

Quantum dynamics in a dcSQUID:

From a phase qubit to a 2D quantum oscillator

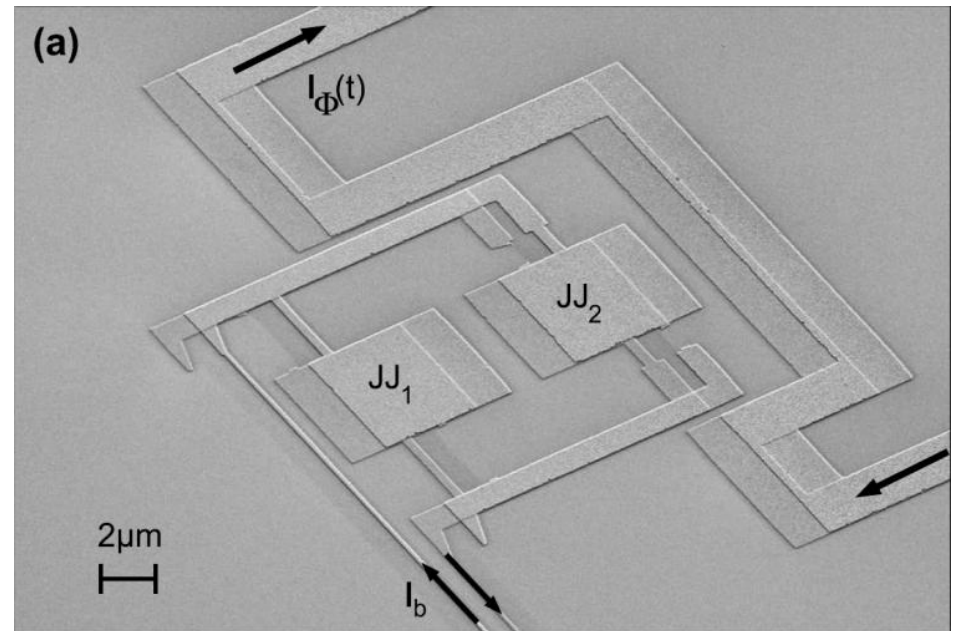
Florent LECOCQ

11 mai 2011

Soutenance de thèse pour
obtenir le titre de Docteur de
l'Université de Grenoble

Directeur de thèse :

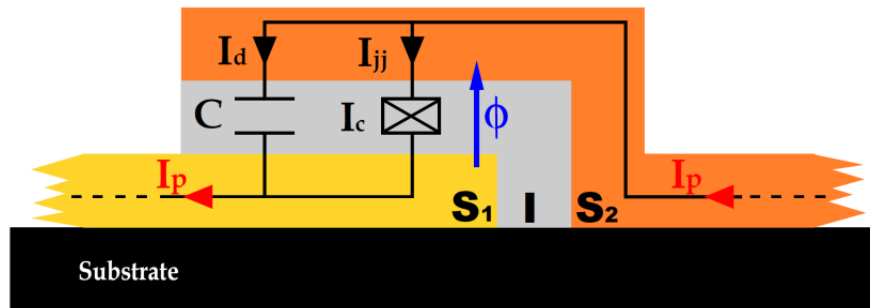
Olivier BUISSON



Quantum integrated circuits

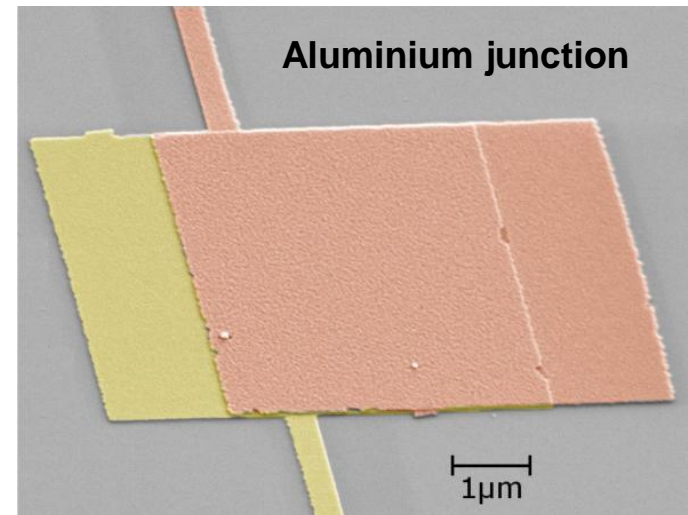
- **Ultra-low dissipation** : superconductivity
- **Ultra-low noise** : low temperature
- **Non-linear, non-dissipative element** : Josephson junction

