Detection of Quantum Noise from an Electrically-Driven Two-Level System

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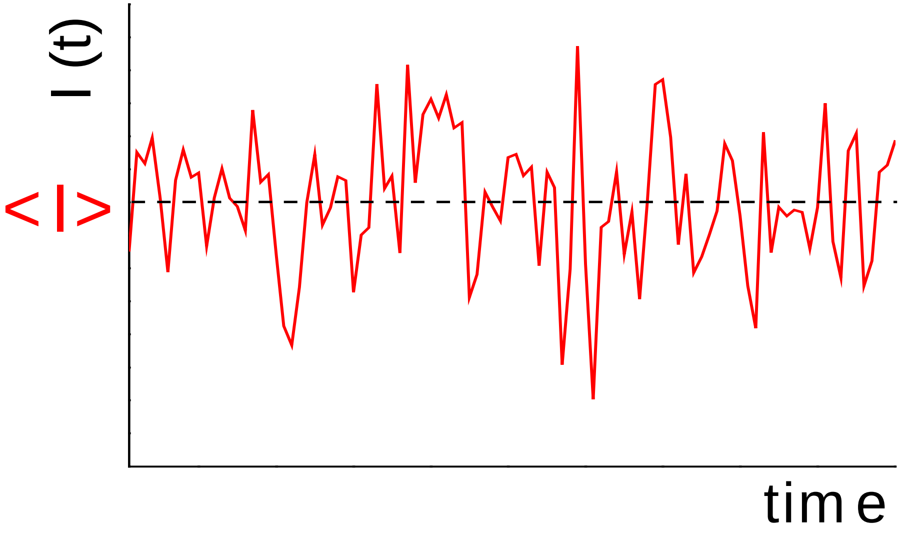
« The noise is the signal »

Current fluctuations :

$$\Delta I(t) = I(t) - < I >$$



Spectral density of noise :

$$S_I(\omega) = \int_{-\infty}^{+\infty} d\tau \exp(i\omega\tau) < \Delta I(\tau)\Delta I(0) >$$ (non-symmetrized)

- <u>equilibrium fluctuations</u> : Nyquist noise

$$S_I(\omega) + S_I(-\omega) = 4k_B T G$$

- <u>non-equilibrium fluctuations</u> : shot noise (discrete transfer of charge quanta)

  -charge of the current carriers (Cooper pairs, FQHE, …) : $2e^* < I >$

  -correlation effects (statistics, interactions)

High-frequency noise

Noise properties at high frequency

- quantum noise : zero point fluctuations (e.g. R. Schoelkopf *et al.* PRL (1997))
- internal energy scales and dynamic
- Back action of a device and quantum measurement

Requirements :

- frequency resolved detection (1-100 GHz)
- high-sensitivity
- good calibration

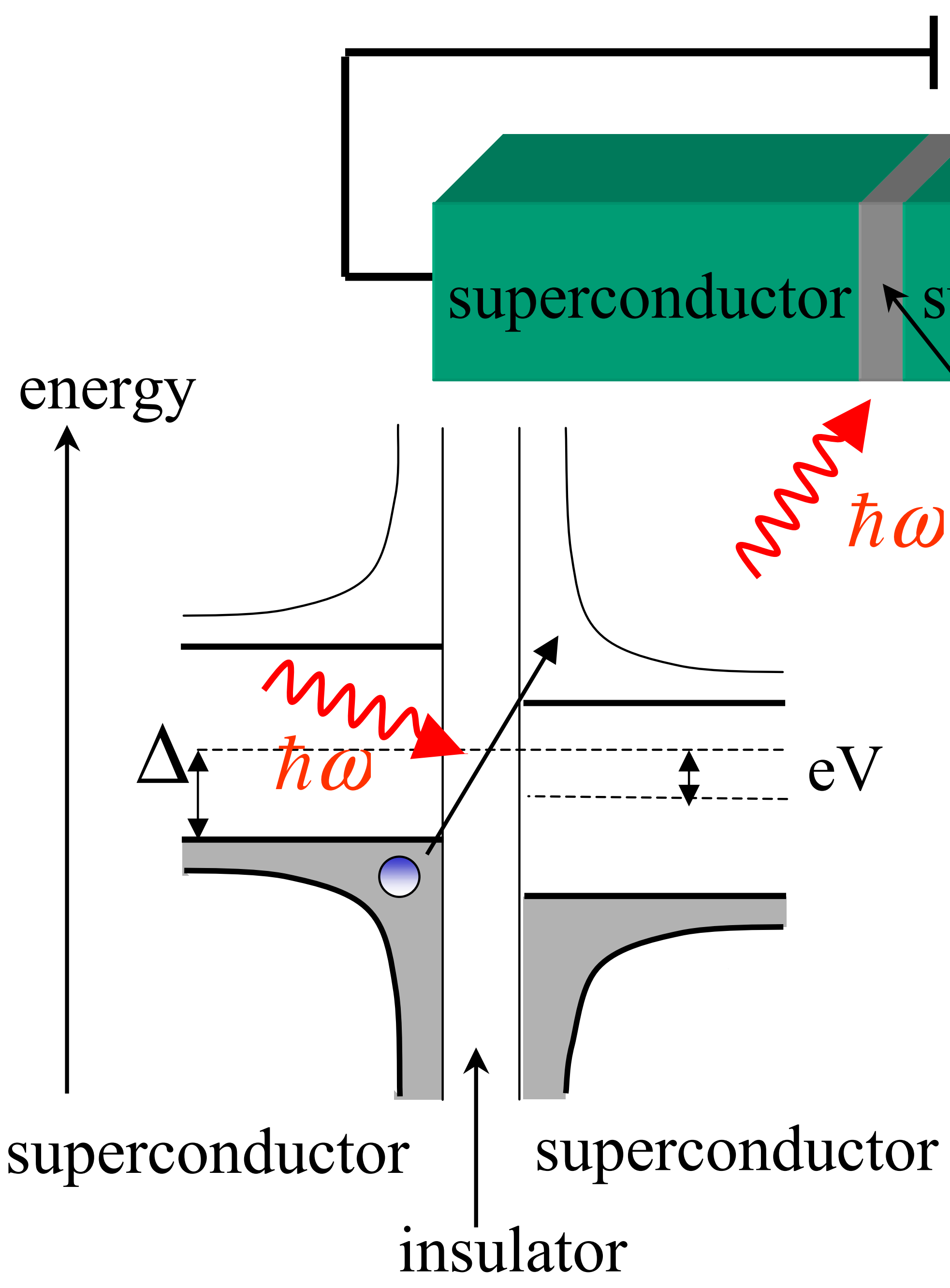
HF electronics ?

or

Detector (« spectrometer ») on-chip :

