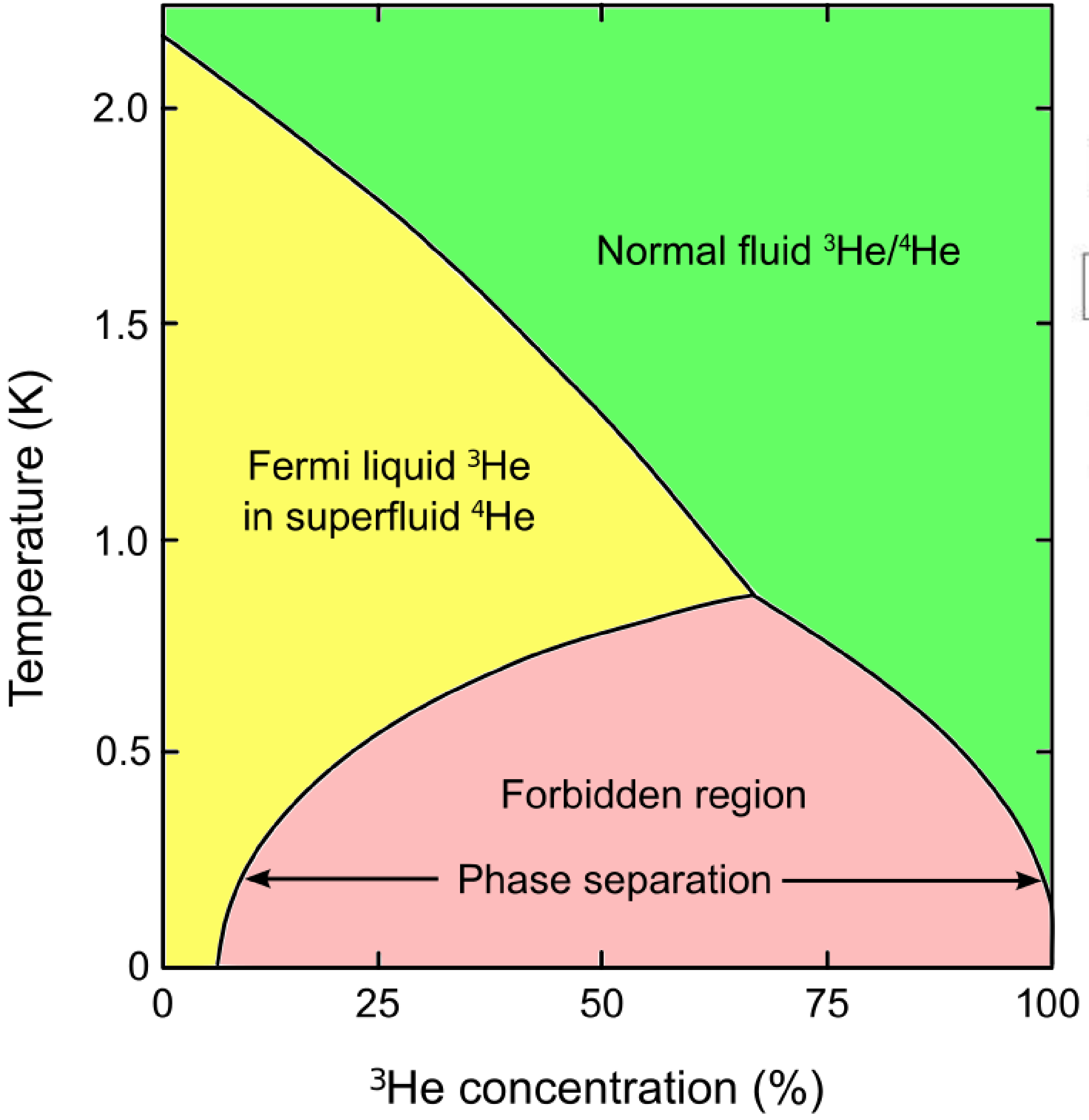
Mixing Chamber:
He^3 rich phase
He^3 diluted phase (6.6%He^3, 93.4He^4)

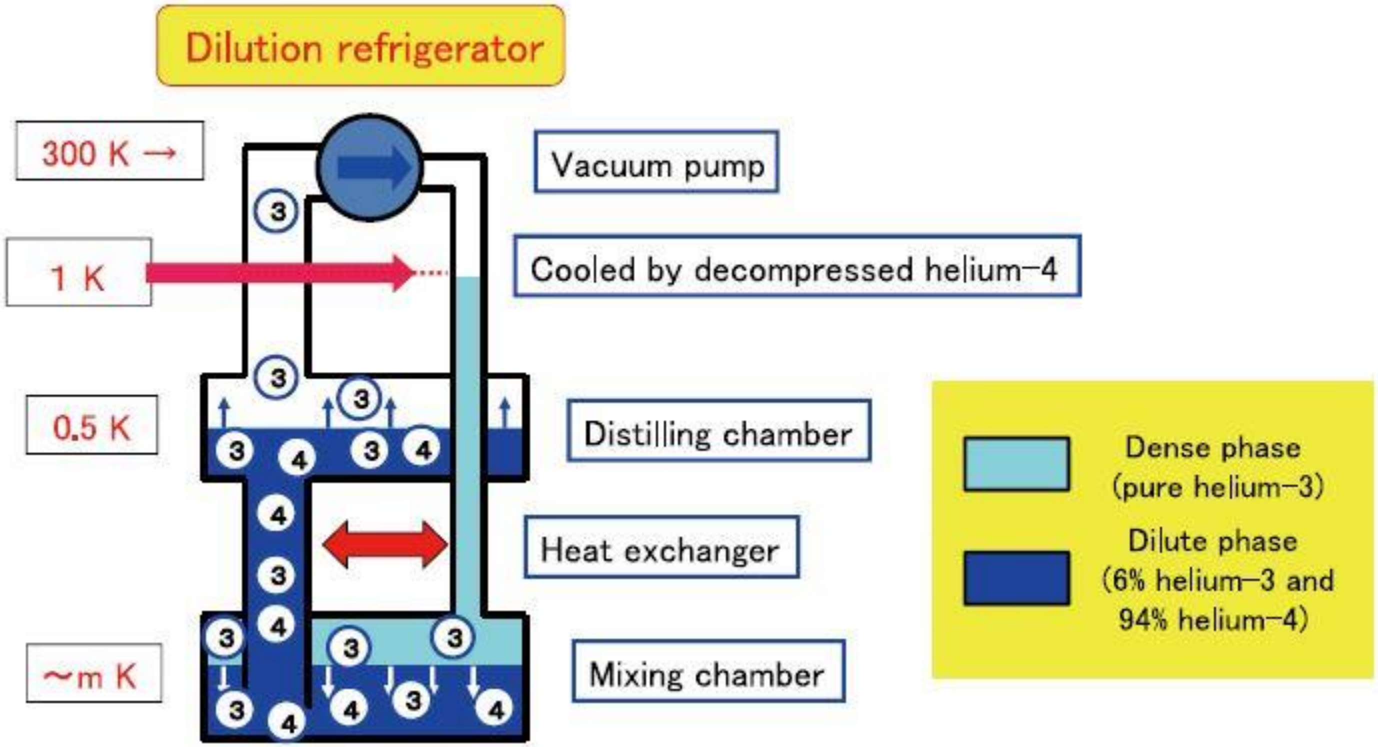
Transport measurements:

- Low temperature filtered lines
- Cryogenic temperatures amplifiers
- Room temperature precision electronics

http://research.physics.illinois.edu/bezryadin/links/practical%20Cryogenics.pdf

Measurements at cryogenic temperatures





Mixing Chamber:
He^3 rich phase
He^3 diluted phase (6.6%He^3, 93.4He^4)

http://research.physics.illinois.edu/bezryadin/links/practical%20Cryogenics.pdf

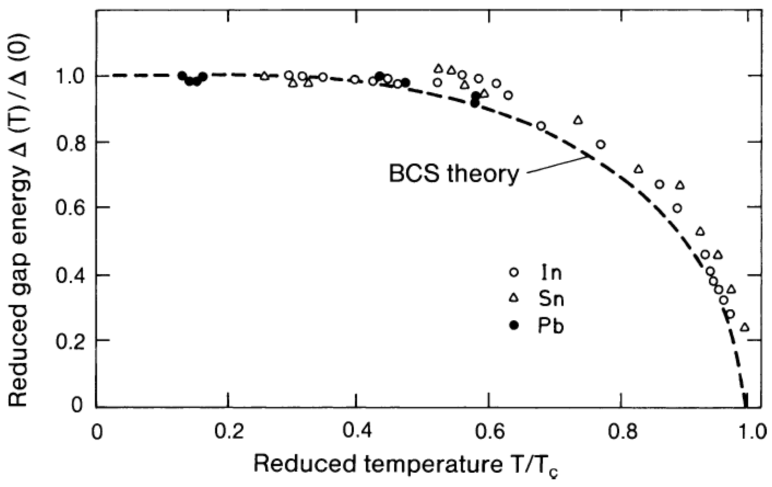
superconducting quantum detection

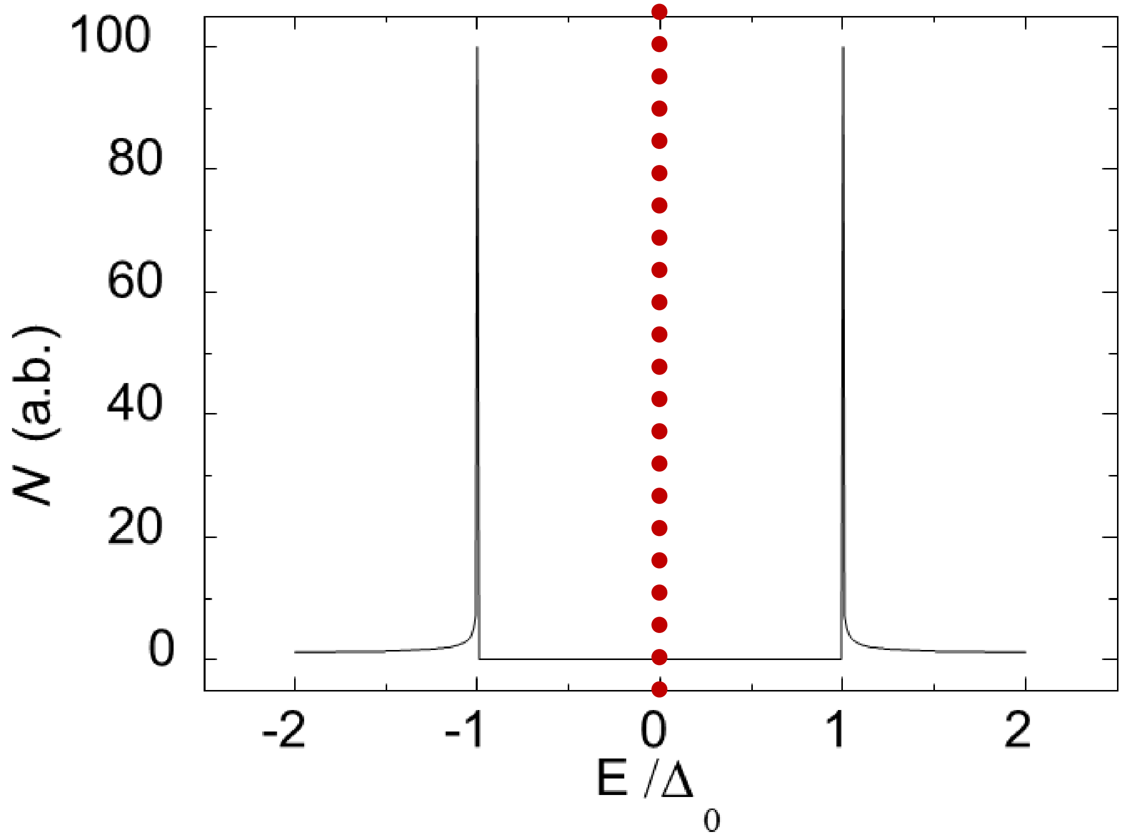
superconducting detectors

magnetometers (SQUID, SQUIPT)
thermometers (SIN)
photons (STJ, TES, KID, SNS, SNSPD, CEB)
phonons (TES)