Josephson junction based electronics and superconducting qubits



$$E_J = \frac{\Phi_0}{2\pi} I_c$$

$$E_C = \frac{(2e)^2}{2C}$$



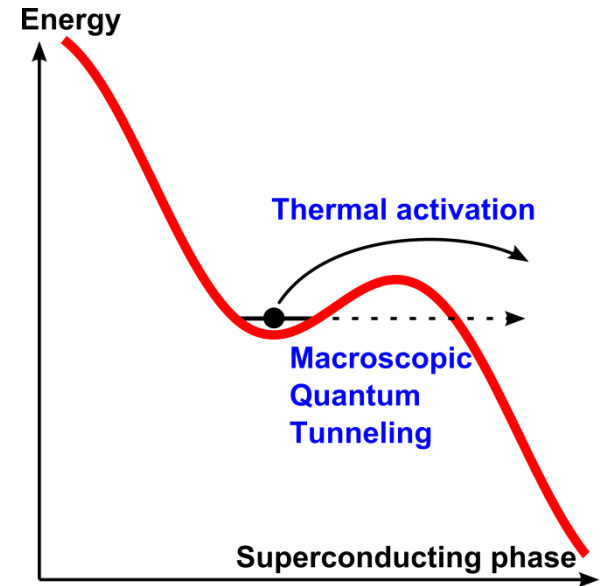
Macroscopic quantum effects...

Voss *et al*, PRL (1981)

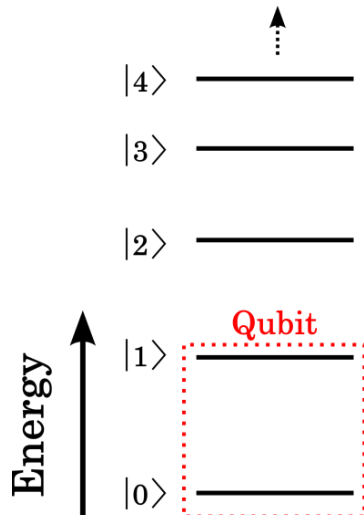
Devoret *et al*, PRL (1985)

... and quantized energy levels (microwave frequency regime)

Martinis *et al*, PRL (1985)



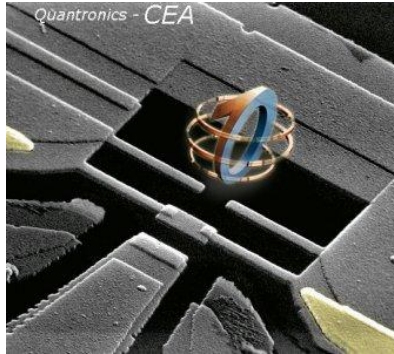
An artificial atom controlled by electronics signals



- Non-linear quantum oscillator
- Superconducting qubit

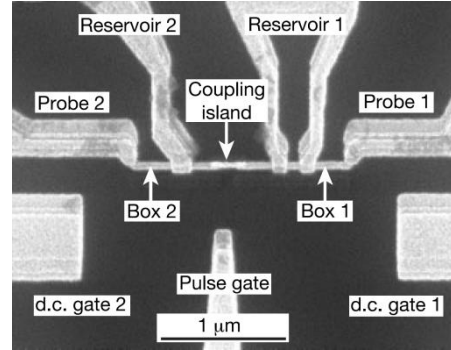
Nakamura *et al*, Nature (1999)

Engineering quantum mechanics



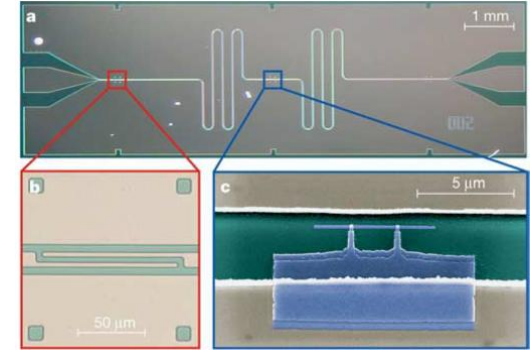
Vion et al, Science (2002)