- single electron transistor
- double quantum dots
- qubit
- …

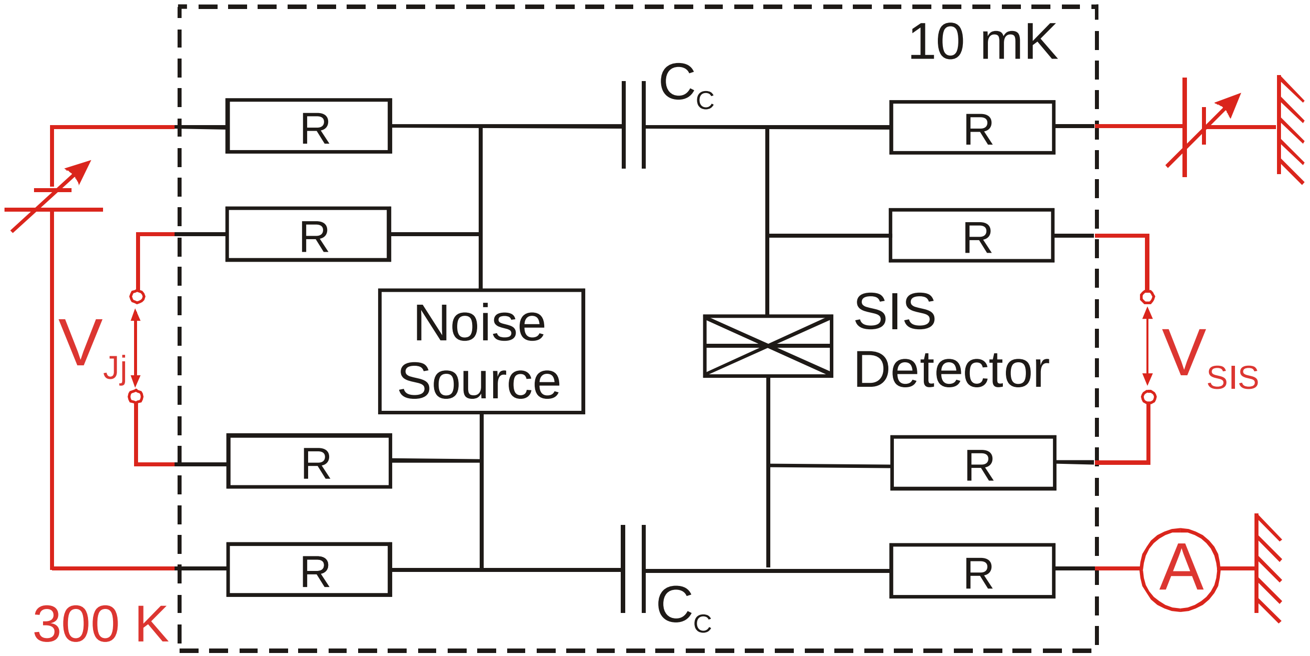
High-frequency detection with SIS junctions



photon-assisted tunneling current

Frequency range determined by 2Δ :
- Al : 100 GHz (Nb : 1 THz)

Coupling to the SIS detector : on-chip HF circuit



- R : resistance (Pt, 2kΩ)

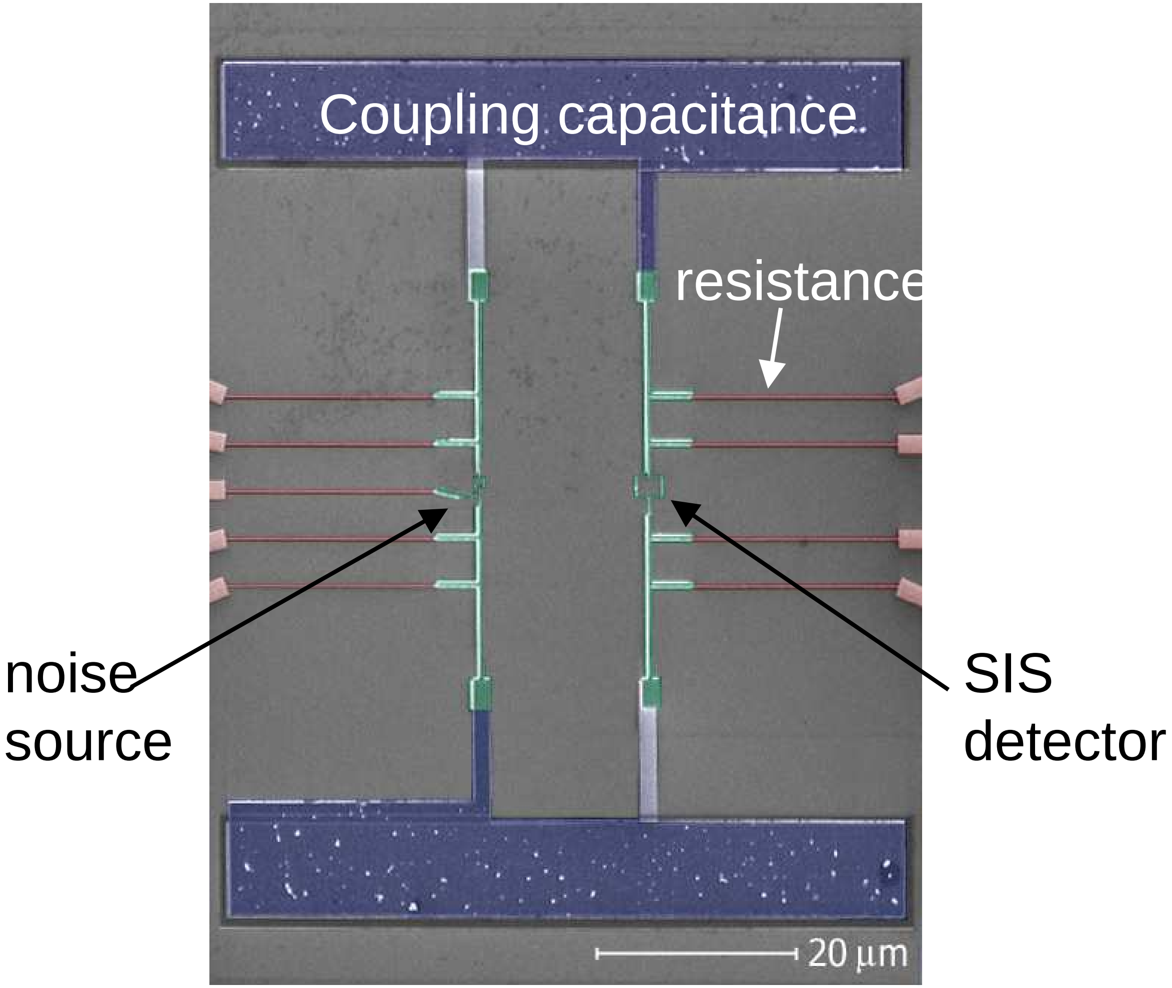
  decoupling from external environment at high frequency

- C_C : coupling capacitances (50 nm SiO_2, 550 fF)

  coupling at high frequency the device and the detector

$$\Rightarrow \text{Transimpedance } Z(\omega) = \frac{\text{Voltage fluctuations at the detector}}{\text{Current fluctuation of the noise source}}$$

Experimental realization



Three electron beam lithography steps :

1. On-chip resistances, contact pads and bottom plate of C_c (Pt)
2. insulating layer for the coupling capacitances (SiO_2)
3. Top plate of C_c, noise source + SIS detector (Al)