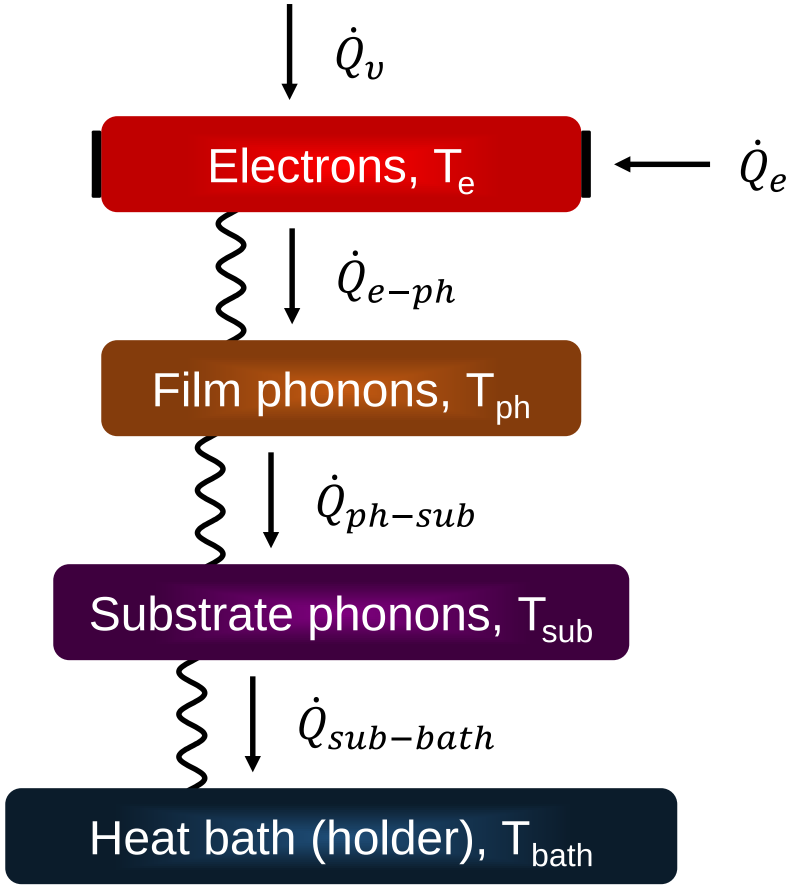
superconducting quantum detection

Bolometers or calorimeters



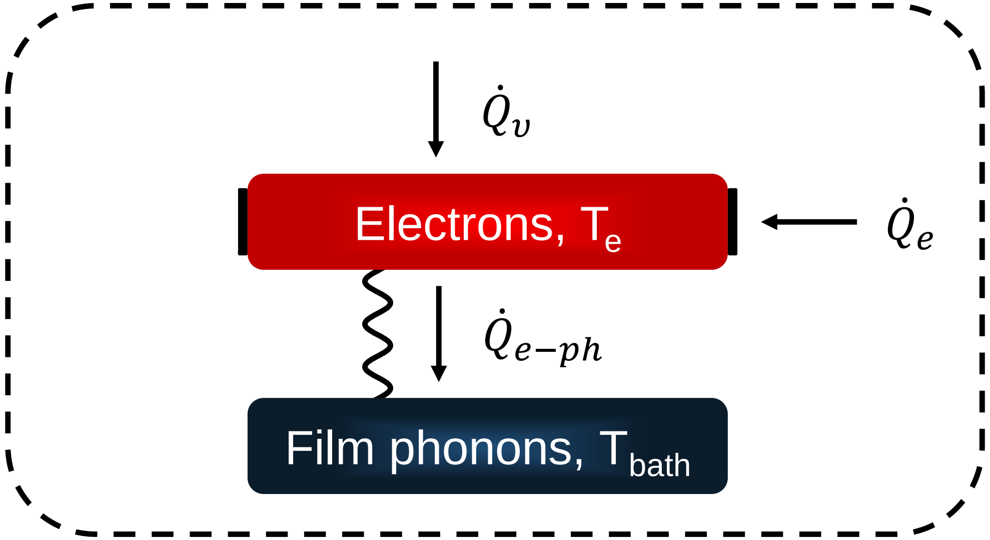


Energy exchange at nanoscale



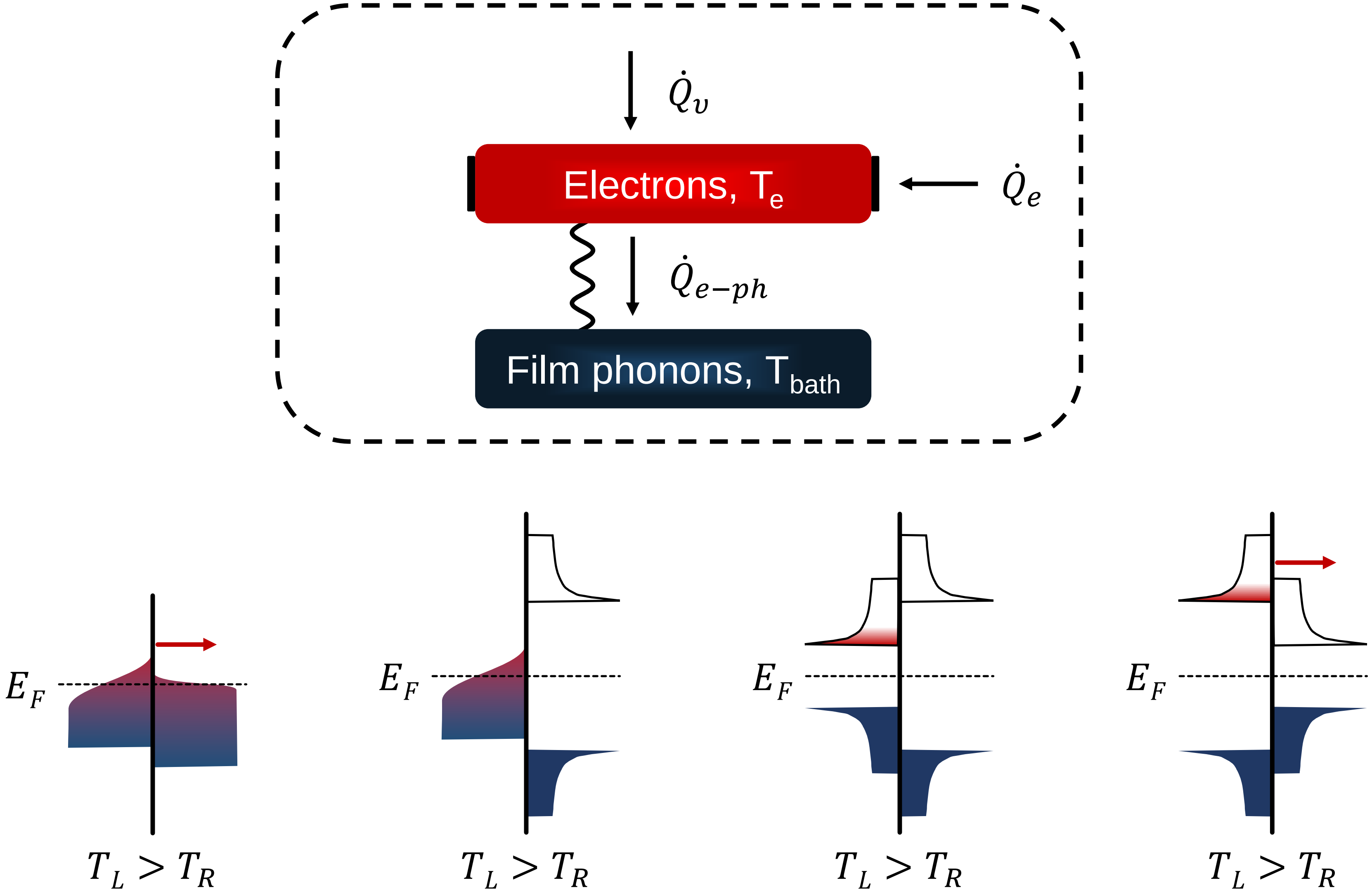
$\dot{Q}_e$: e-e interaction
$\dot{Q}_v$: e-photon interaction
$\dot{Q}_{e-ph}$: e-phonon coupling

Vanishing Kapitza resistance:
sample phonons thermalized with substrate



F.G. et al., Rev. Mod. Phys. **78**, 217−274 (2006)

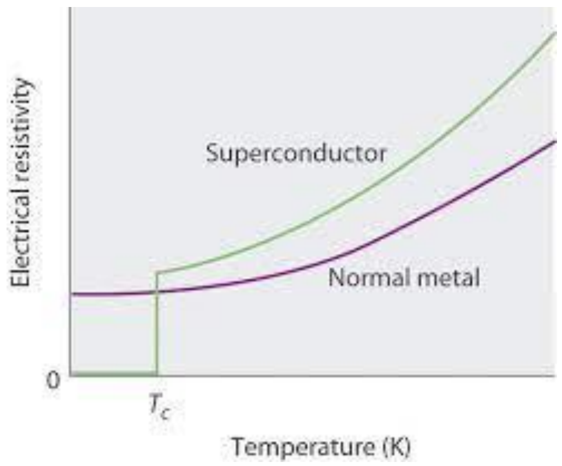
Electron-electron heat diffusion

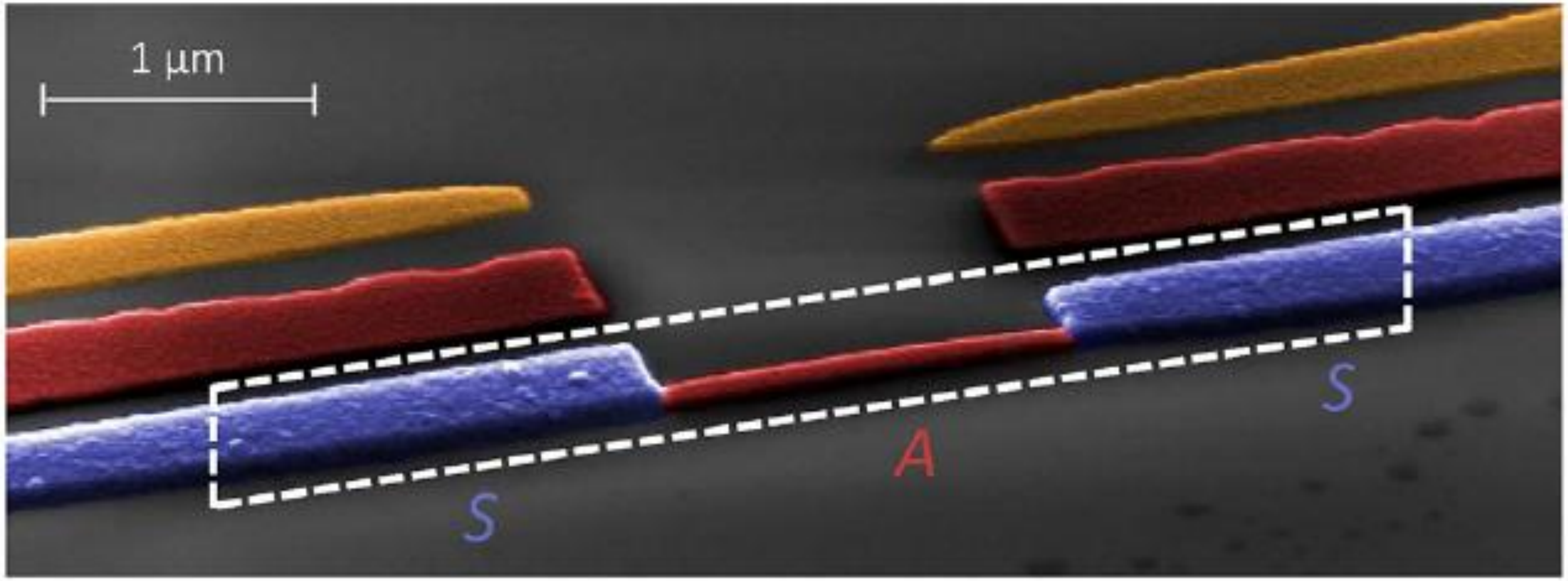


F.G. et al., Rev. Mod. Phys. **78**, 217−274 (2006)

Transition-Edge Sensor

TES - idea

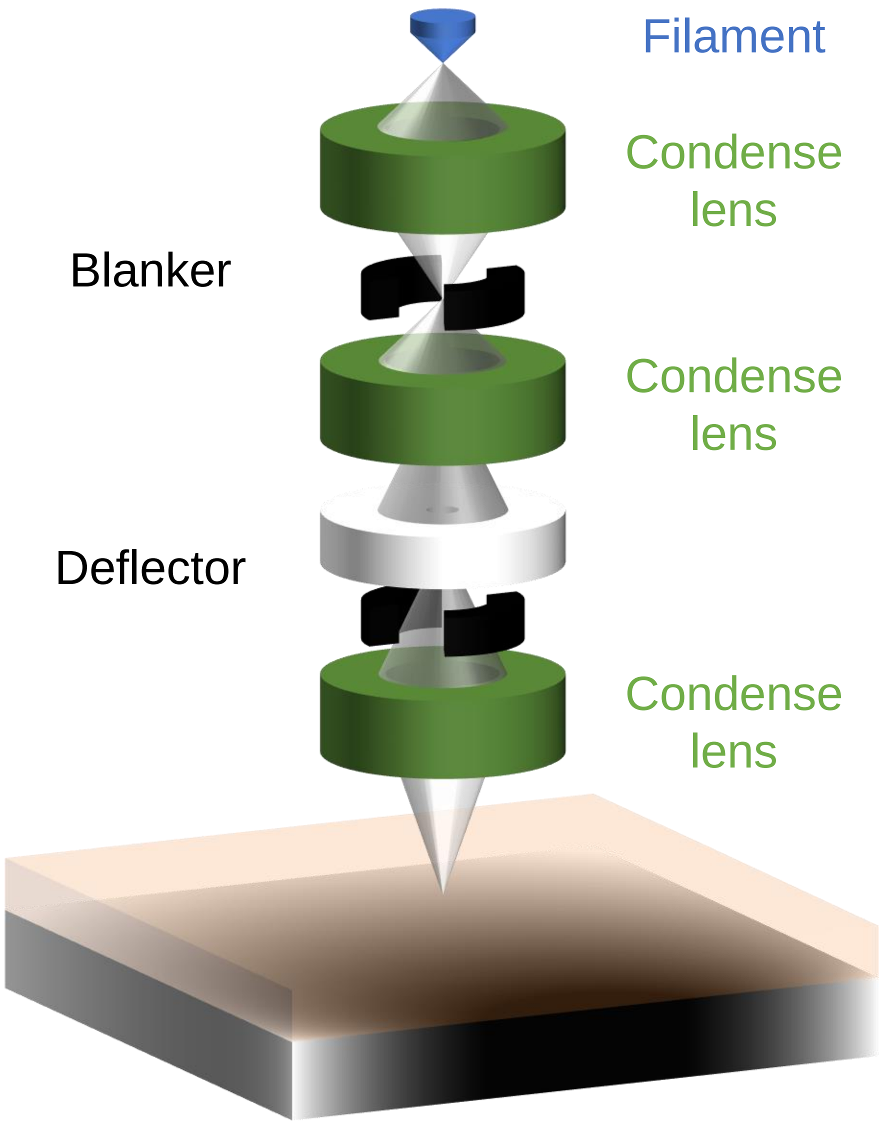

Electrical resistivity
Superconductor
Normal metal
0
T_c
Temperature (K)


1 µm
S
A
S

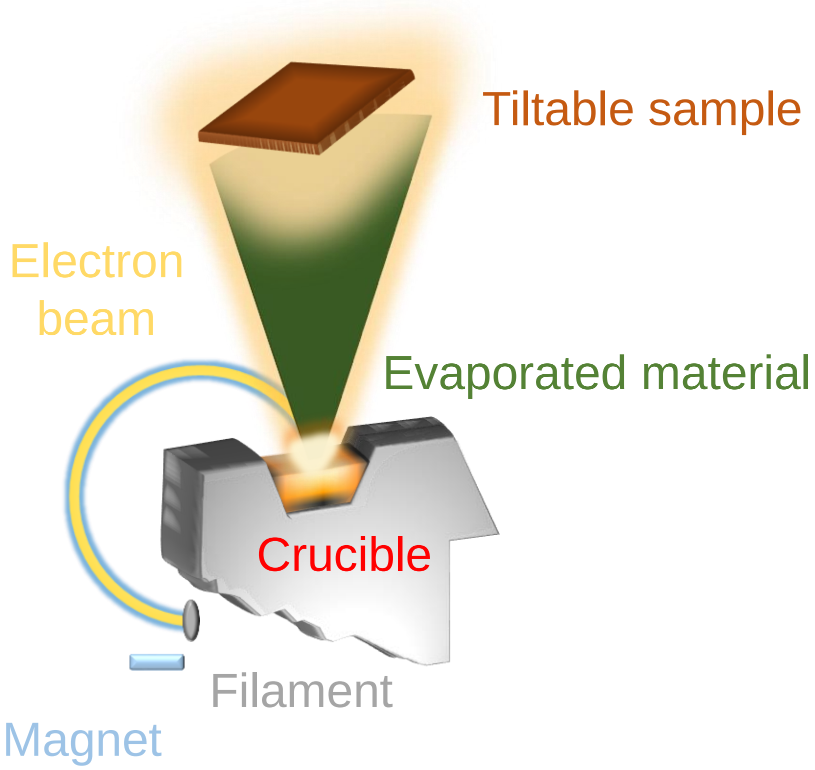
Nano-Fabrication

CUT

Electron-beam lithography



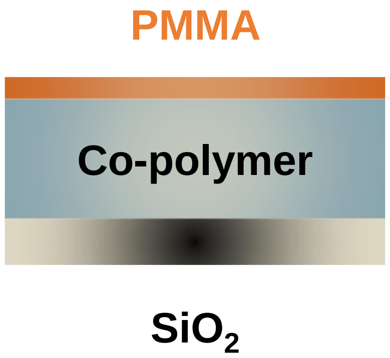
Electron-beam evaporator

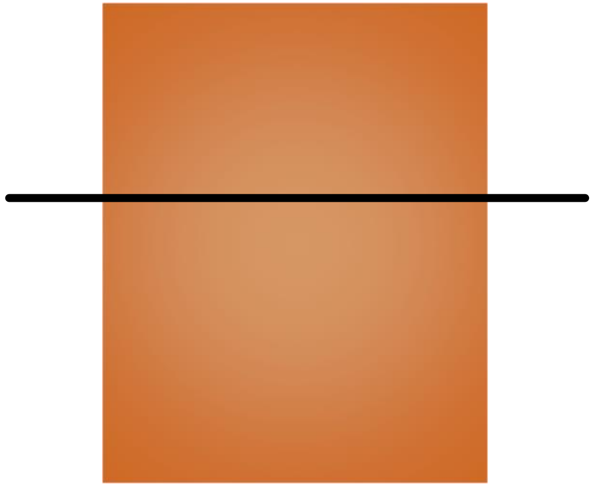


CUT

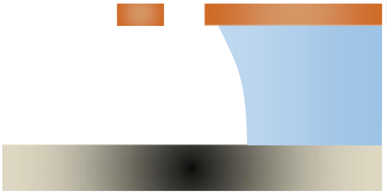
Side view | **Top View** | **Substrate**