- Coherence
- Optimal point



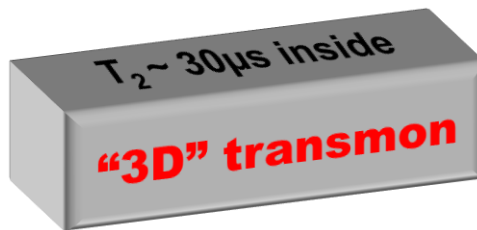
Pashkin et al, Nature (2003)

- Coupling
- Gates
- Algorithm

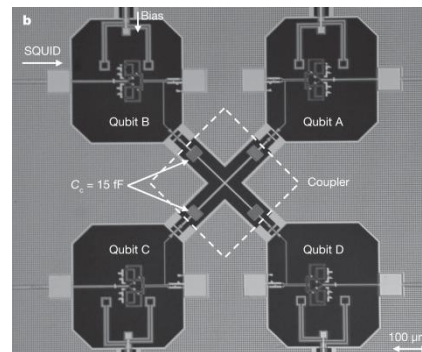


Wallraff et al, Nature (2004)

- Readout
- Memory
- Bus

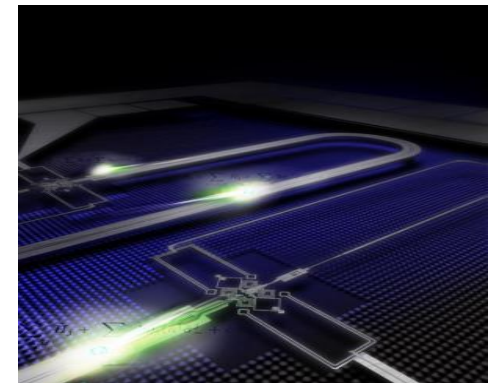


Yale, APS Meeting (2011)



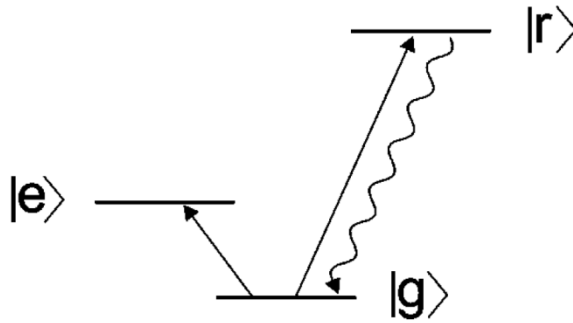
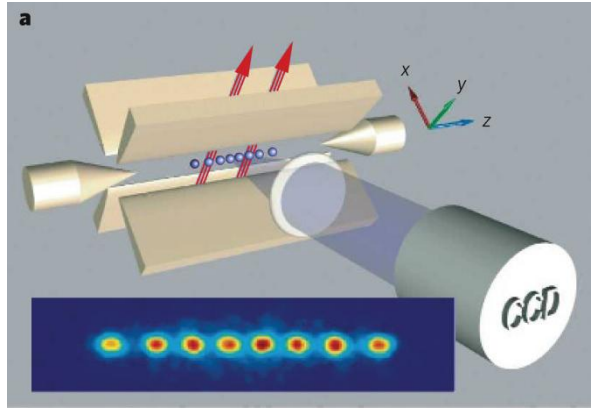
Neelley et al, Nature (2010)

DiCarlo et al, Nature (2010)



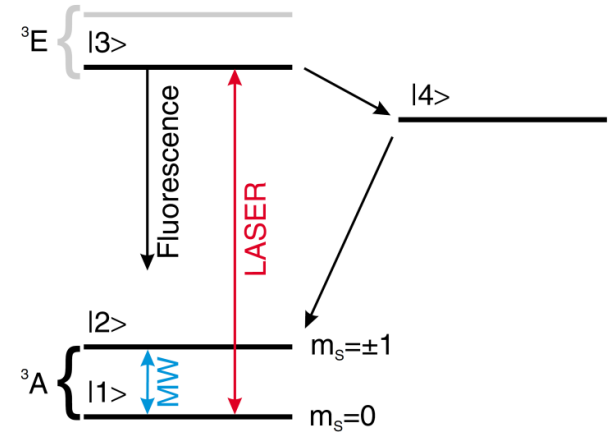
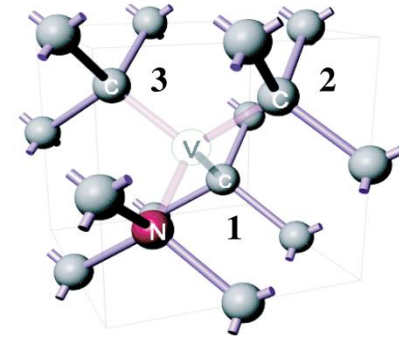
Sillanpaa et al, Nature (2007)