Current fluctuations of the device

Photon-assisted tunneling current :

emission $(\omega<0)$

$$\begin{aligned} I_{PAT}(V) &= I_{QP}(V) - I_{QP,0}(V) \\ &= \int_0^{+\infty} d\omega \left(\frac{e}{\hbar\omega}\right)^2 |Z(\omega)|^2 S_I(-\omega) I_{QP,0}\left(V + \frac{\hbar\omega}{e}\right) \\ &+ \int_0^{eV} d\omega \left(\frac{e}{\hbar\omega}\right)^2 |Z(\omega)|^2 S_I(\omega) I_{QP,0}\left(V - \frac{\hbar\omega}{e}\right) \\ &- \int_{-\infty}^{+\infty} d\omega \left(\frac{e}{\hbar\omega}\right)^2 |Z(\omega)|^2 S_I(\omega) I_{QP,0}(V) \end{aligned}$$

absorption $(\omega<0)$

Ingold and Nazarov (1992)

Aguado and Kouwenhoven (2000)

$Z(\omega)$: transimpedance

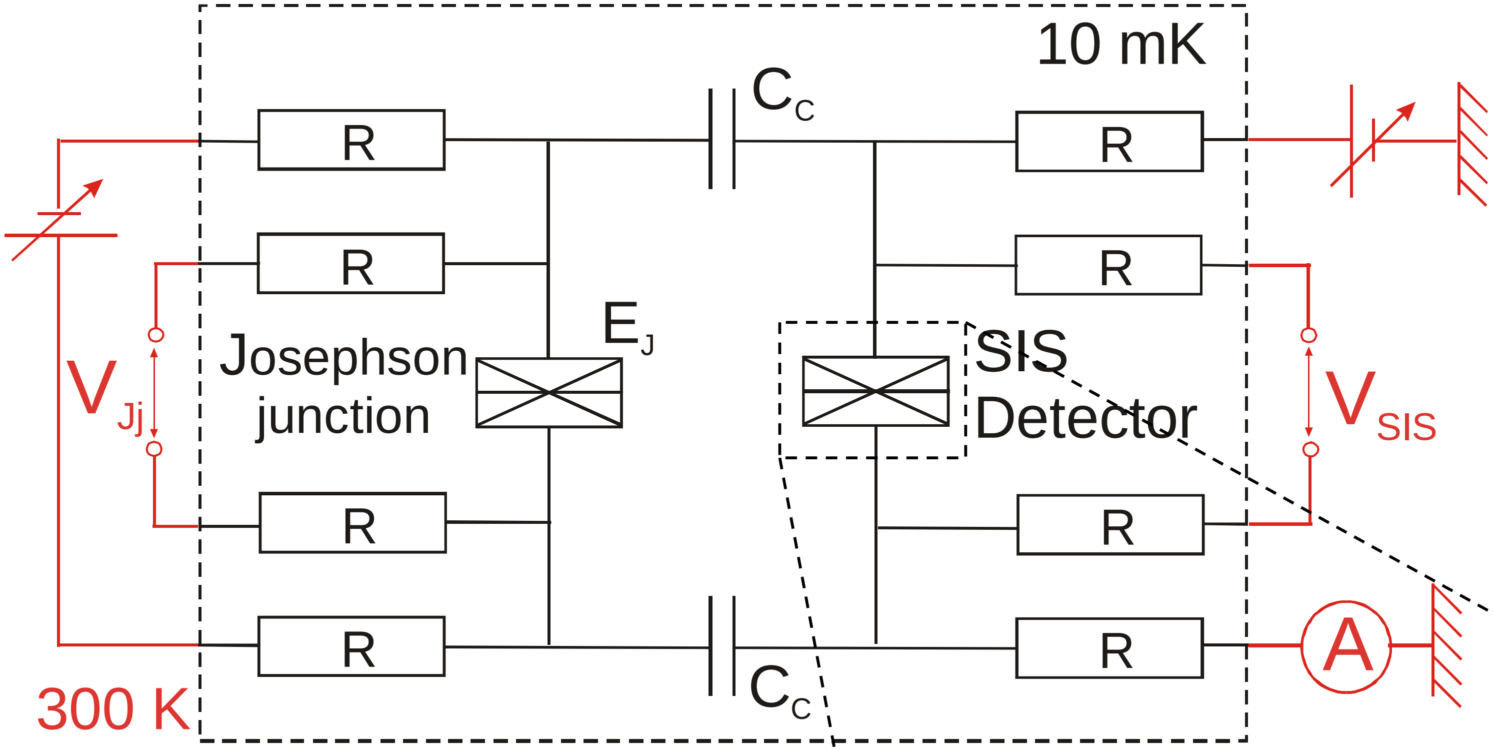
$S_I(\omega)$: *non-symmetrized* current noise correlator of the noise source

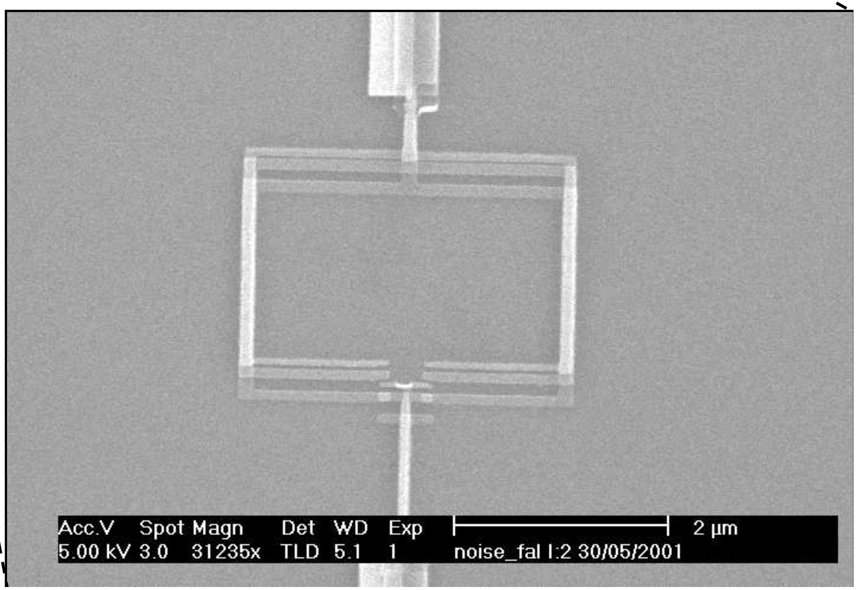
$I_{QP,0}(V)$: IV of the junction without noise

noise source = electromagnetic environment of the SIS detector

When $V < 2\Delta$: only emission is measured.

The noise of a Josephson junction





SQUID geometry to tune the critical current :

- SIS detector : no Josephson coupling
- Josephson junction : high Josephson coupling (I_c= 23 nA)

AC Josephson effect

« noise » source

(i.e. Josephson junction)