1) spin-coating resist

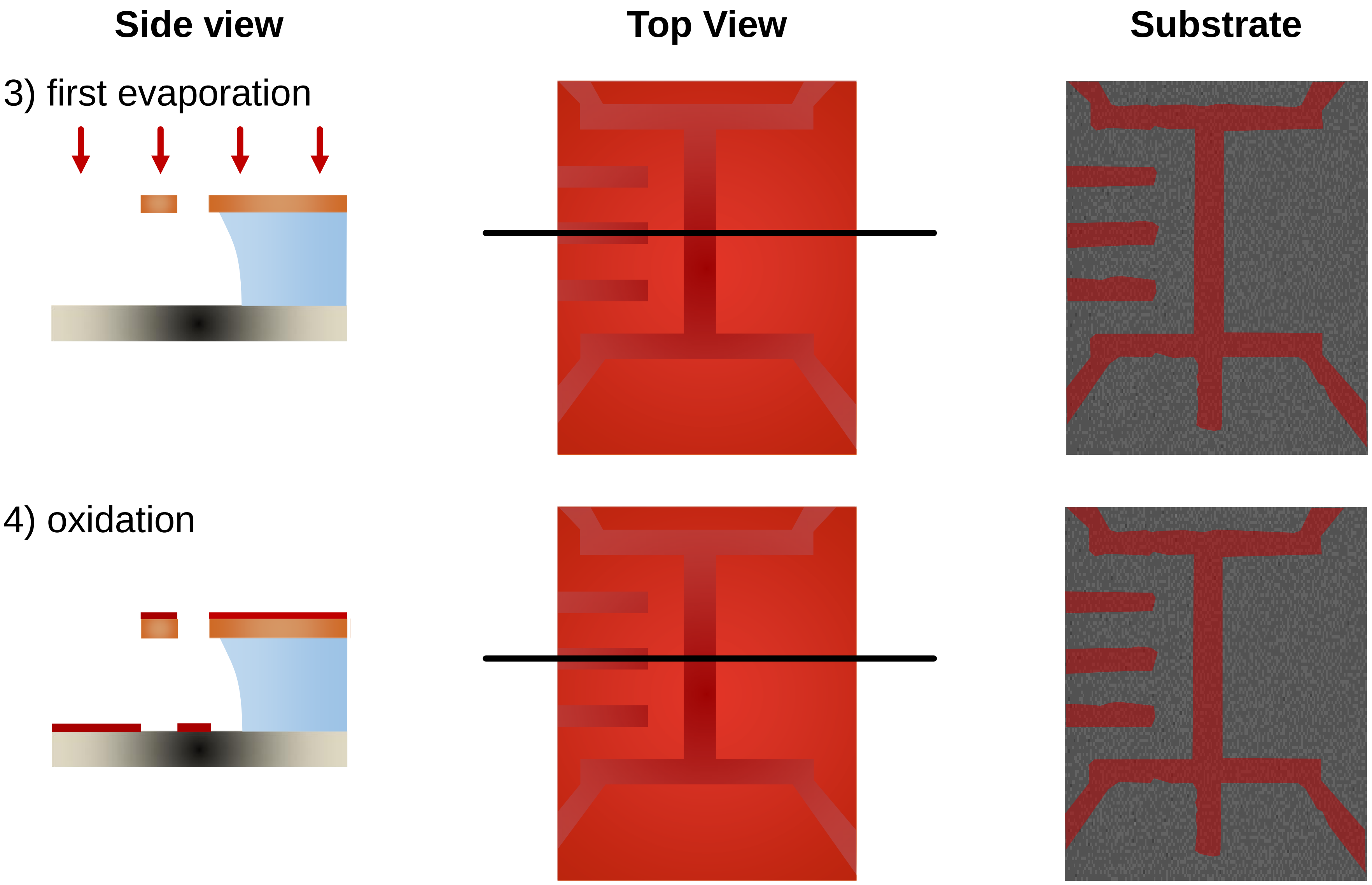




2) electron-beam lithography



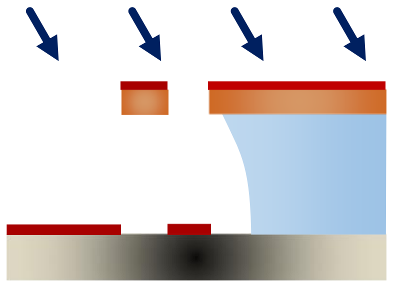
CUT

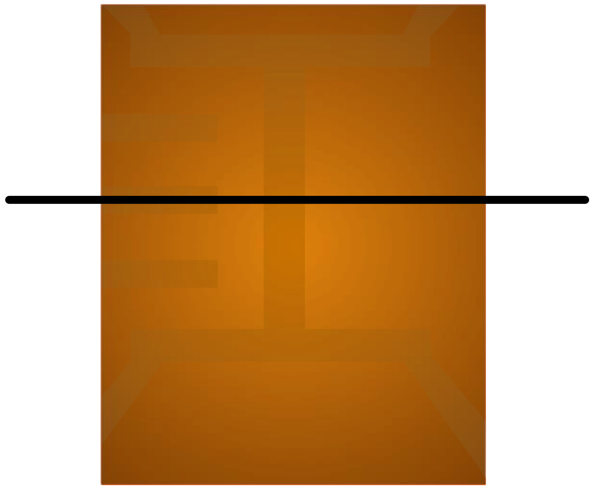

Side view
Top View
Substrate
3) first evaporation
4) oxidation

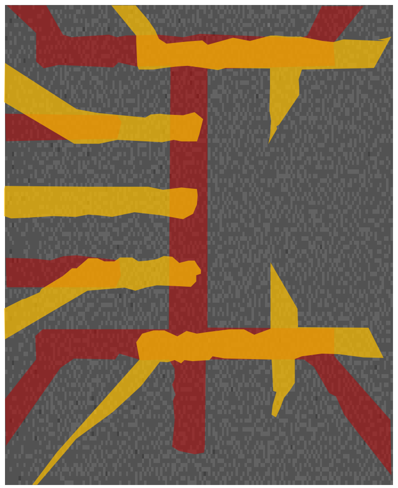
CUT

Side view | **Top View** | **Substrate**

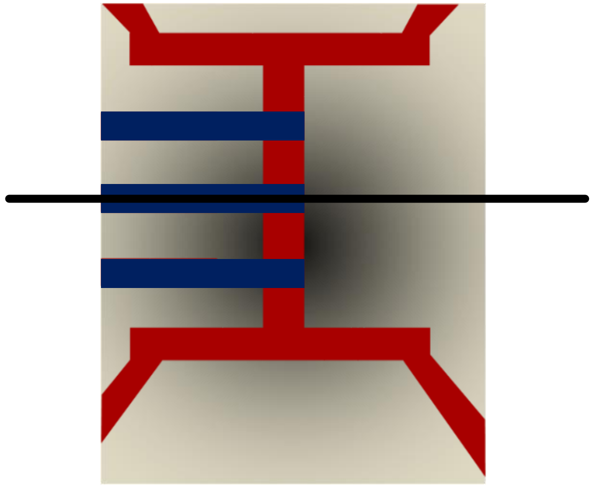
5) second evaporation

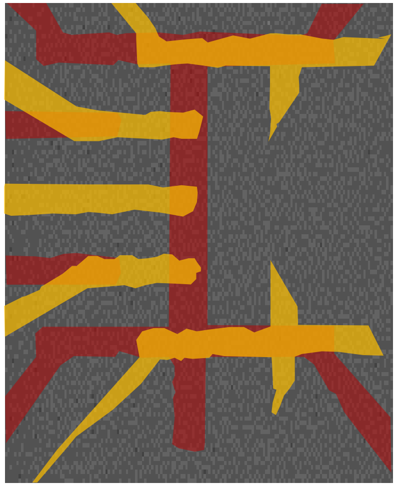




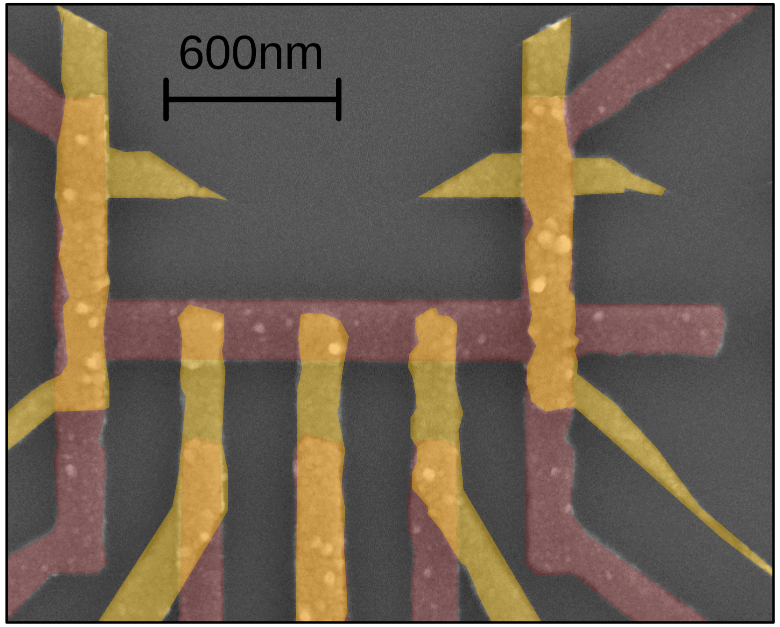


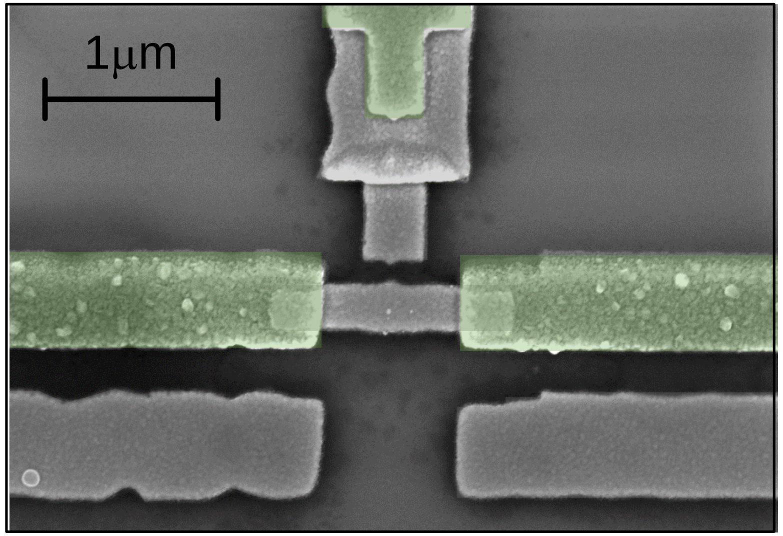
6) lift-off



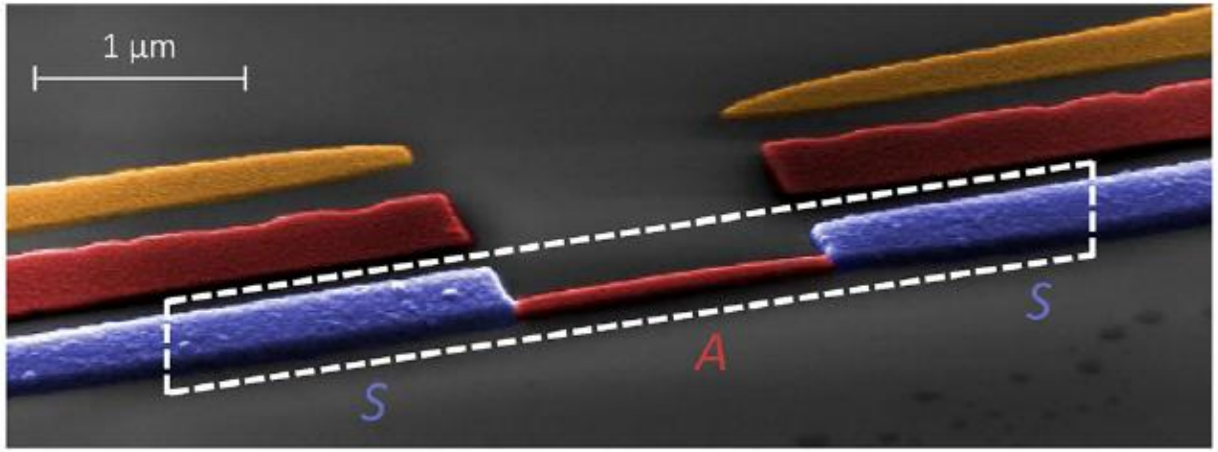


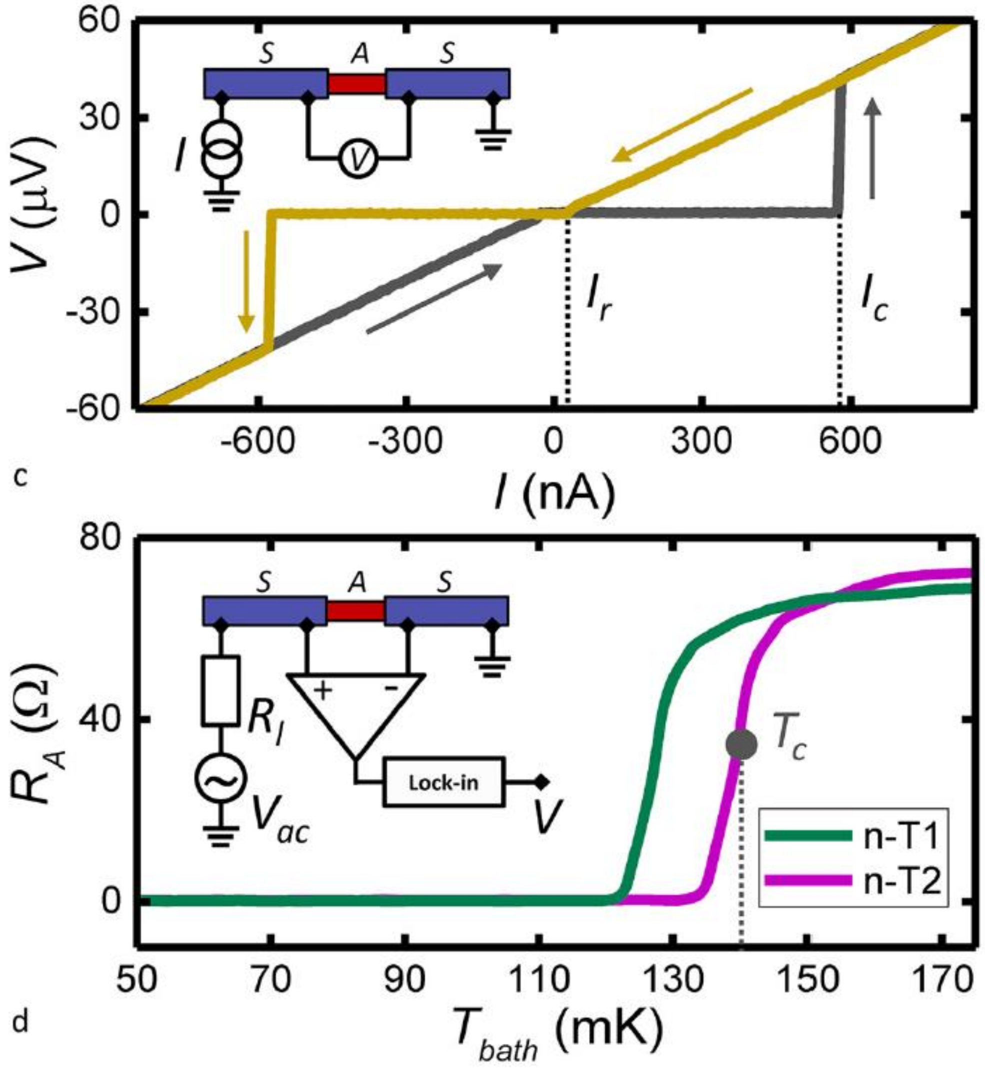
Examples of devices





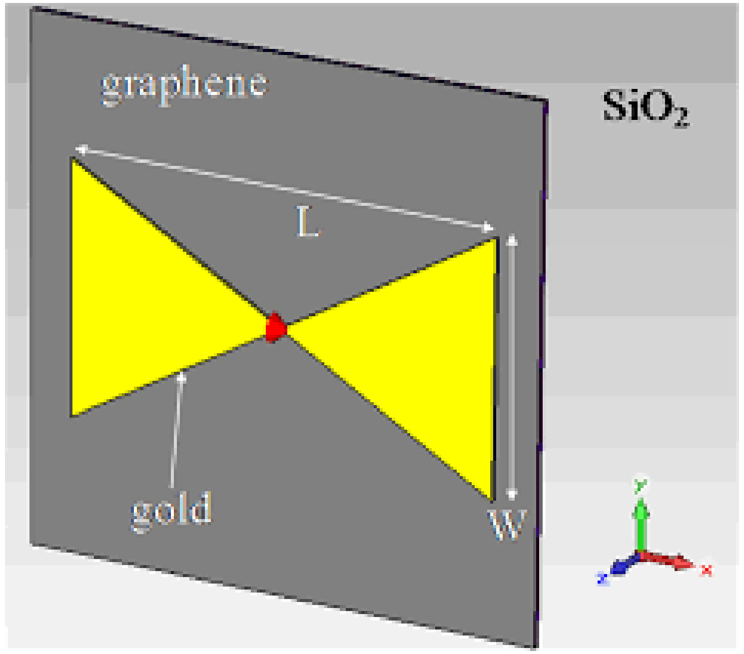
TES

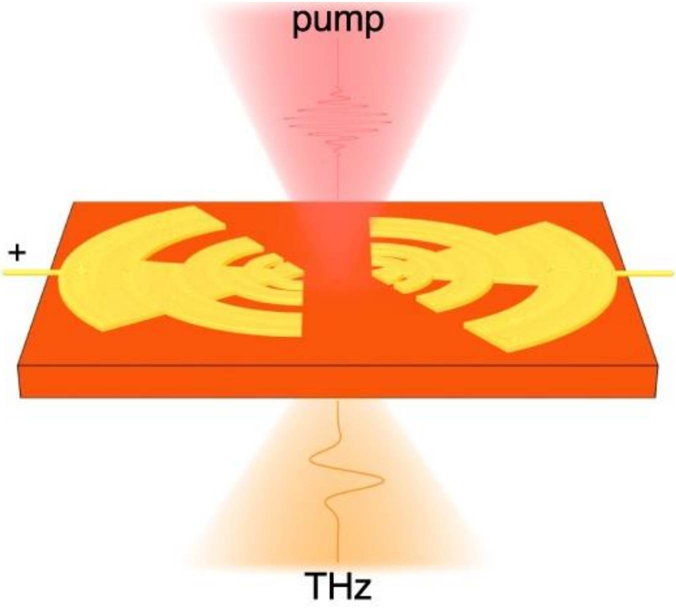


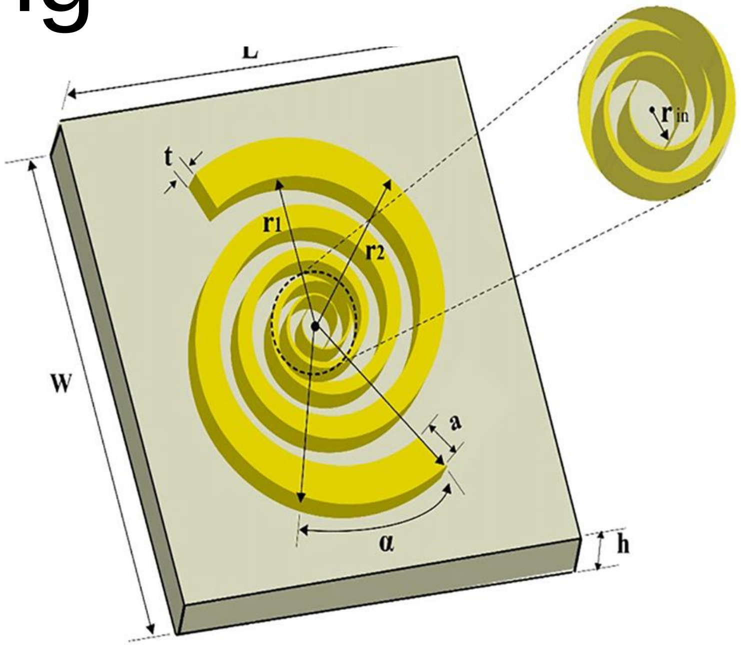


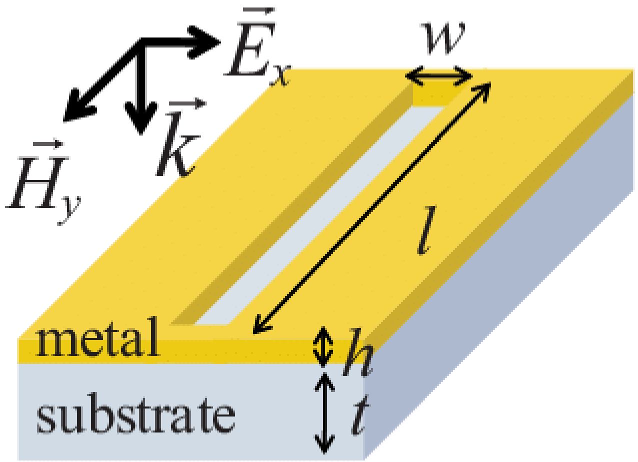
K. D. Irwin, "An application of electrothermal feedback for high resolution cryogenic particle detection". Appl. Phys. Lett., 66, 1998 (1995)