Trapped ion



Leibfried, *Rev.Mod.Phys* (2003)
Blatt and Wineland, *Nature* (2008)

NV centers in diamond



Jelezko et al, *PRL* (2004)

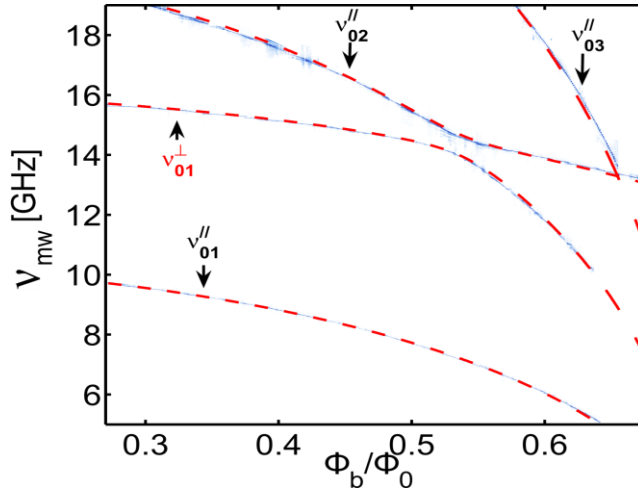
High fidelity readout & Electromagnetically Induced Transparency

**Superconducting artificial atom
with multiple degrees of freedom ?**

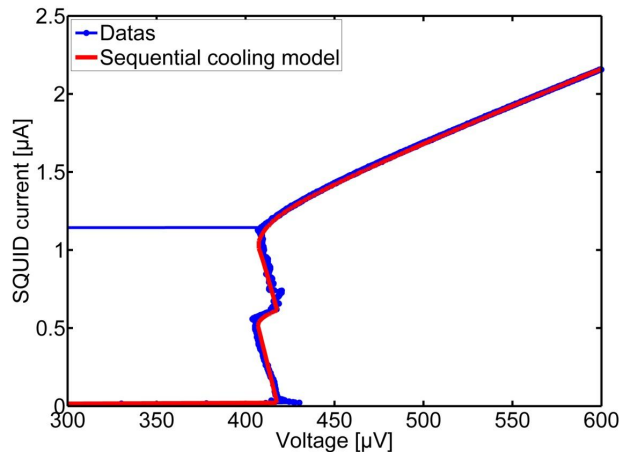
1. Quantum dynamics in a dcSQUID

2. Bridge-Free Nanofabrication Technique

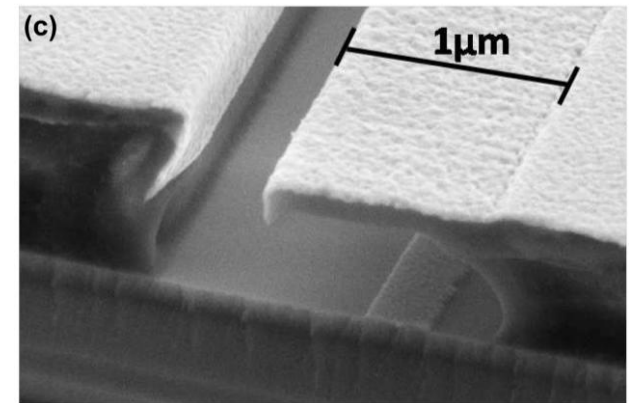
3. Sequential junction cooling in dcSQUID