$V_{Jj} < 2\Delta$

No quasi-particle current

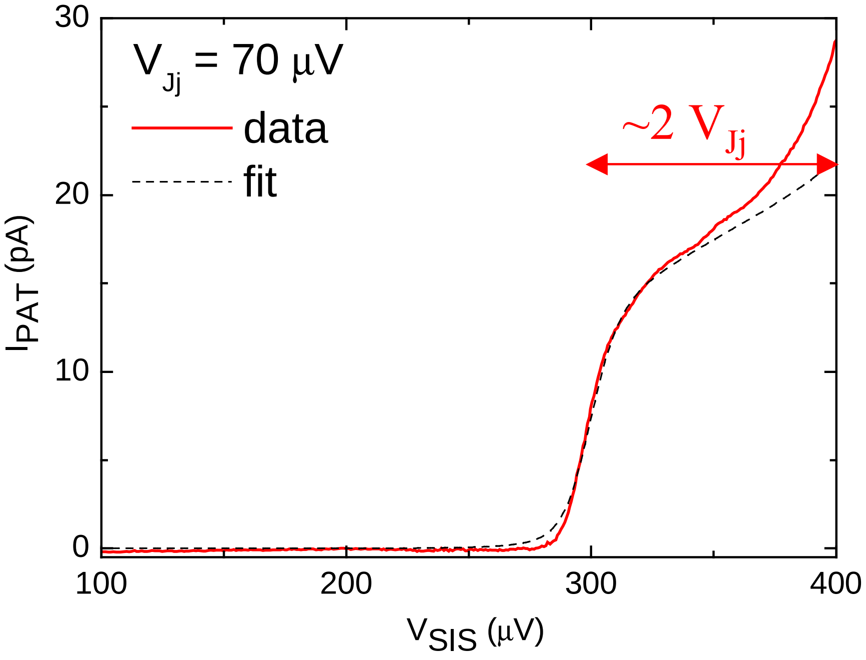
Josephson current :

- $I = I_c \sin(\Phi)$
- $d\Phi/dt = 2\pi\, 2eV_{Jj} / h$

I_c the critical current
Φ superconducting phase difference

Josephson junction
= HF generator at frequency $2eV_{Jj}/h$

SIS detector



Fit with :

- $Z(\omega)$ fitting parameter
- noise spectrum with one frequency

Transimpedance $Z(\omega)$

White noise

« noise » source

(i.e. Josephson junction)

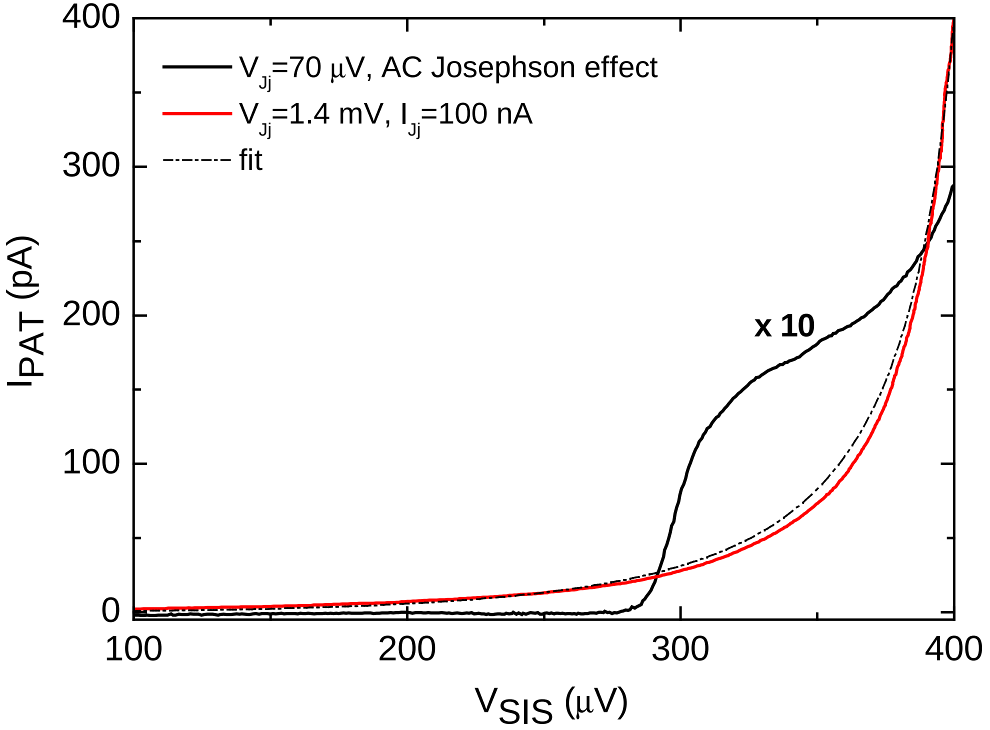
$V_{Jj} > 2\,\Delta$

➡ quasi-particle current I

➡ poissonian shot-noise :

- symmetrized noise $S_{I,SYS}(\omega) = 2eI$
- *unsymmetrized* noise : $S_I(\omega) \sim eI$

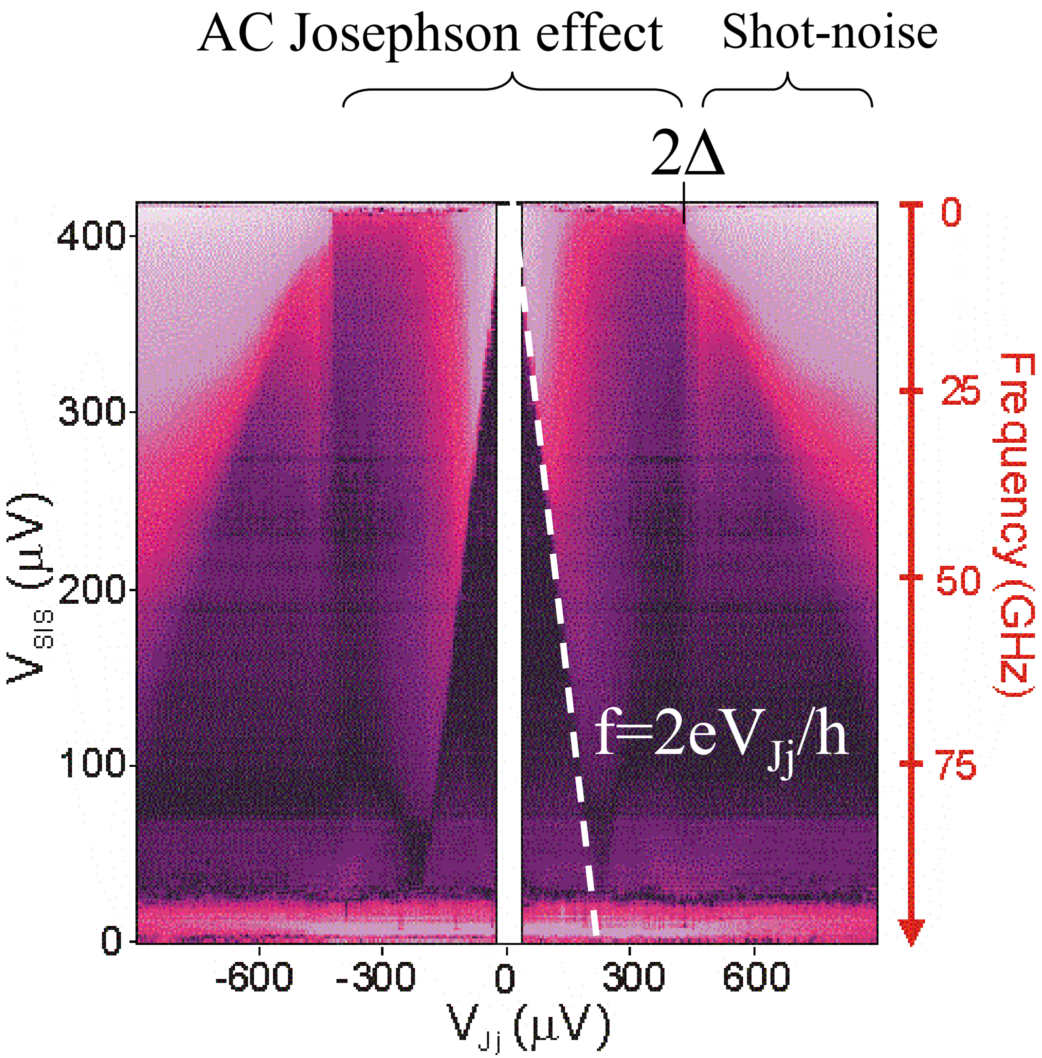
SIS detector



Calculation using (no fit parameter):