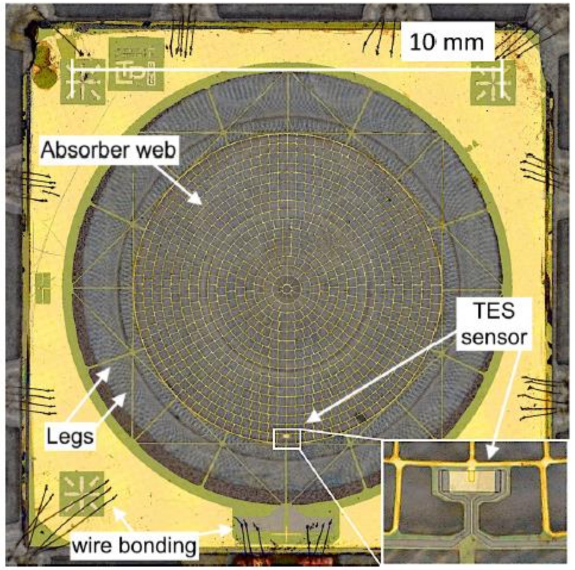
TES – antenna coupling



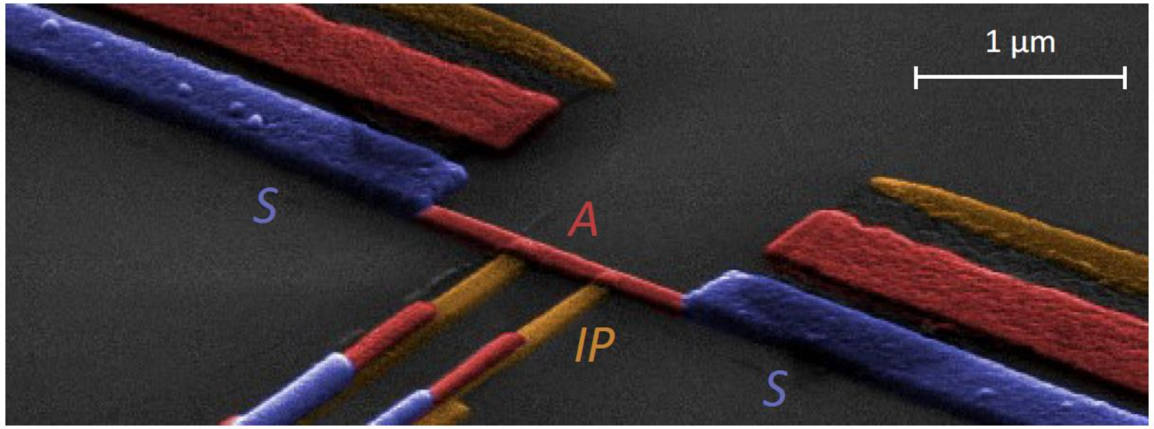




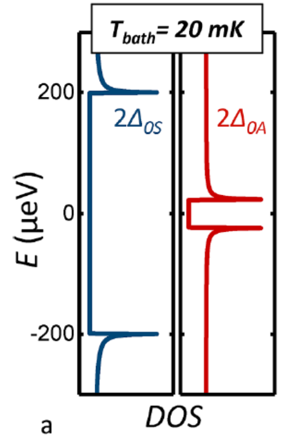




TES



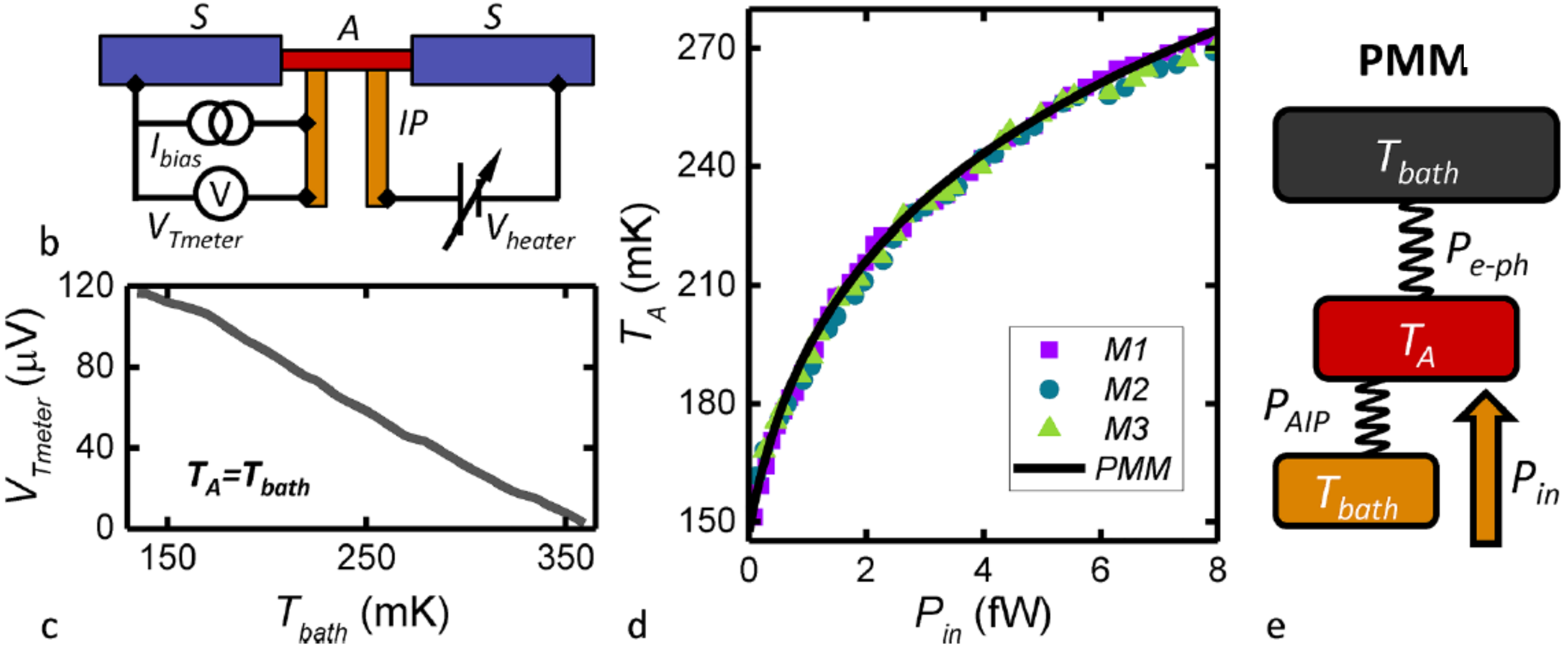
- Superconductor transition due to heating
- Zero-current Bias
- Working at critical temperature
- **Andreev mirror**
- High efficiency



$$P_{in} = P_{e-ph} + P_{AIP} + P_{loss},$$

$$P_{e-ph} = \Sigma_A \mathcal{V}_A \left(T_A^5 - T_{bath}^5\right),$$

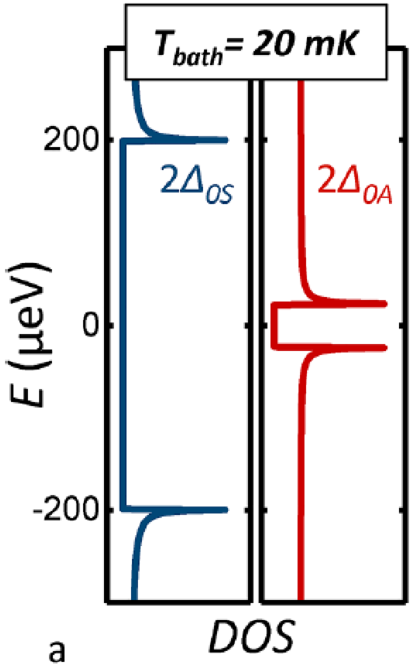
$$P_{AIP} = \frac{1}{e^2 R_{Tmeter}} \int_{-\infty}^{+\infty} \mathrm{d}EE\, DOS_P(E, T_{bath}) \times \left[f_0(E_A, T_A) - f_0(E, T_{bath})\right],$$



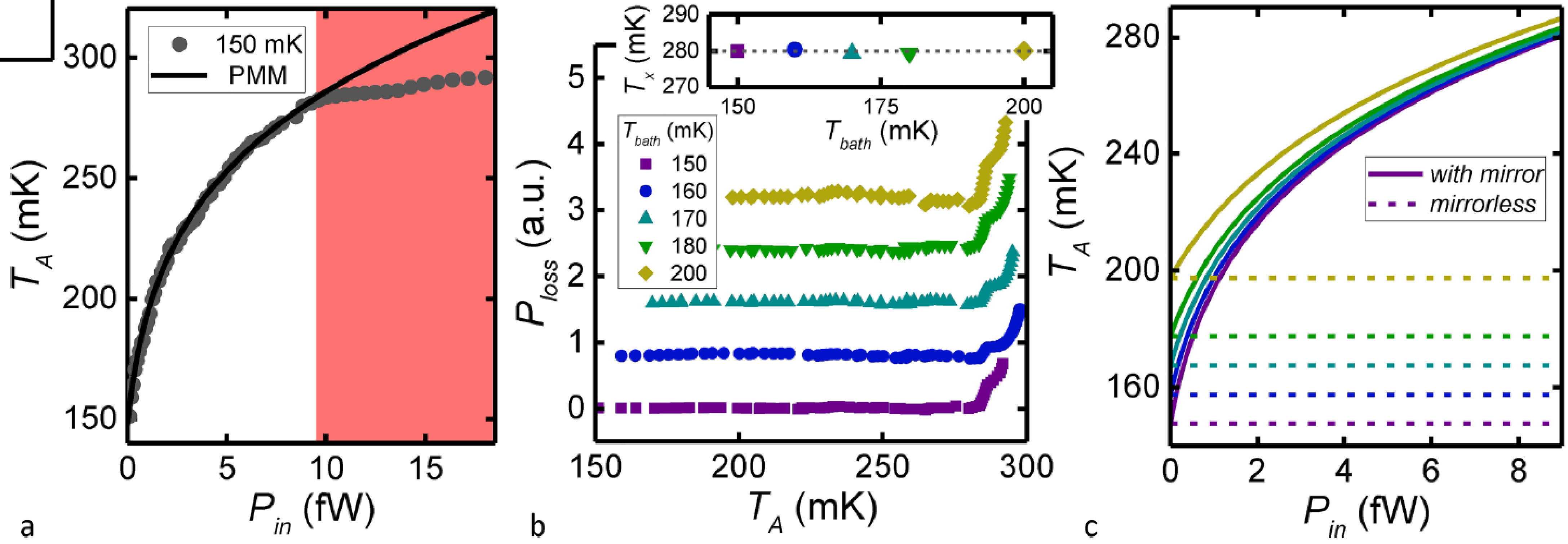
$$DOS(E, T) = \frac{|E|}{\sqrt{E^2 - \Delta^2(T)}} \Theta(E^2 - \Delta^2(T)).$$

K. D. Irwin, "An application of electrothermal feedback for high resolution cryogenic particle detection". Appl. Phys. Lett., 66, 1998 (1995)