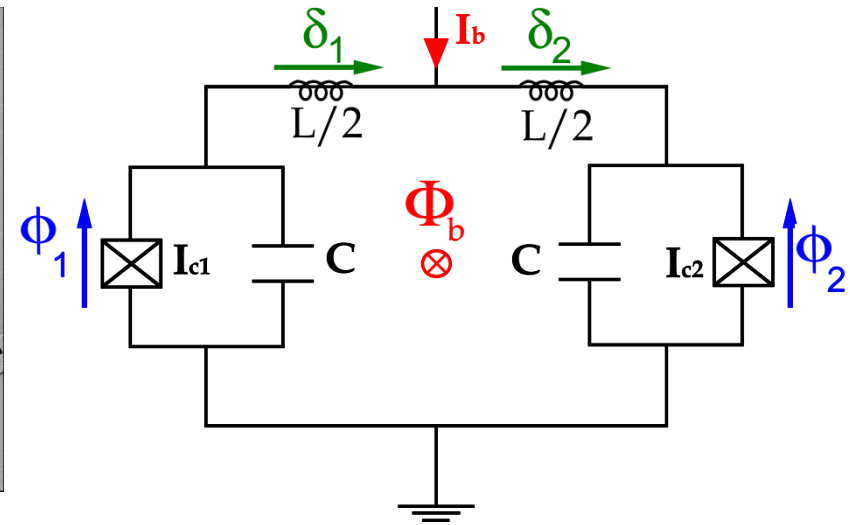
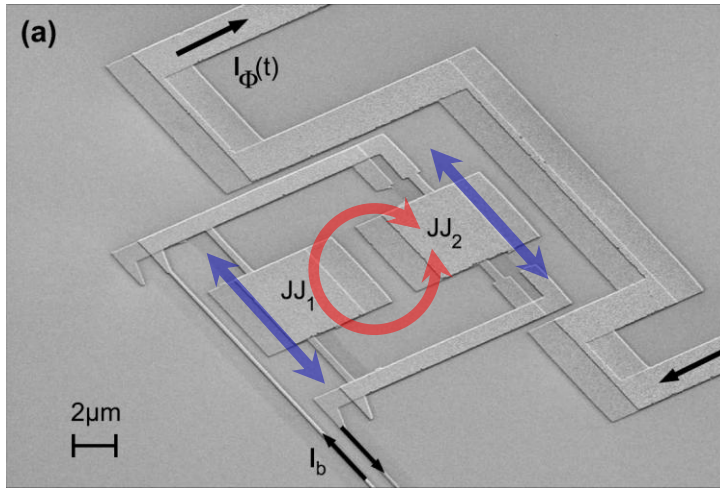
Part 2 Nano-Fabrication: Bridge-Free Technique



Part 1 Quantum dynamics in a dcSQUID From a phase Qubit to a 2D oscillator



Part 3 Sequential junction cooling in a dcSQUID



1. Quantum dynamics in a dcSQUID

- Th description

- Spectroscopy

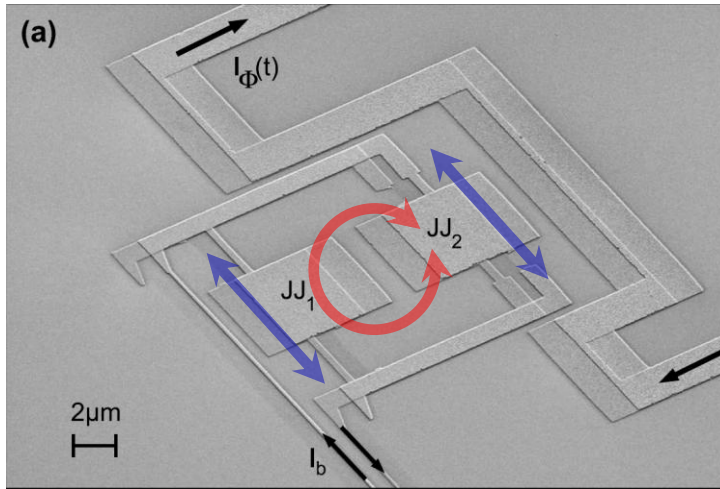
- Coherent control

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

$$U(\mathbf{x}, \mathbf{y}) = U_0 \left[-\cos x \cos y + b \left(y - \pi \frac{\Phi_b}{\Phi_0} \right)^2 \right] \quad \text{where} \quad \left\{ \begin{array}{l} x = \frac{\phi_1 + \phi_2}{2} \end{array} \right.$$