- $Z(\omega)$ determined with AC Josephson effect
- *non-symmetrized* value of noise : eI

Noise of a Josephson junction



Detection of :

-AC Josephson effect :

- frequency resolved detection up to 90 GHz
- detection of low power (100 fW)

-Shot-noise of quasi-particle current :

- detection of broad-band signal
- only emission ($\omega<0$)

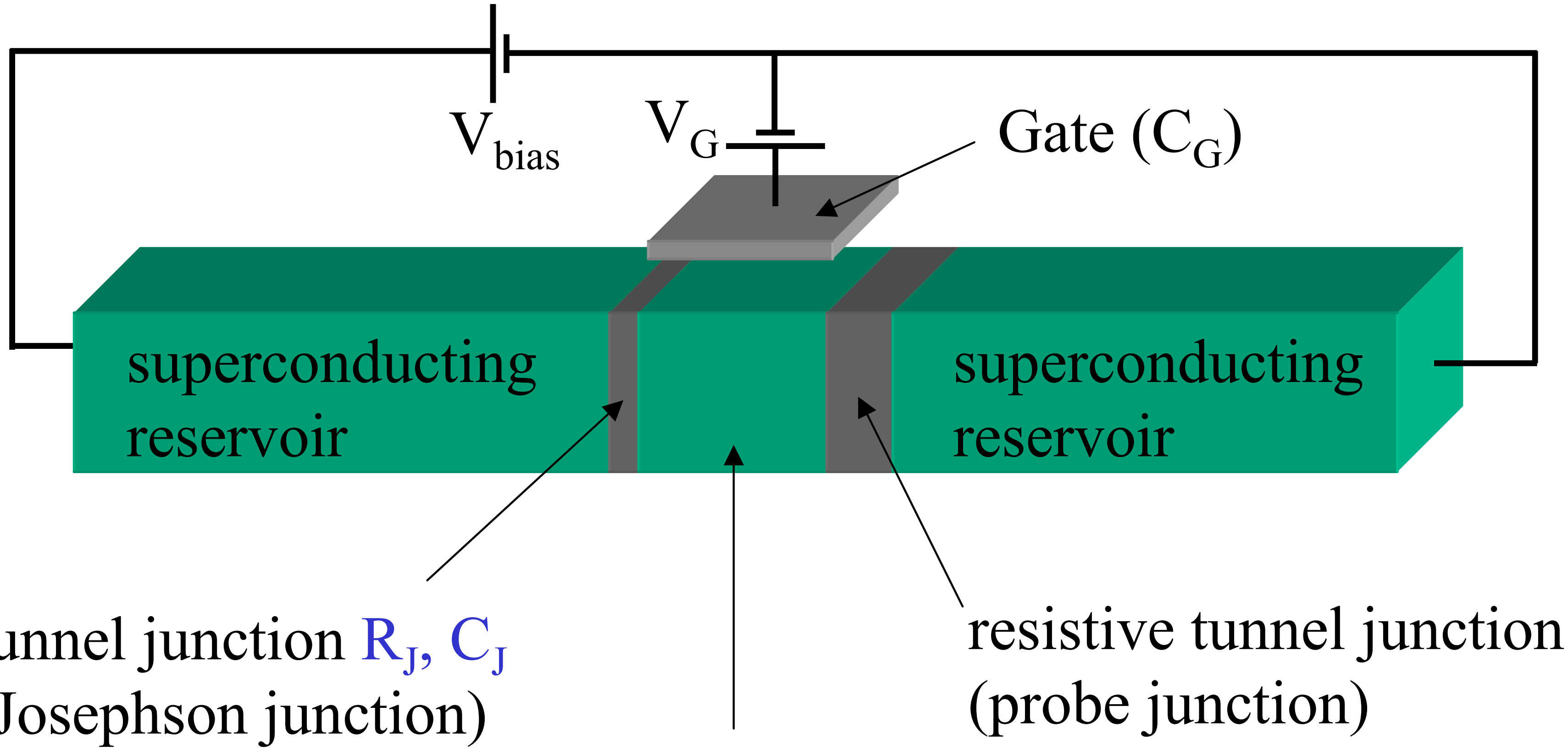
Conclusion for the Josephson junction

-AC Josephson effect :
- frequency resolved detection up to 90 GHz
- detection of low power (100 fW)
- determination of the transimpedance $Z(\omega)$

-Shot-noise of quasi-particle current :
- detection of broad-band signal
- detection of *non-symmetrized* noise : emission ($\omega<0$)

Detect high-frequency noise of other devices :
Noise of a superconducting single electron transistor

The cooper-pair box



tunnel junction R_J, C_J
(Josephson junction)

resistive tunnel junction R_P, C_P
(probe junction)