TES

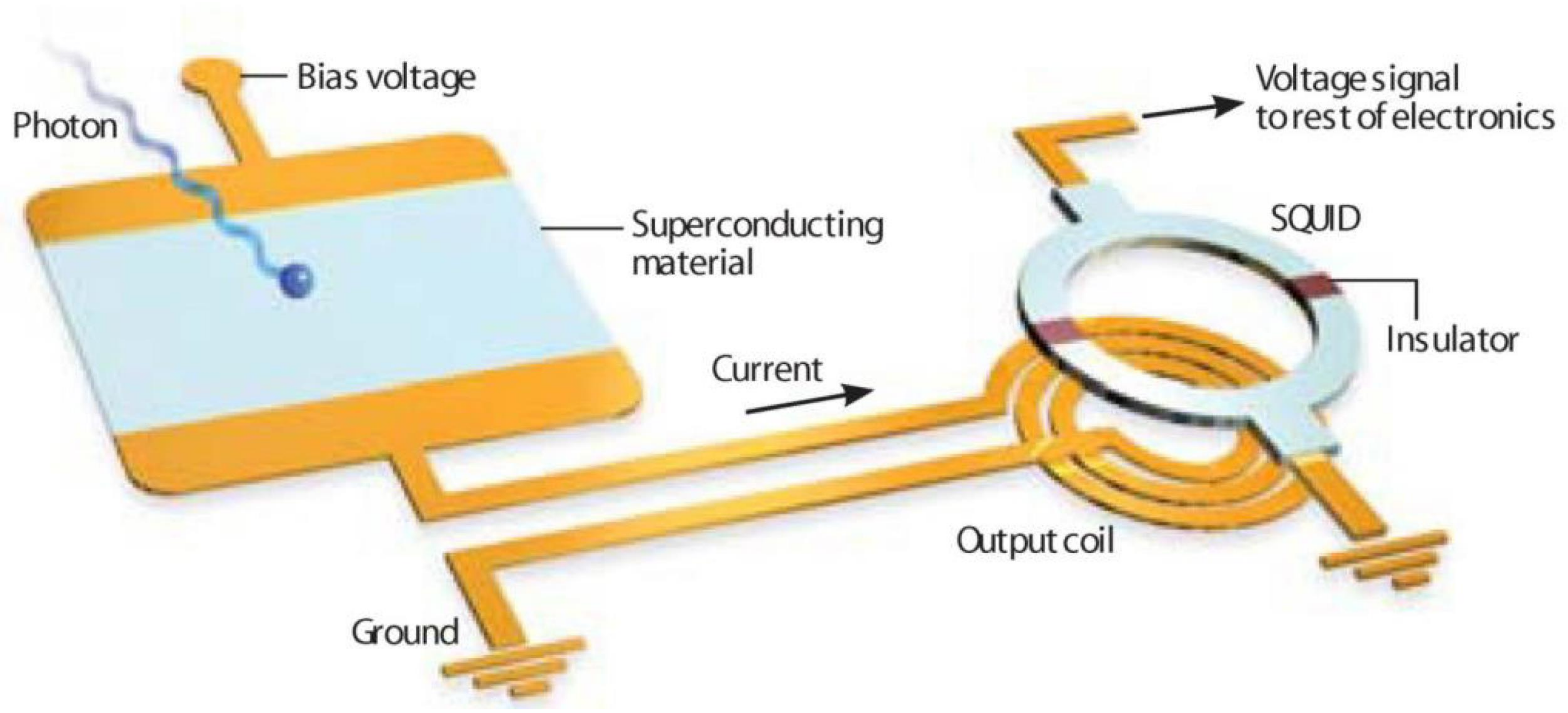


$$P_{in} = P_{e-ph} + P_{AIP} + P_{loss},$$



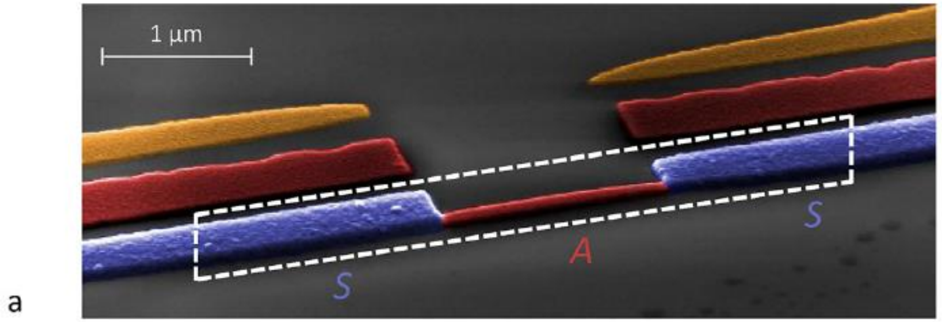
K. D. Irwin, "An application of electrothermal feedback for high resolution cryogenic particle detection". Appl. Phys. Lett., 66, 1998 (1995)

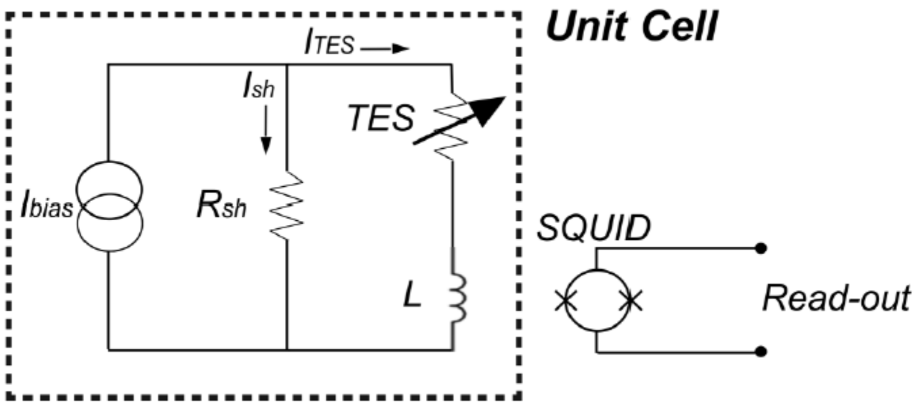
TES - Readout



Photon
Bias voltage
Superconducting material
Current
Ground
Voltage signal to rest of electronics
SQUID
Insulator
Output coil

TES - bolometer





$$NEP_{tot} = \sqrt{NEP^2_{TFN,nano\text{-}TES} + NEP^2_{Jo} + NEP^2_{R_S}},$$

$$NEP_{TFN,nano\text{-}TES} = \sqrt{4\Upsilon G_{th,nano\text{-}TES} k_B T_C{}^2},$$

$$NEP_{Jo} = \sqrt{2k_B R_N T_C}\frac{G_{th,nano\text{-}TES} T_C}{V\alpha}\sqrt{1 + 4\pi^2 f^2 \tau^2_{eff}},$$

$$NEP_{R_S} = \sqrt{4k_B R_S T_{bath}}\frac{G_{th,nano\text{-}TES} T_C}{V\alpha}\sqrt{(1 - L_0)^2 + 4\pi^2 f^2 \tau^2_{eff}},$$

$$\tau = \frac{C_{e,A}}{G_{th,A}}.$$

$$G_{th,A} = \frac{dP_{e-ph}}{dT_A} = 5\Sigma_A \mathcal{V}_A T_A^4.$$

$$C_{e,A} = \Upsilon_A \mathcal{V}_A T_{c,A},$$

Υ_A being the Sommerfeld coefficient of A.

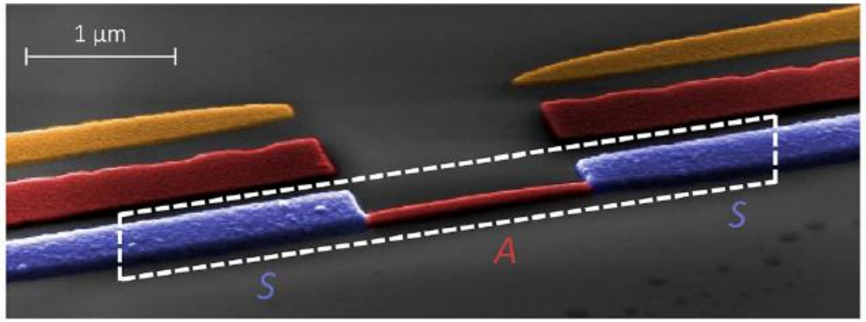
Negative Electro-Thermal Feedback

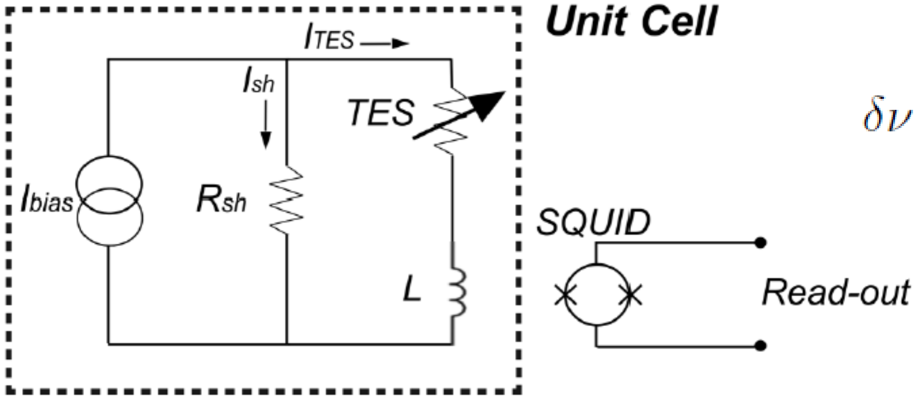
Fast or sensitive

K. D. Irwin, "An application of electrothermal feedback for high resolution cryogenic particle detection". Appl. Phys. Lett., 66, 1998 (1995)

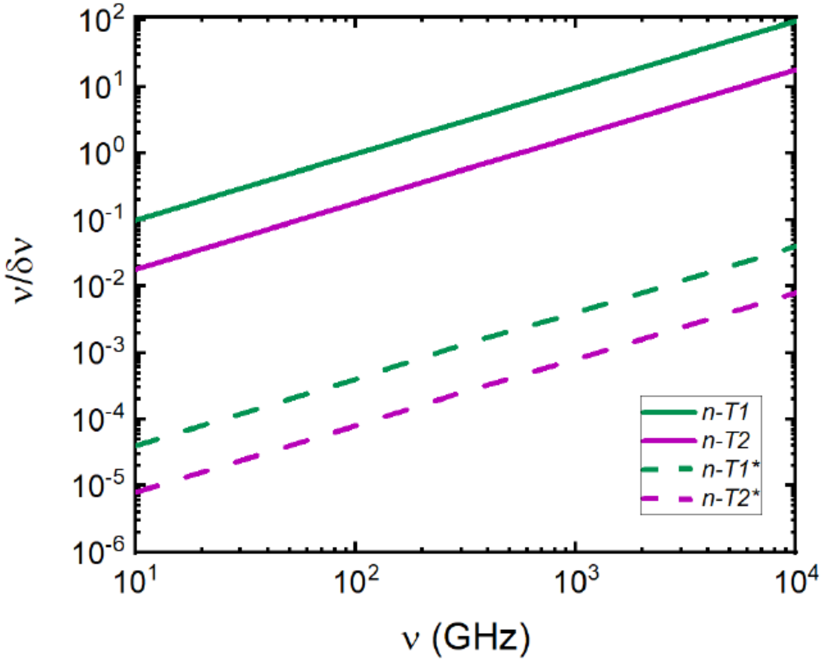
TES - calorimeter

a





$$\delta\nu = \frac{2.36}{h}\sqrt{4\sqrt{\frac{n}{2}}k_B T_c^2 \frac{C_{e,A}}{\alpha}}.$$



$$\tau = \frac{C_{e,A}}{G_{th,A}}.$$

$$G_{th,A} = \frac{dP_{e-ph}}{dT_A} = 5\Sigma_A \mathcal{V}_A T_A^4.$$

Negative Electro-Thermal Feedback

$$C_{e,A} = \Upsilon_A \mathcal{V}_A T_{c,A},$$

Fast or sensitive

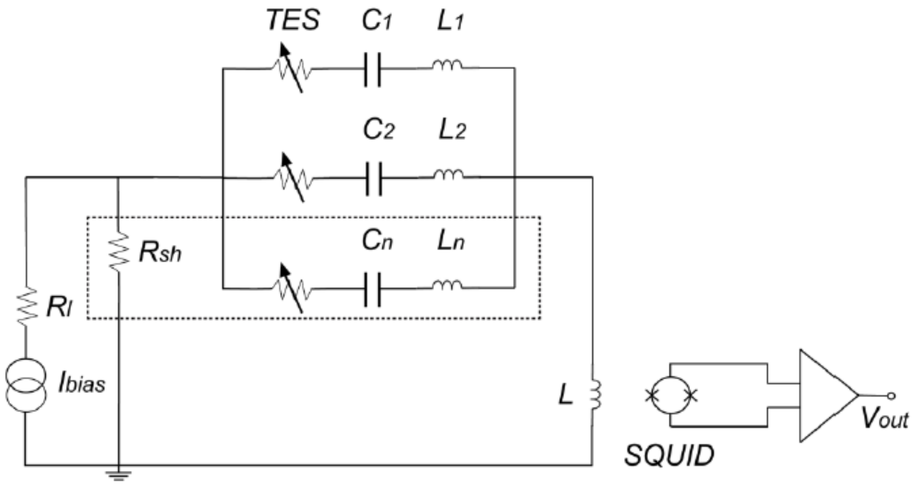
Υ_A being the Sommerfeld coefficient of A.

K. D. Irwin, "An application of electrothermal feedback for high resolution cryogenic particle detection". Appl. Phys. Lett., 66, 1998 (1995)

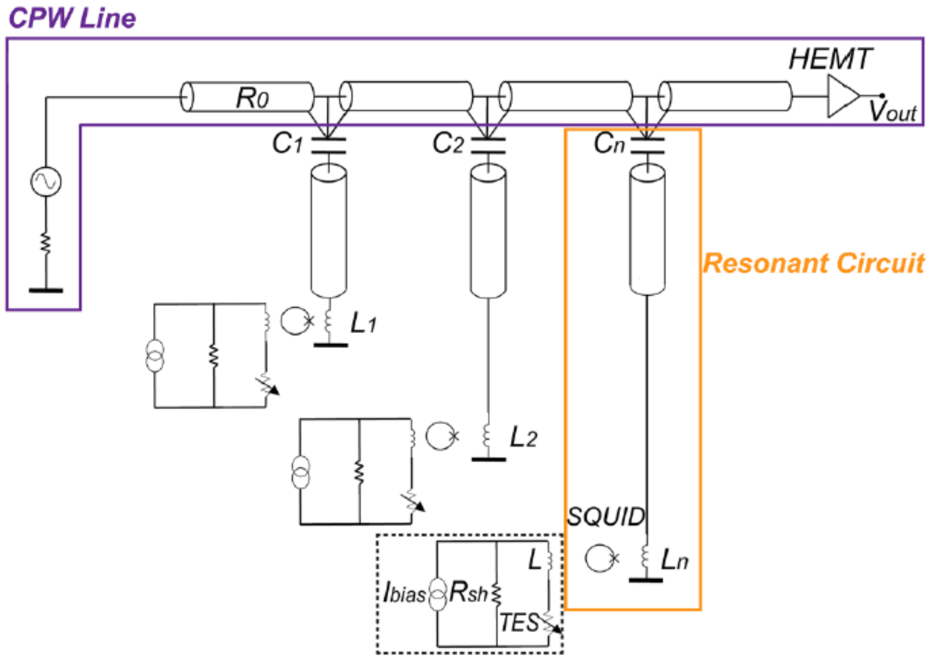
TES - Multiplexing

n-T	T_c (mK)	τ (μs)	τ_{eff} (μs)	NEP_{TFN} ($W/\sqrt{Hz}$)	NEP_{tot} ($W/\sqrt{Hz}$)	$\delta\nu$ (GHz)	$\nu/\delta\nu$ 100 GHz	$\nu/\delta\nu$ 300 GHz	$\nu/\delta\nu$ 1 THz
1	128	6	0.01	5.2×10^{-20}	5.2×10^{-20}	100	1	3	10
1*		6	0.01	1.1×10^{-16}	4.7×10^{-16}	2×10^{5}	4×10^{-4}	1×10^{-3}	4×10^{-3}
2	139	5	0.2	6.7×10^{-20}	6.7×10^{-20}	540	0.18	0.55	1.8
2*		5	0.2	1.5×10^{-16}	8.3×10^{-15}	1×10^{6}	8×10^{-5}	2×10^{-4}	8×10^{-4}