$$b = \frac{L_J}{L} = \frac{\Phi_0}{2\pi L I_c}$$



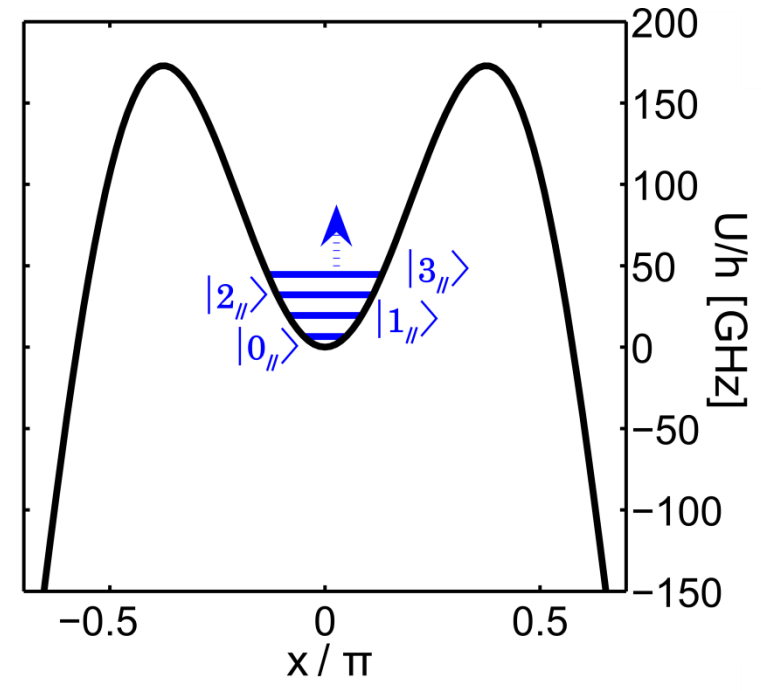
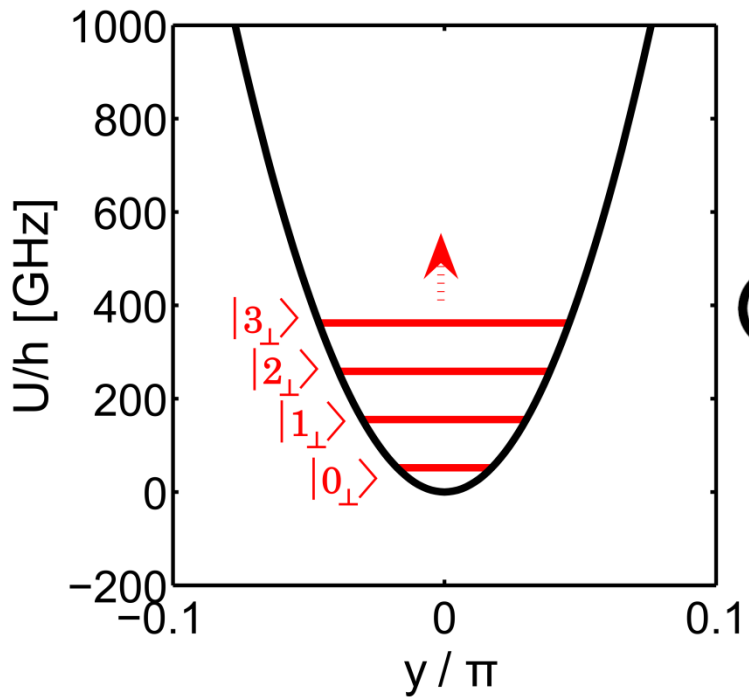
$$U(x, y) = U_0 \left[-\cos x \cos y + b \left(y - \pi \frac{\Phi_b}{\Phi_0} \right)^2 \right]$$



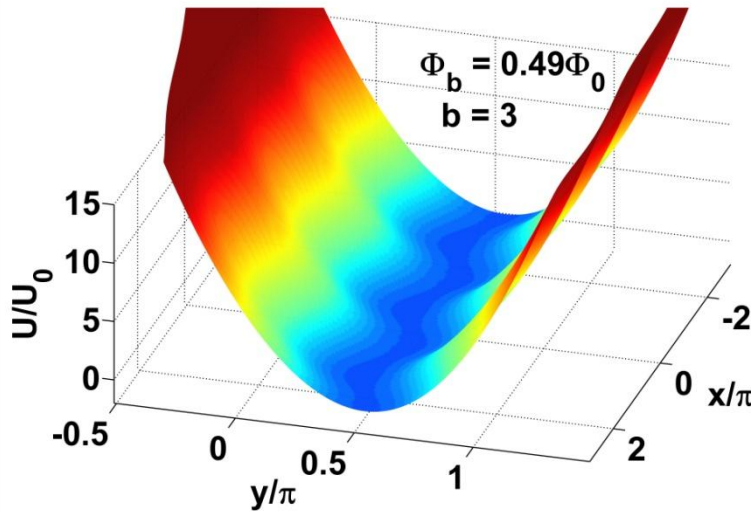
$$\hat{H}_{2D} = \hat{H}_{\parallel} \quad \hat{H}_{\perp}$$

$$\hat{C}_{\parallel\perp} = h\nu_{21}^c \hat{X}^2 \hat{Y} + h\nu_{12}^c \hat{X} \hat{Y}^2 + h\nu_{22}^c \hat{X}^2 \hat{Y}^2$$