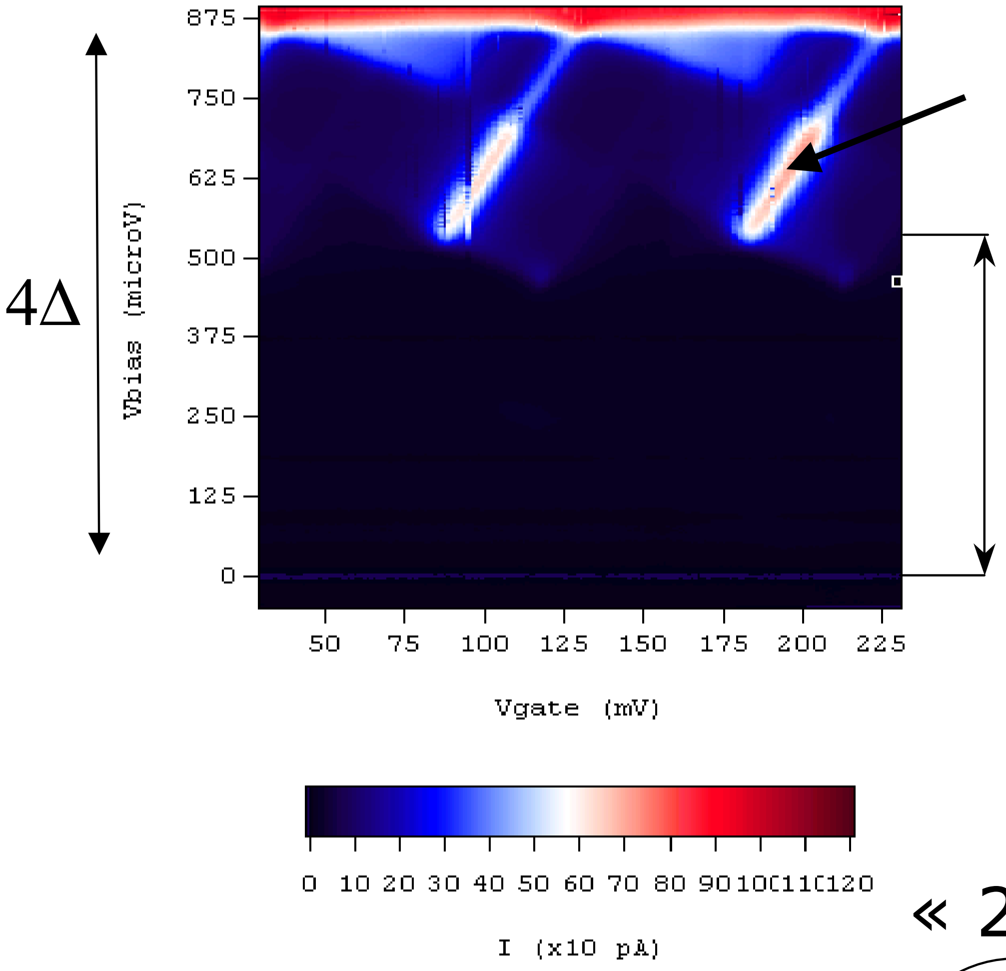
superconducting island

For $k_B T < E_c, \Delta$

$E_c = e^2/2\,C$ charging energy

- number of Cooper pairs on the island controlled by V_G
- quasiparticle tunneling suppressed by the superconducting gap Δ

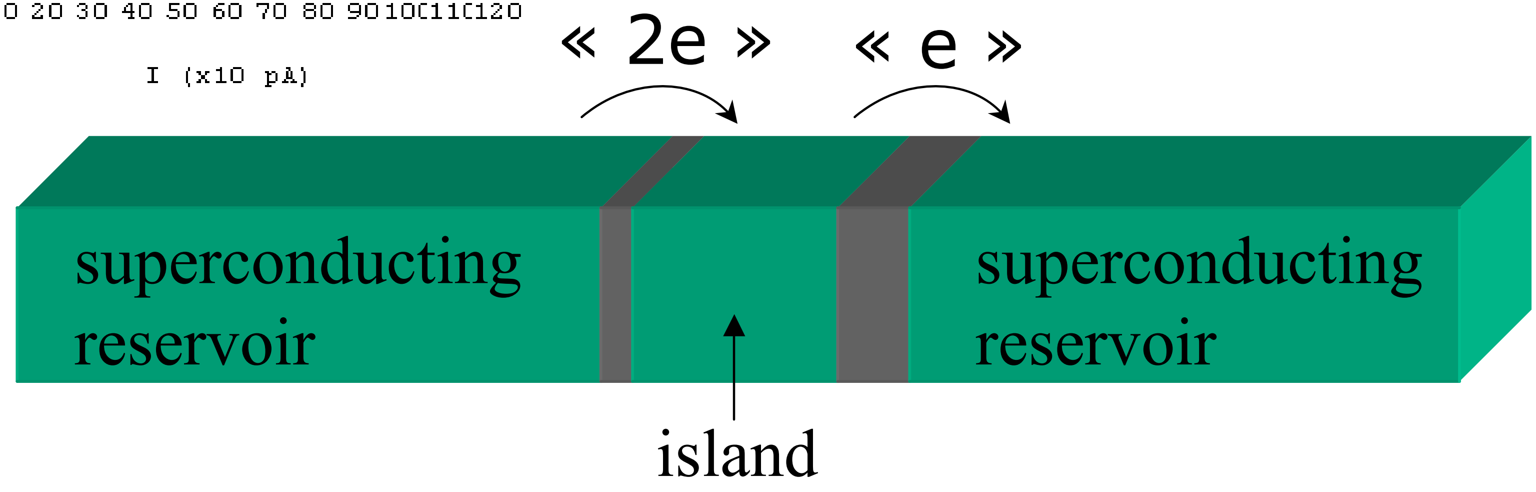
The Josephson-quasiparticle cycle



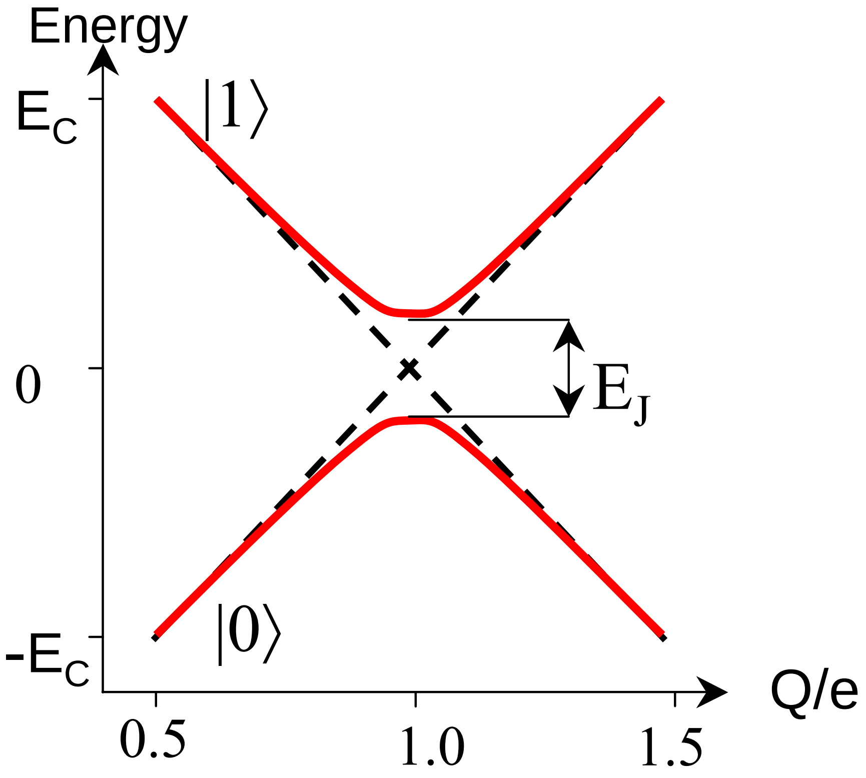
Josephson-quasiparticle peak

At the Josephson junction :
tunneling of Cooper pairs
(Josephson coupling E_J)

At the probe junction :
tunneling of quasiparticles
(rate Γ)



The Cooper pair box : a two-level system



|0> : N Cooper pairs
|1> : N+1 Cooper pairs

$$Q=C_GV_G$$

|1> can decay to |0> via quasiparticle tunneling at the probe junction

➡ Quasiparticle current ~ probability to be in |1>

(used as readout : Nakamura *et al.*, *Nature* (1999))