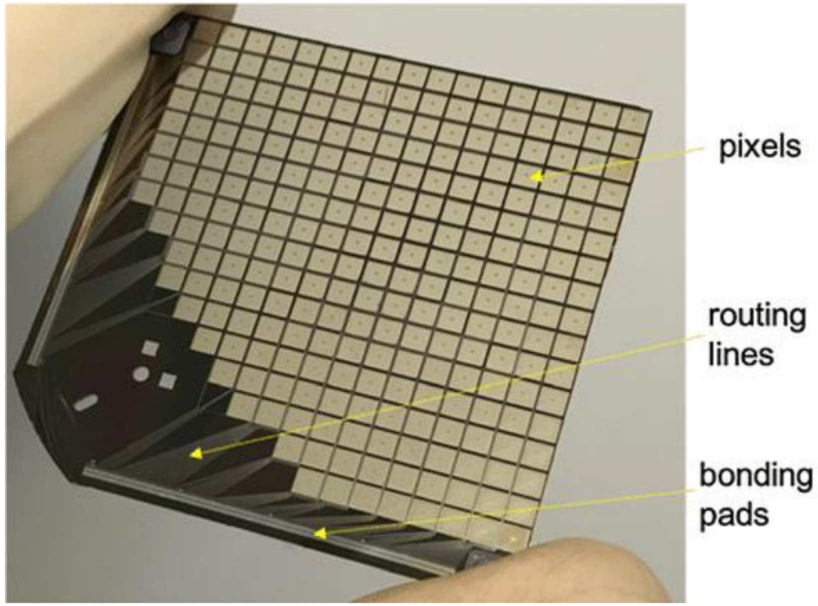
Frequency division multiplexing

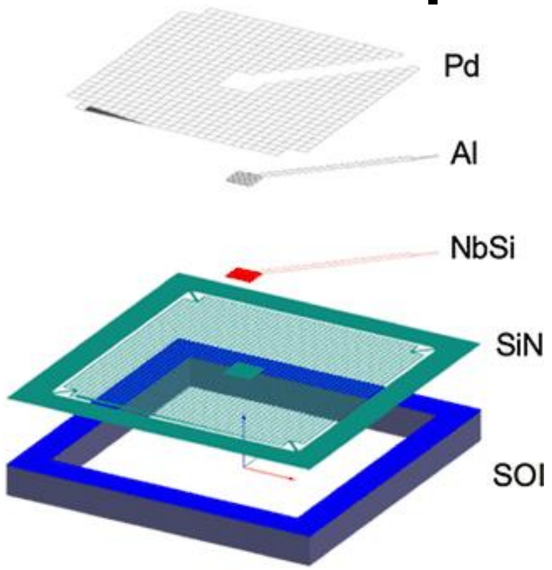


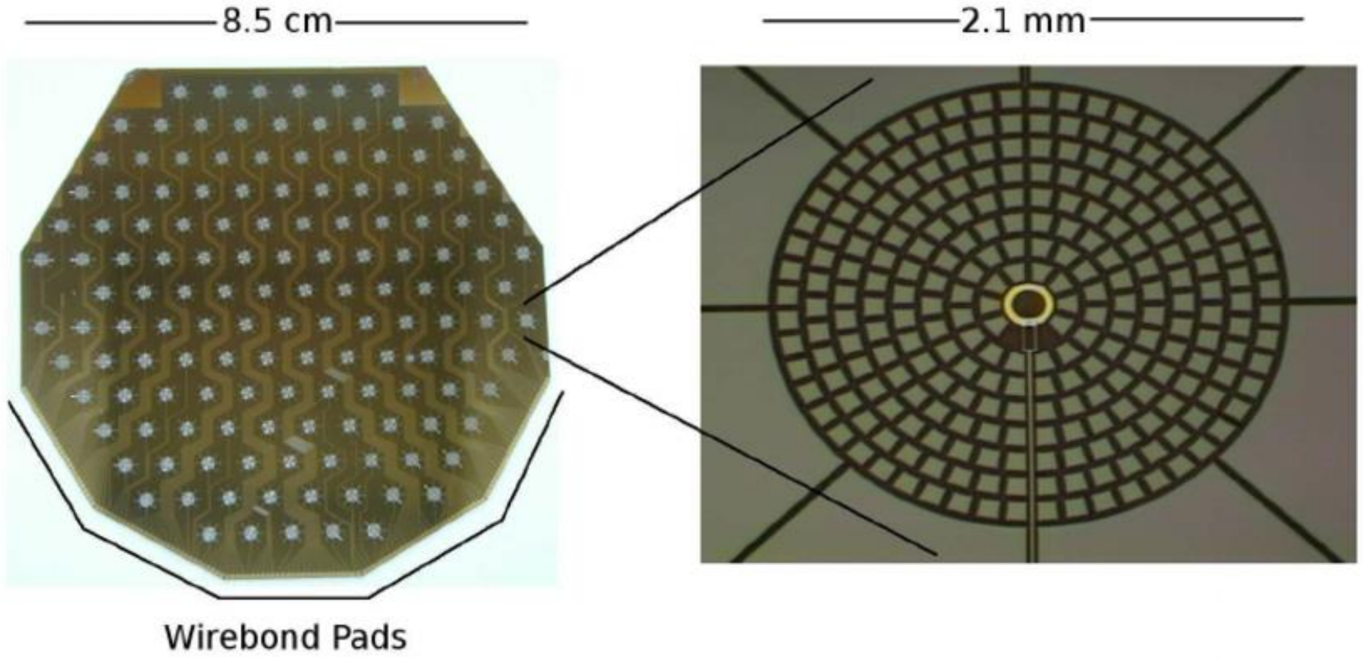
Microwave resonator multiplexing



TES - Multiplexing

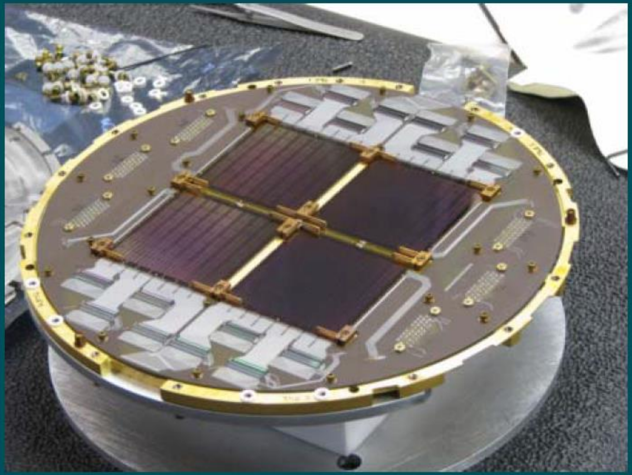




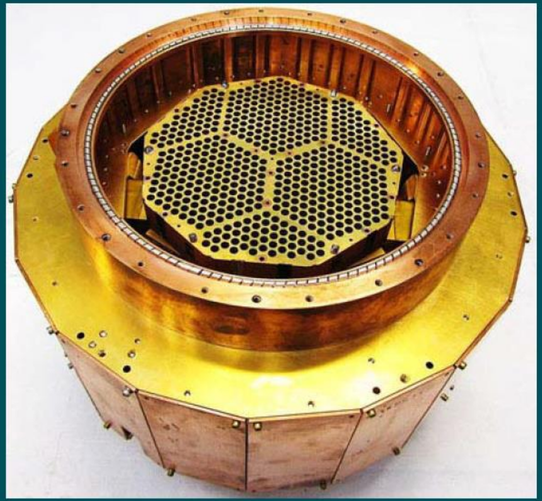


TES - CMB

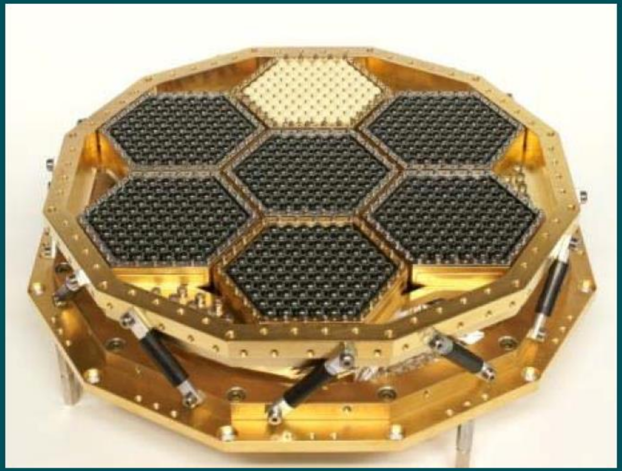
BICEP-2



ACTpol

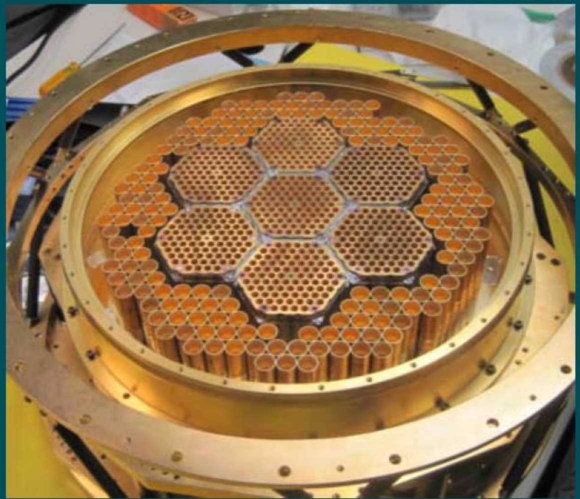


POLARBEAR

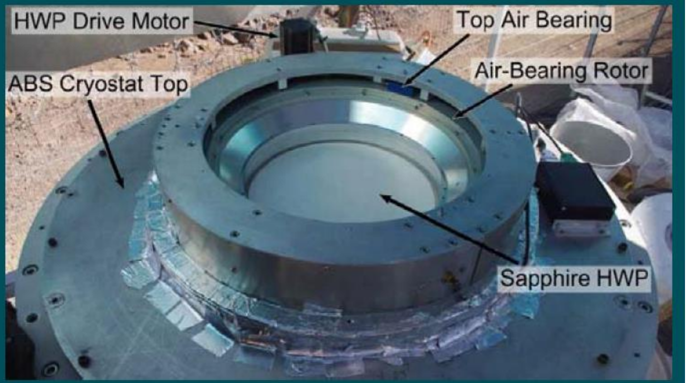


Keck Array

SPTpol

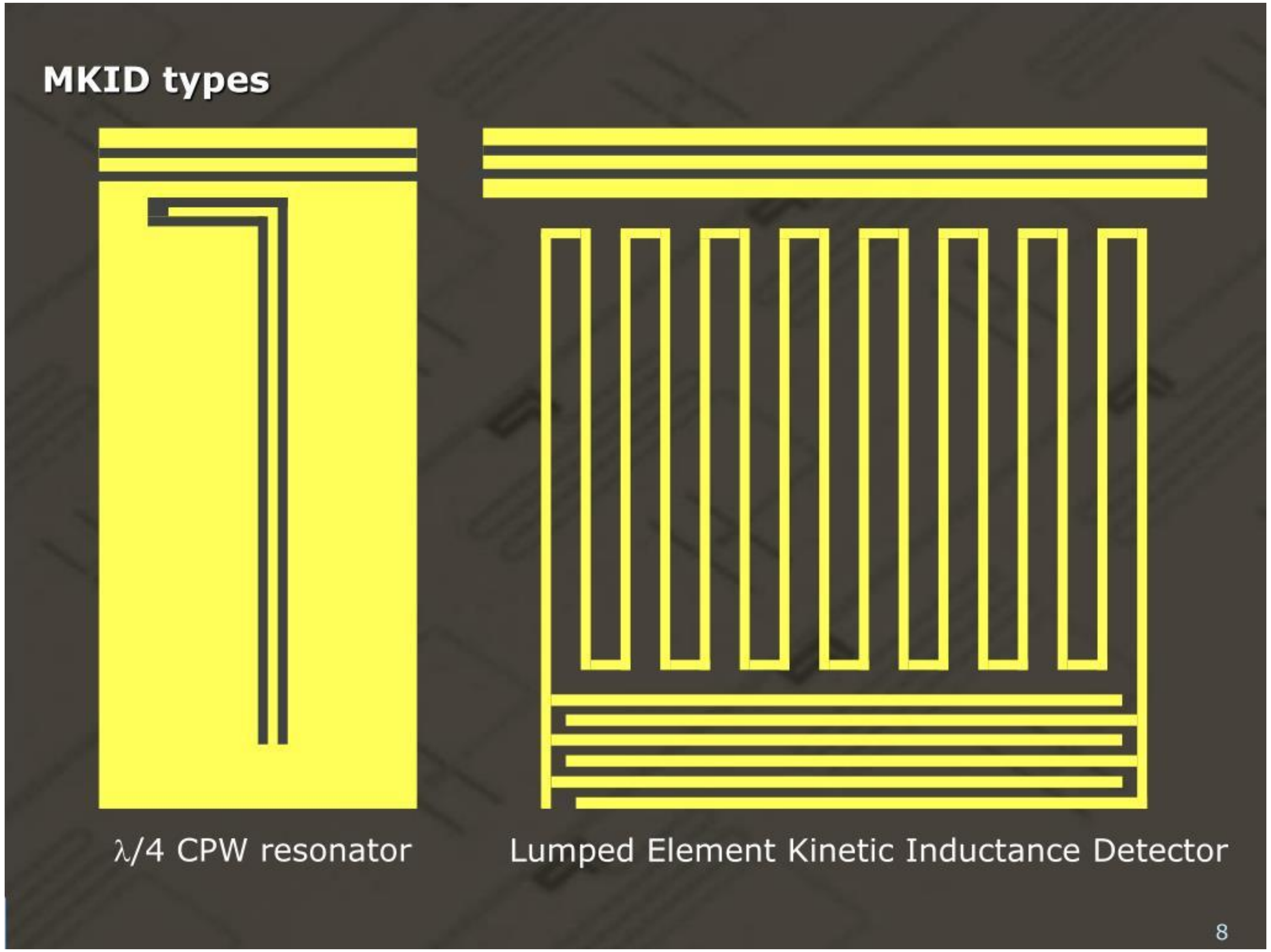


ABS



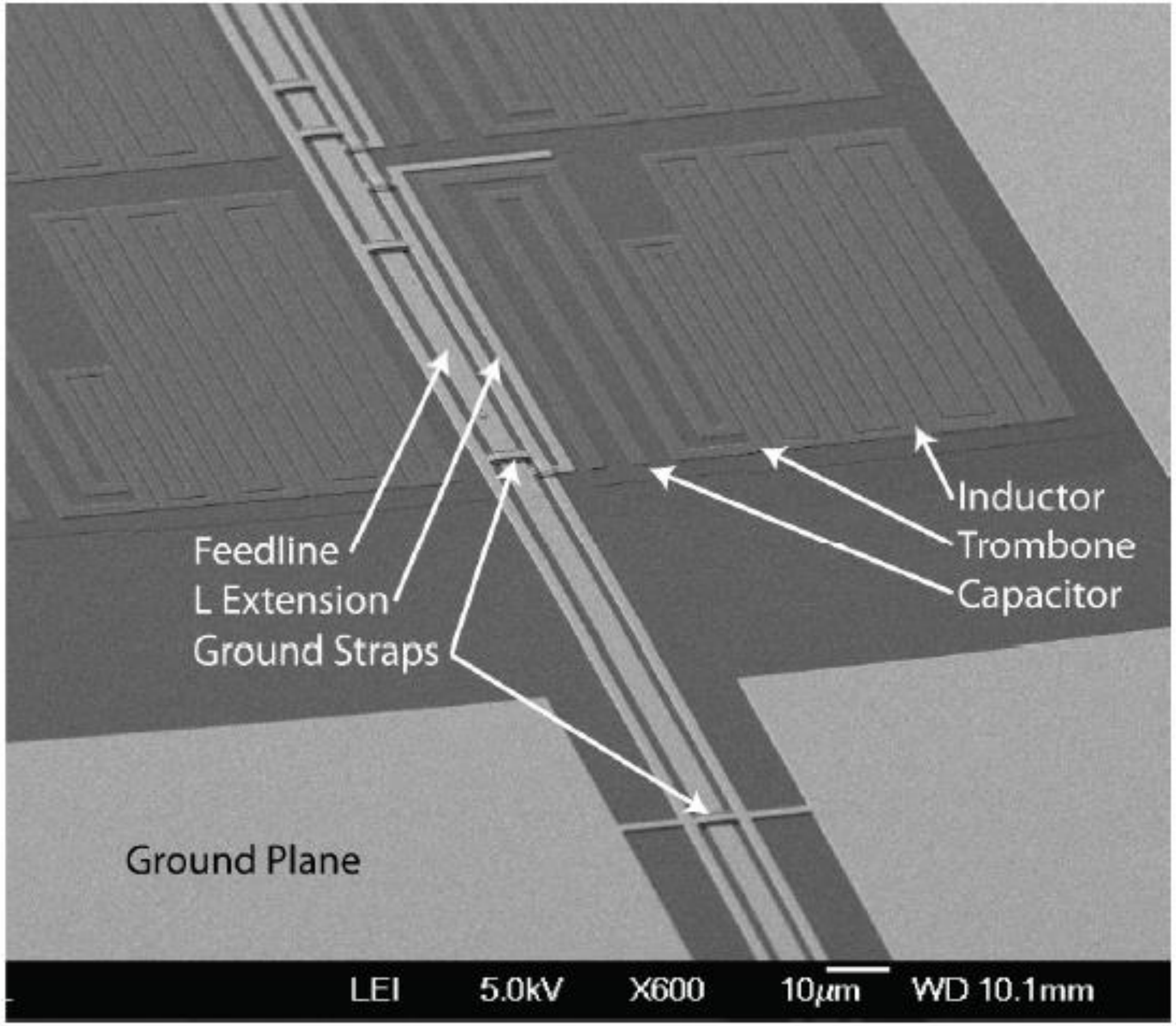
Kinetic Inductance Detector

KID



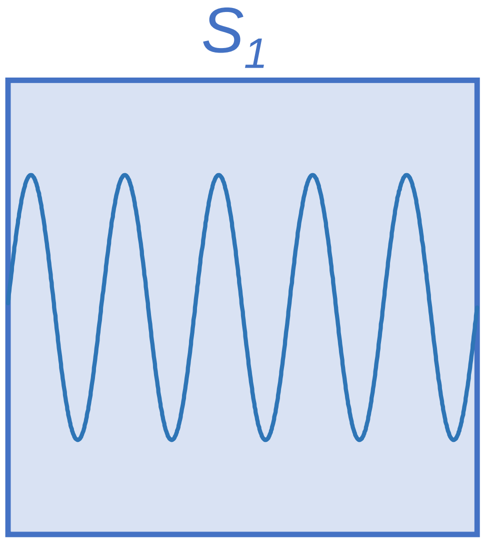
MKID types
λ/4 CPW resonator
Lumped Element Kinetic Inductance Detector
8

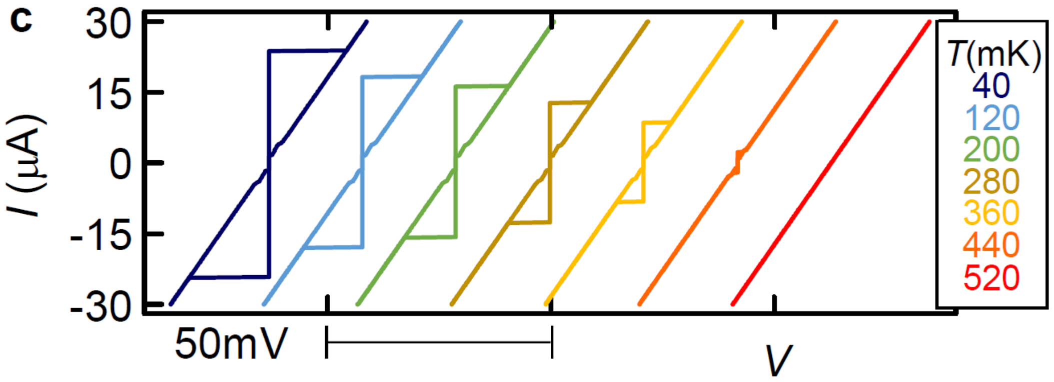
KID


Feedline
L Extension
Ground Straps
Inductor
Trombone
Capacitor
Ground Plane
LEI 5.0kV X600 10μm WD 10.1mm