- 1. Quantum dynamics in a dcSQUID
- Th description
- Spectroscopy
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- 2. Bridge-Free Nanofabrication Technique
- 3. Sequential junction cooling in dcSQUID



$L < L_{\text{Josephson}}$



Hoskinson, Lecocq et al, PRL (2009)



Circuit insensitive to current noise @ zero current bias

Transverse mode high in energy

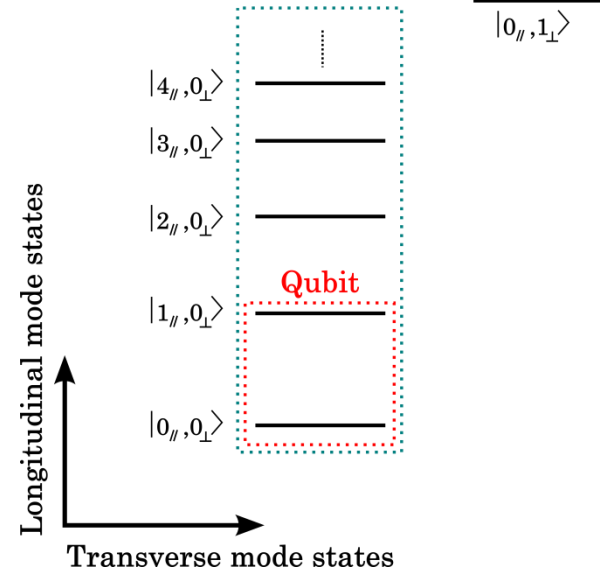


Considered in the ground state



1D dynamics

Quantum anharmonic oscillator



F. Lecocq

Ph.D. Defense
May 11th 2011

1. Quantum dynamics in a dcSQUID

- Th description

- Spectroscopy

- Coherent control

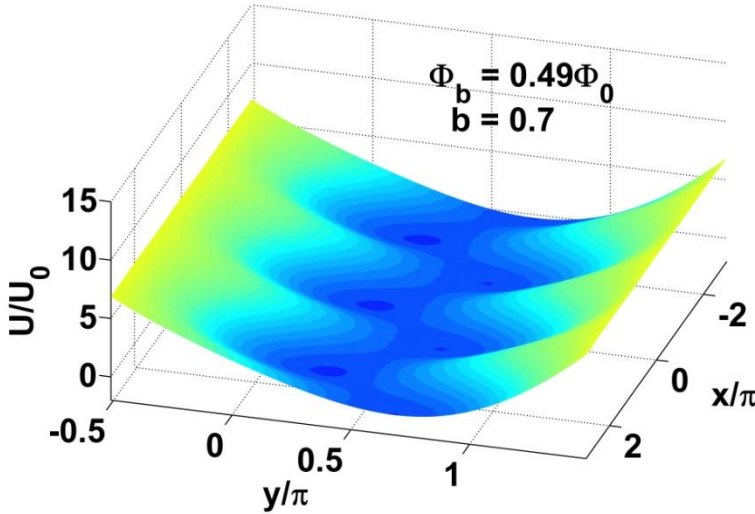
2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