Cooper pair box coupled to the SIS detector

$E_c = 95\ \mu eV$

$E_J \approx 50\ \mu eV$

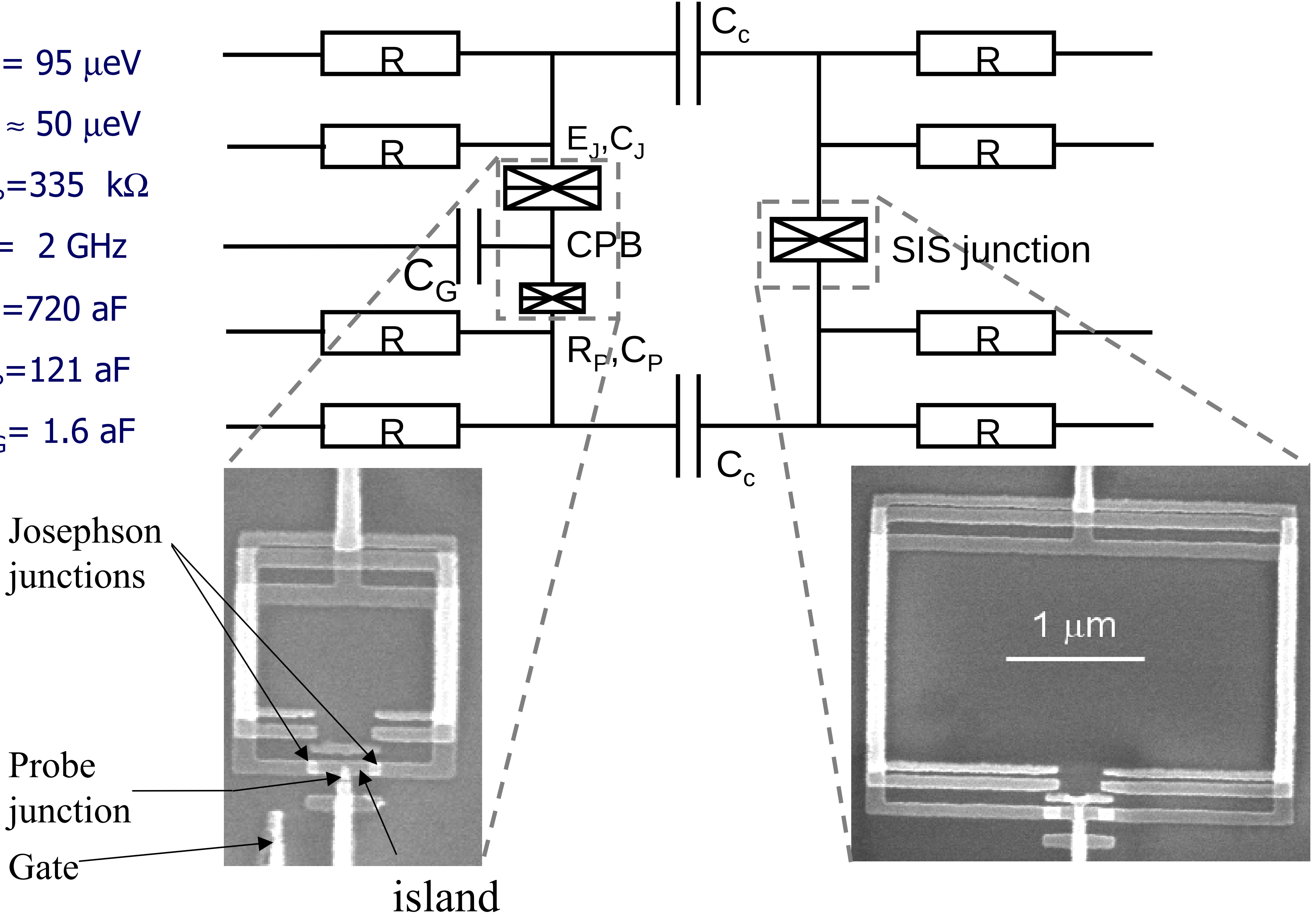
$R_P = 335\ k\Omega$

$\Gamma = 2\ GHz$

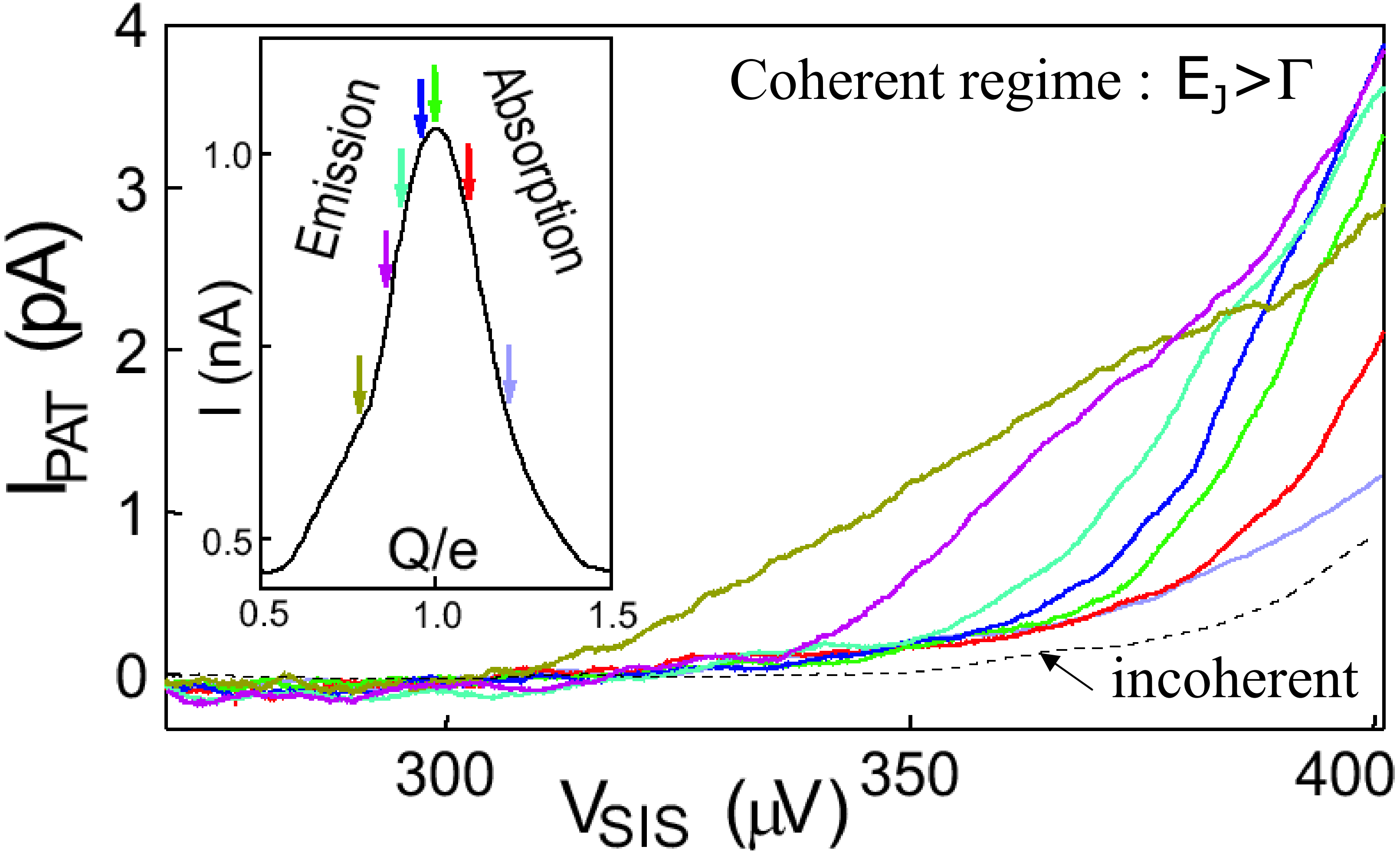
$C_J = 720\ aF$

$C_P = 121\ aF$

$C_G = 1.6\ aF$

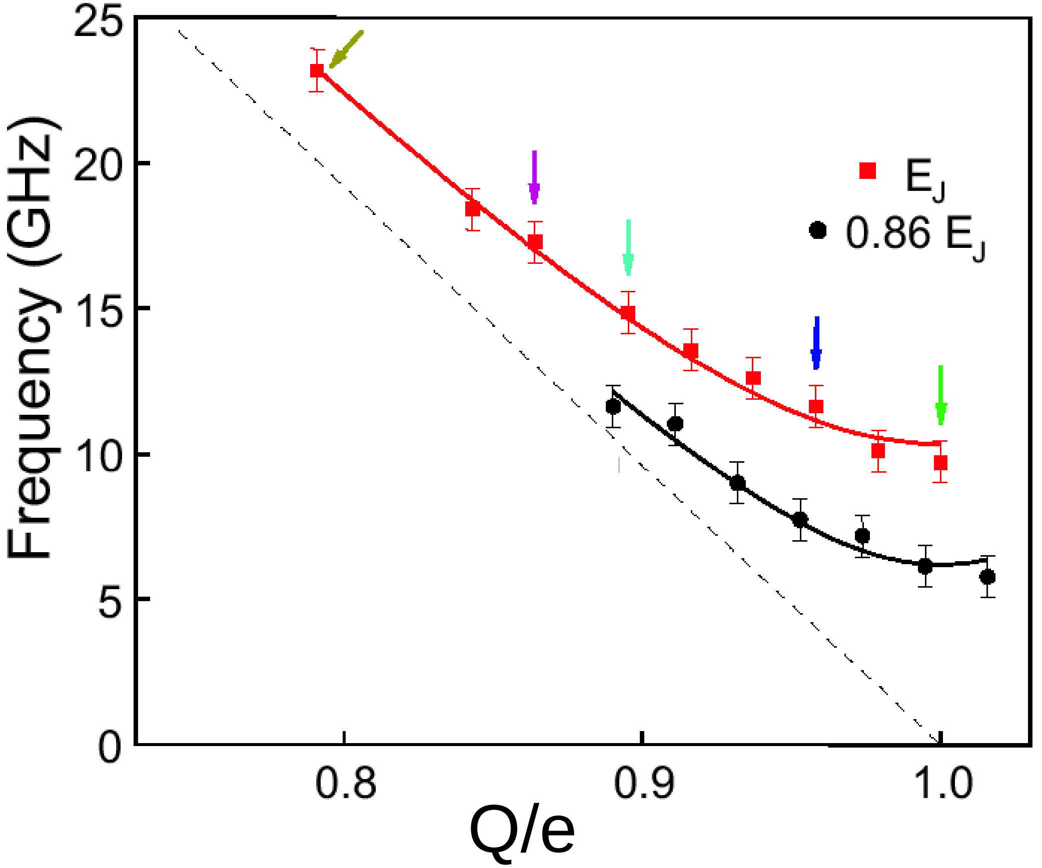


HF noise of the Cooper pair box



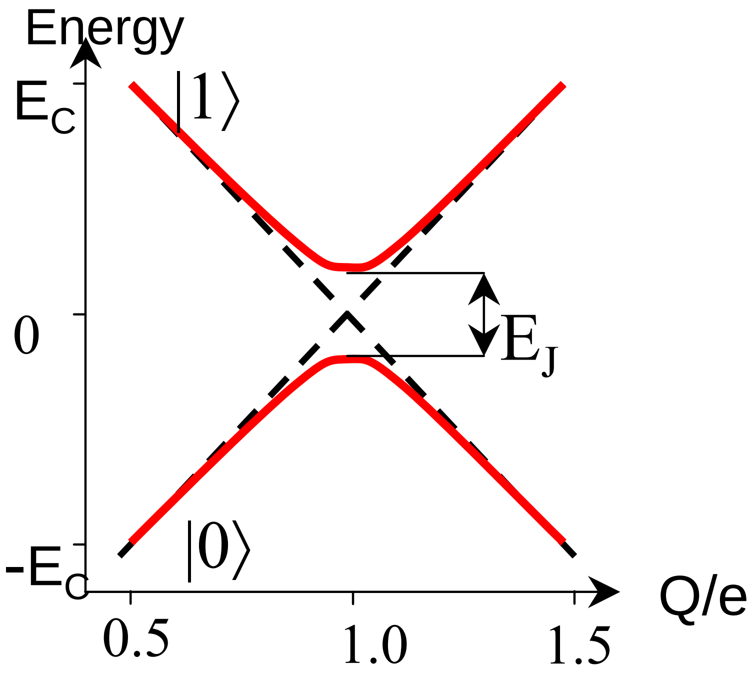
- asymmetry emission/absorption of the JQP
- increase of the dominant frequency for Q→0.5

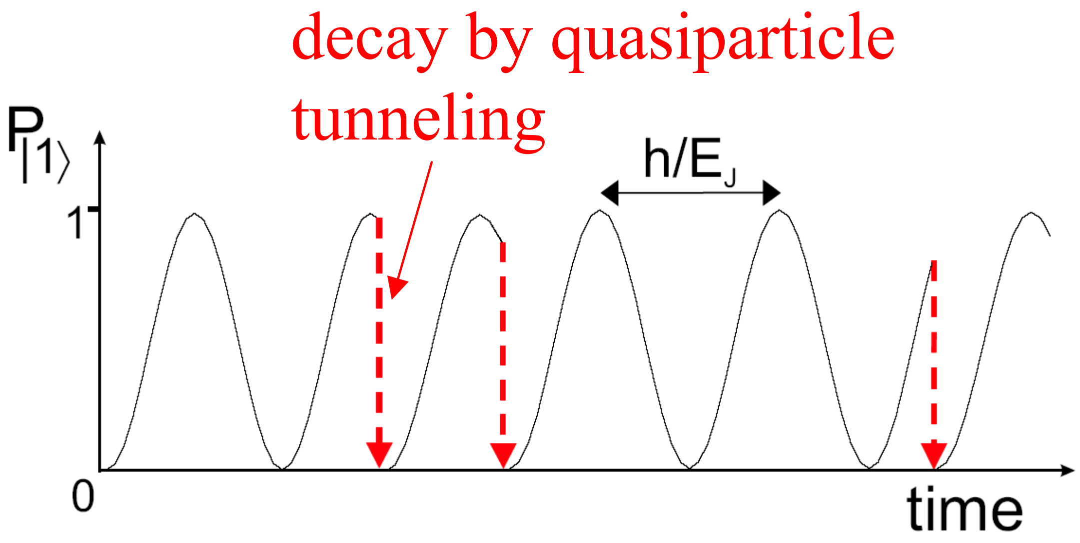
Emission of the Cooper pair box



- fit consistent with the splitting of energy level of the CPB (E_J=42 μeV, Ec=100 μeV)
- frequency decreases with E_J
- no effect in the incoherent regime ($E_J<\Gamma$)

Signature of coherent oscillations in the noise





Charge injection when $P_{|1>}$ is high

⇒ Charge injection at the frequency of coherent oscillations

Rem : - system driven out of equilibrium by DC bias
- disappear in the incoherent regime

Choi *et al.* PRL (2001), PRB (2002)

Conclusions

the SIS detector :

- high-frequency detection (5-90 GHz)
- frequency resolved detection
- sensitive to non-symmetrized noise (emission)

signature of coherent oscillations of a two-level system in the current fluctuations

Science (2003)

Perspectives :

- applicable to a wide range of electronic devices
- higher frequencies (Nb : ~ THz)