Kinetic inductance of a superconductor

$$\psi_1 = \sqrt{n_{S1}} e^{-i\varphi_1}$$





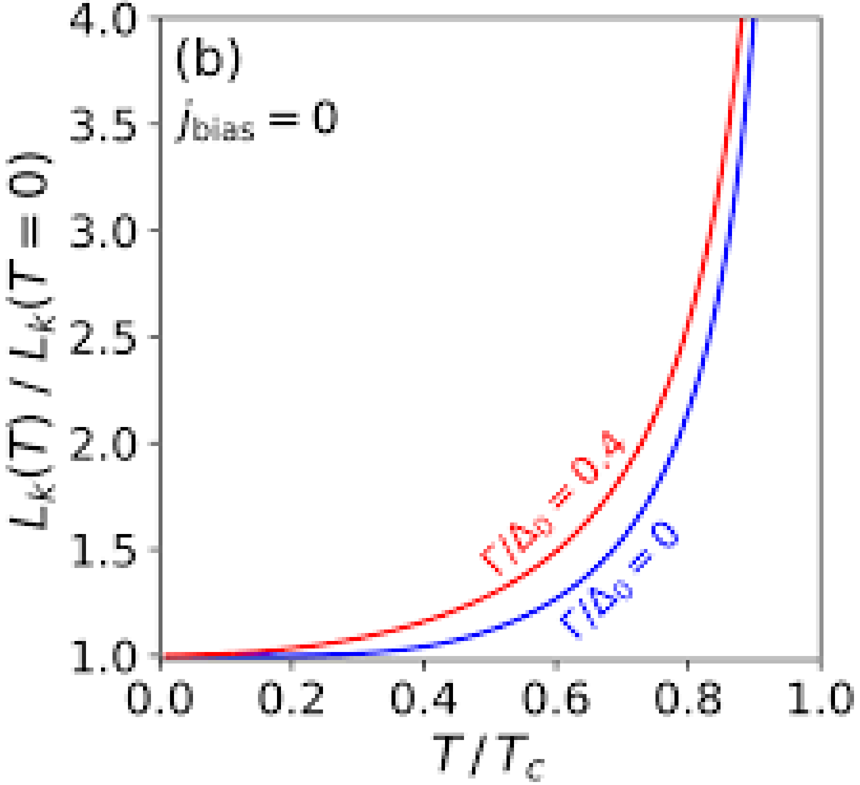
Cooper pair condensate

A lot of energy to "move" the condensate

Much stronger than for single electrons

Energy stored described by inductance

$$L_{J,linear} = \frac{\hbar}{2eI_J}$$

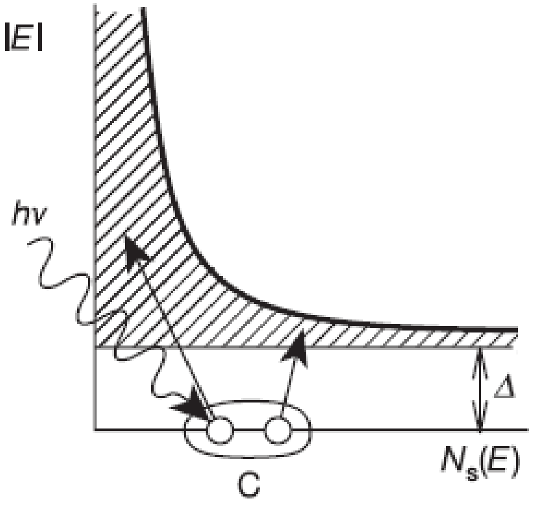


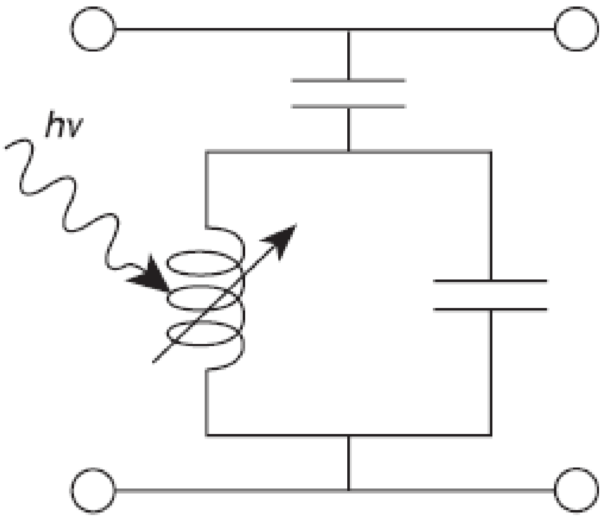
KID – principle

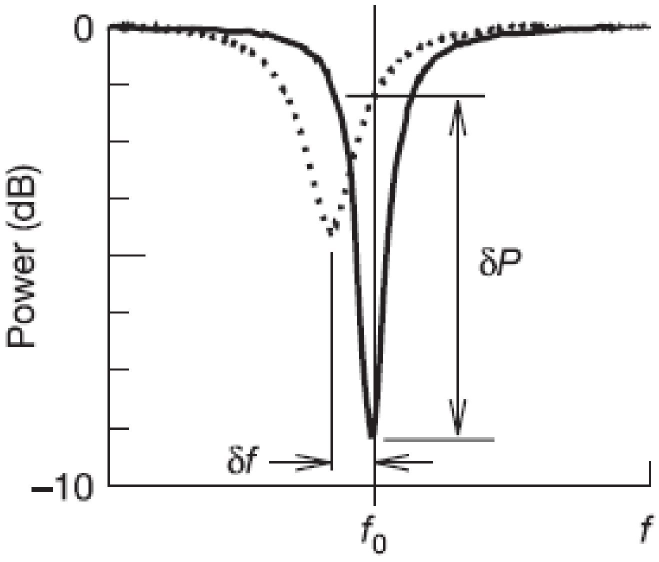
Inductance increases

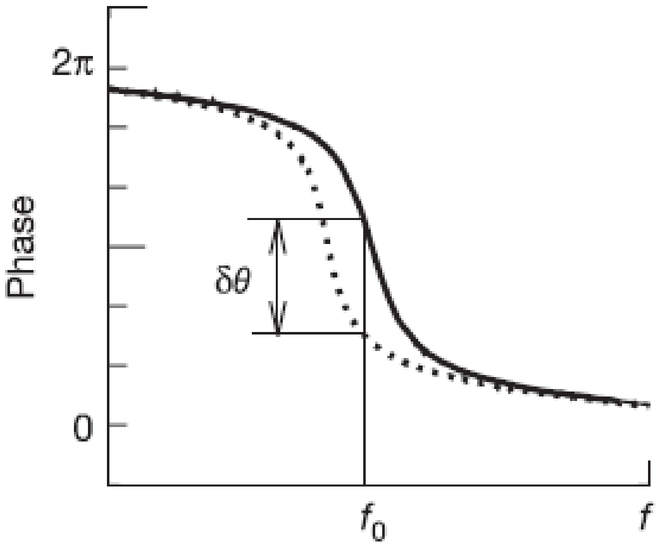
Impedance of resonator

Change of phase of the signal









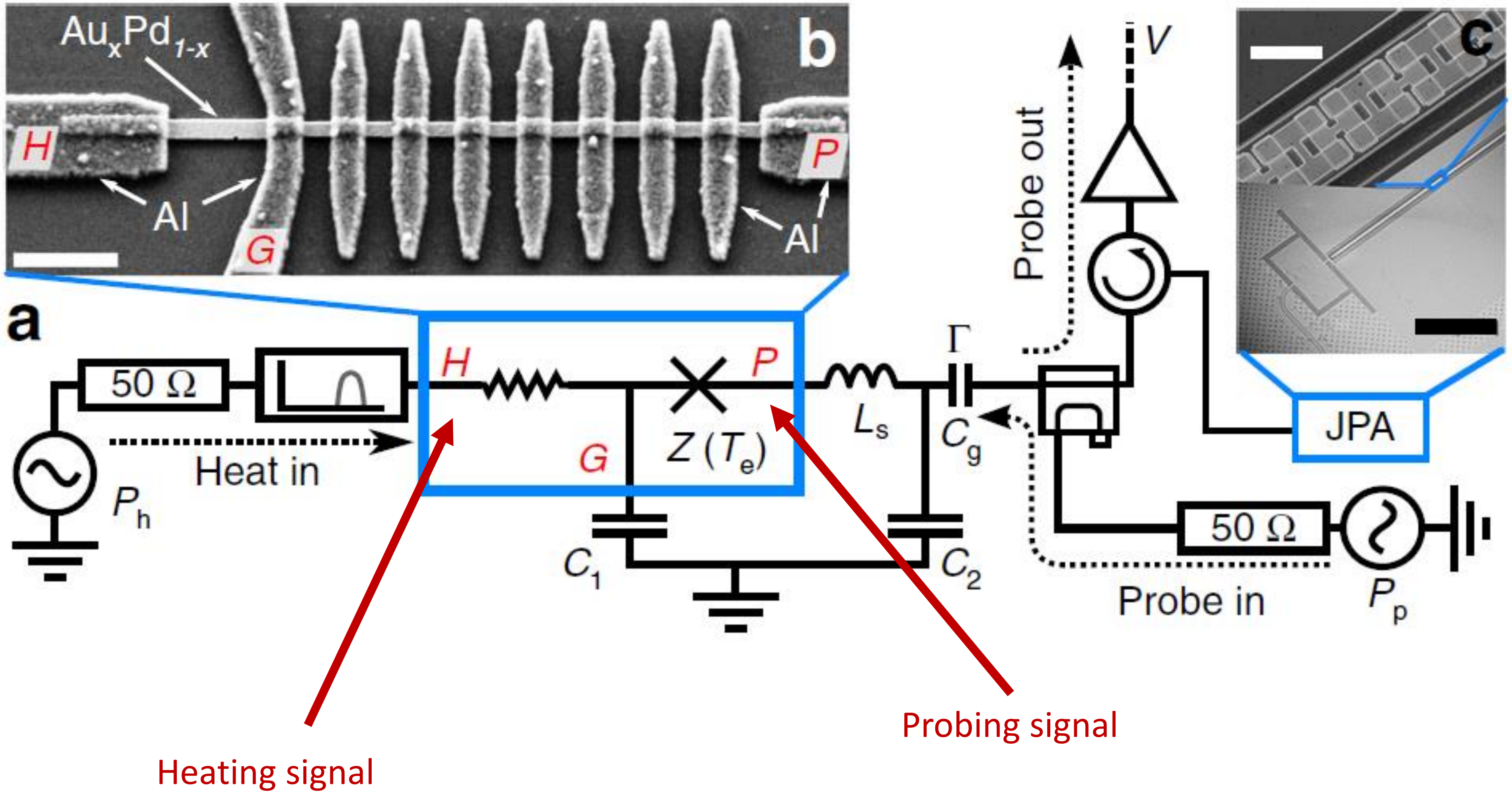
Radiation increases Temperature

Cooper pair break

Critical supercurrent decreases

Change of resonant frequency

Nano-KID – structure and set-up



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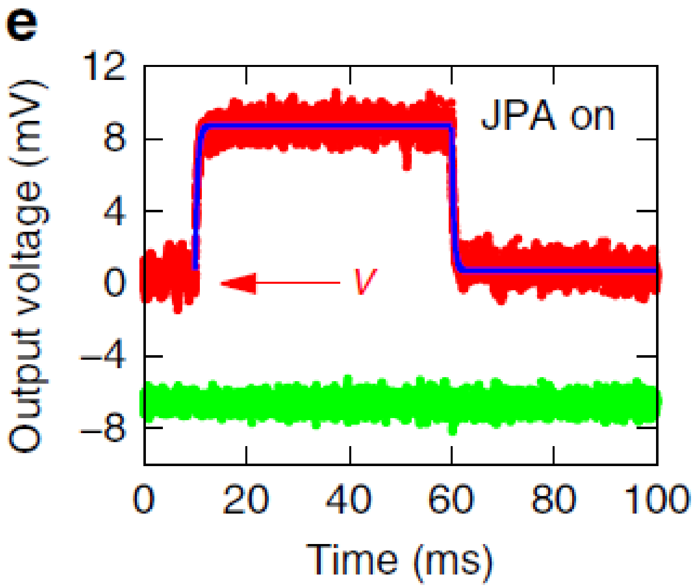
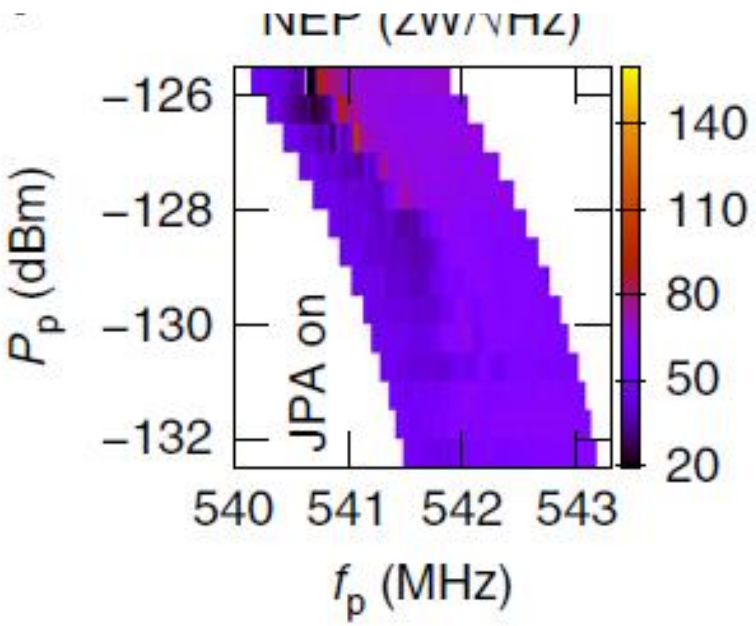
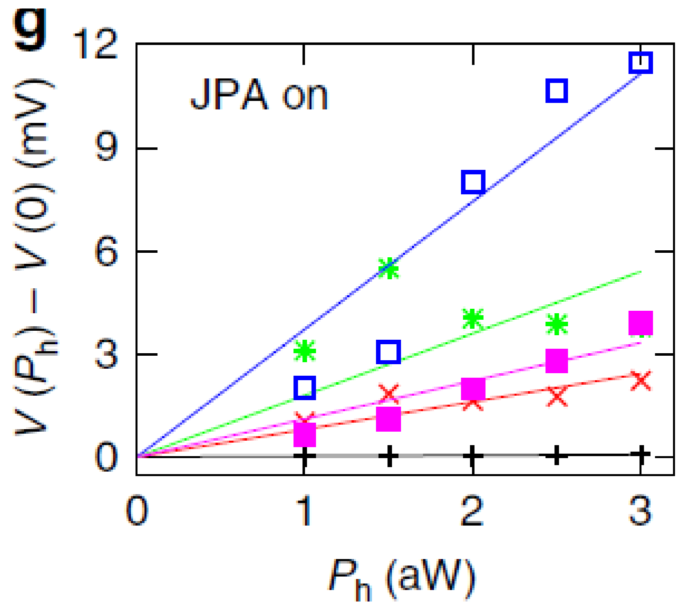
KID – measurements

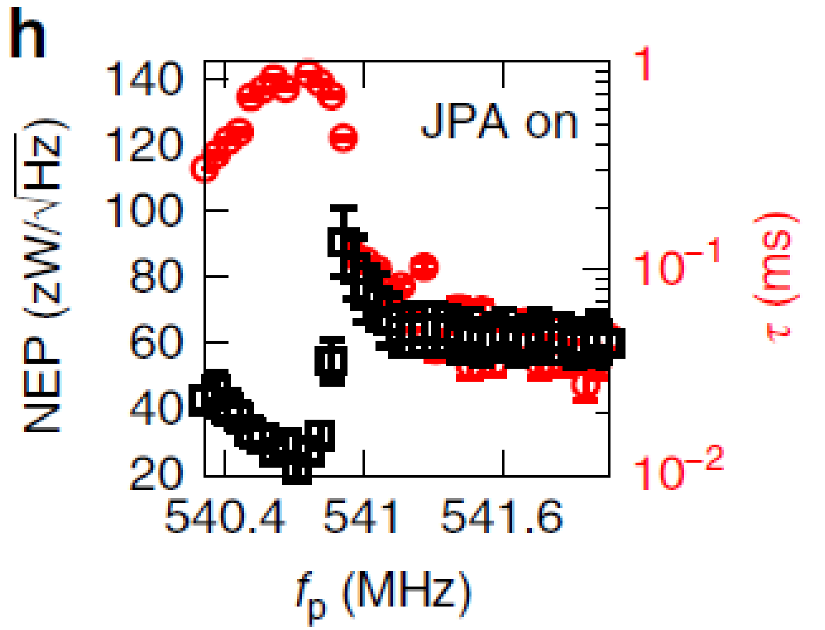


8 GHz signal

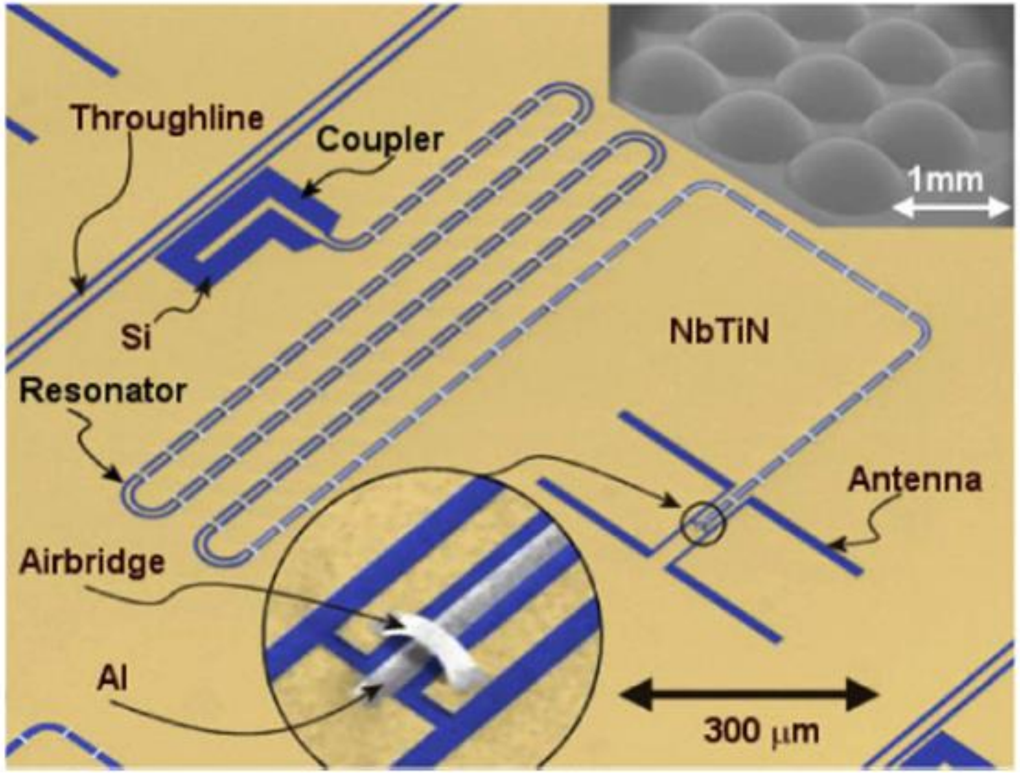
Zepto 10^-21

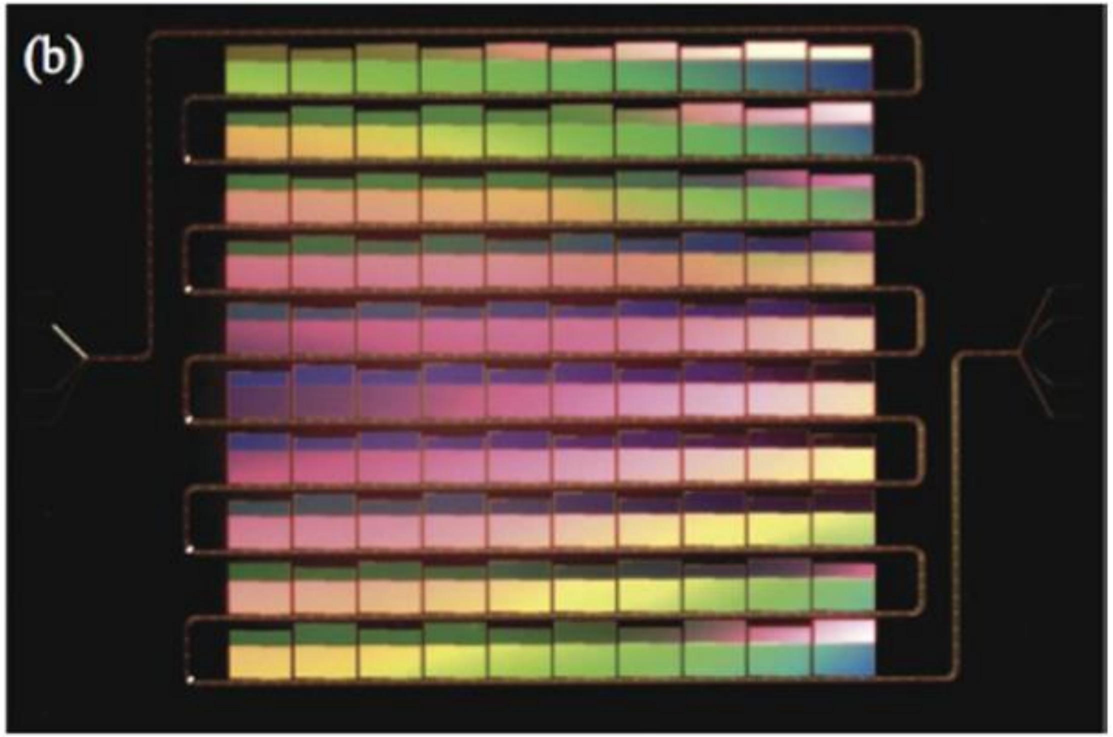




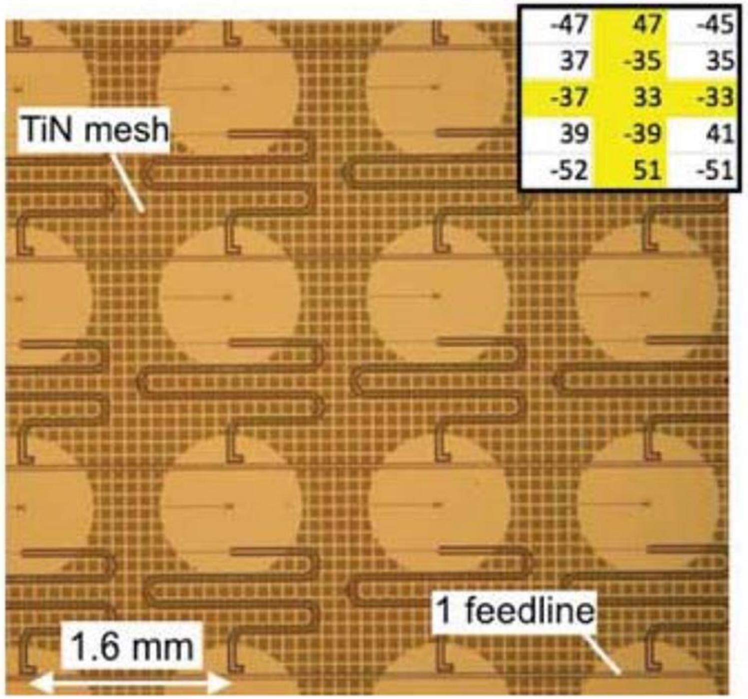


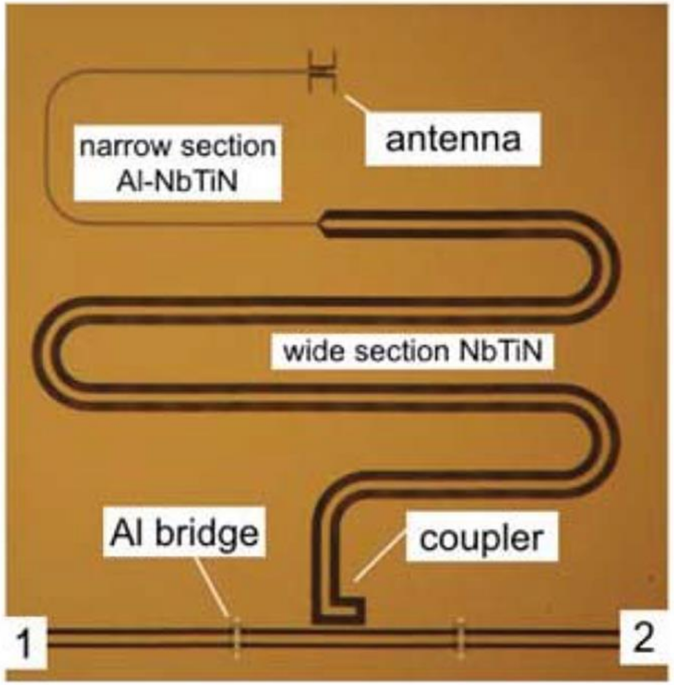
KID

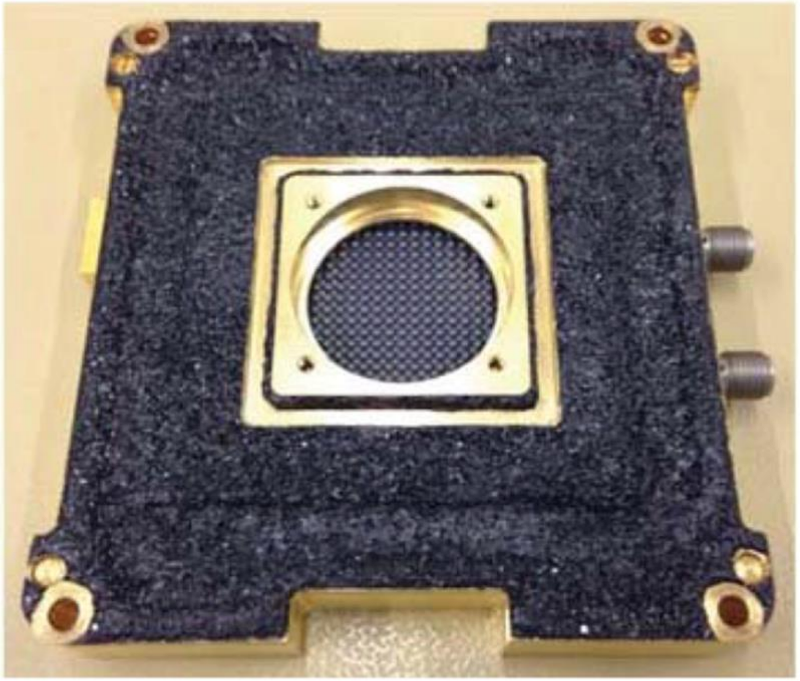

Throughline
Coupler
1mm
Si
NbTiN
Resonator
Antenna
Airbridge
Al
300 μm


(b)

KID - multiplexing







Change of resonance frequency by setting L and C