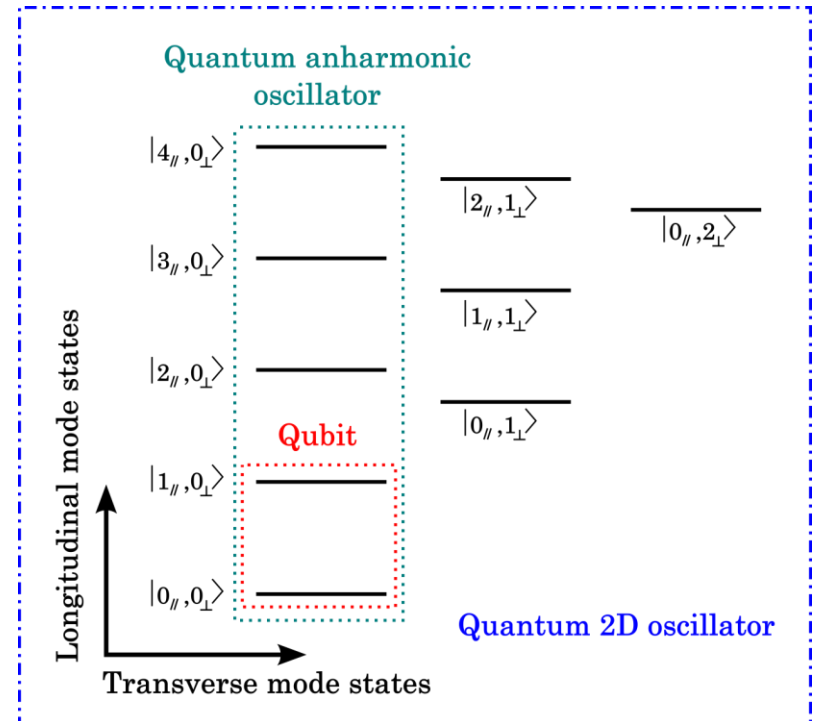
$L > L_{\text{josephson}}$

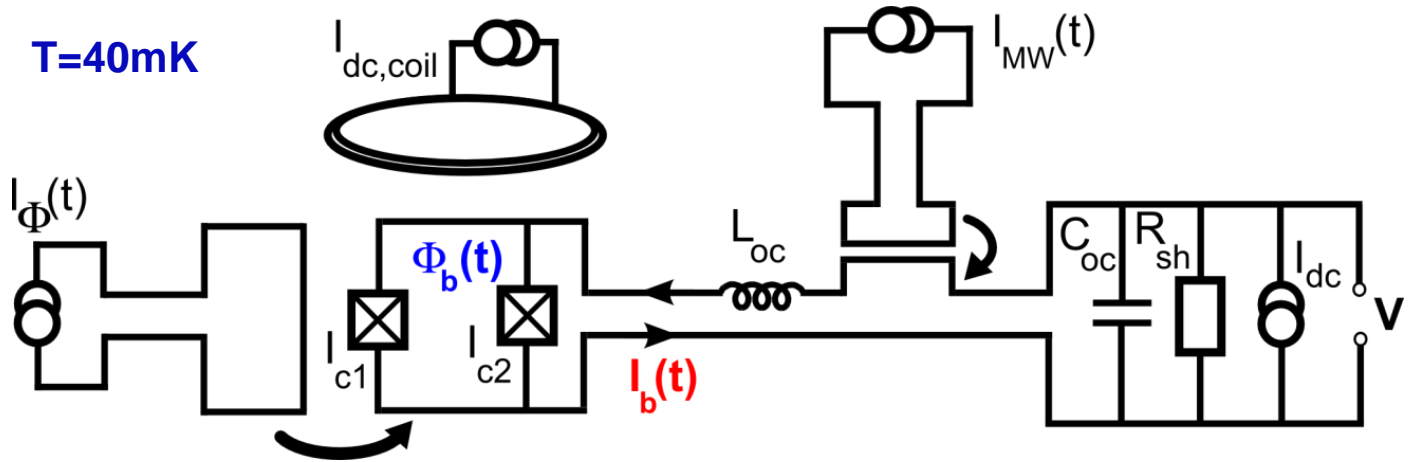


Transverse mode energy decreased



dcSQUID
+
large loop inductance
=
2D oscillator





1. Quantum dynamics in a dcSQUID

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- Coherent control

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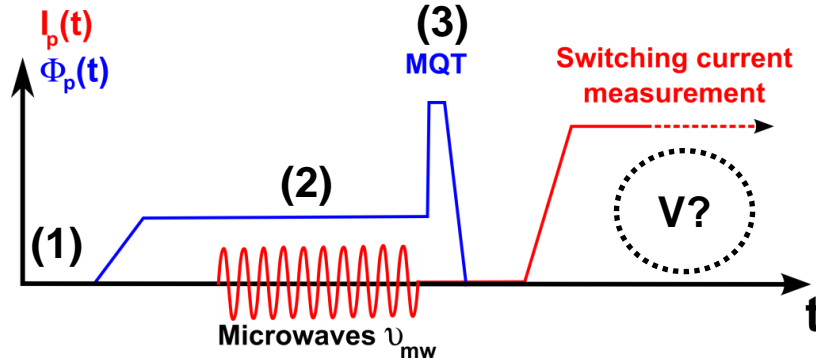
3. Sequential junction cooling in dcSQUID

Critical current per JJ	$0.713 \mu\text{A}$
Capacitance per JJ	510 fF
loop inductance	629.8 pH
JJ's surface	$10 \mu\text{m}^2$
SQUID's surface	$900 \mu\text{m}^2$

$$b = \frac{L_J}{L} = 0.733$$

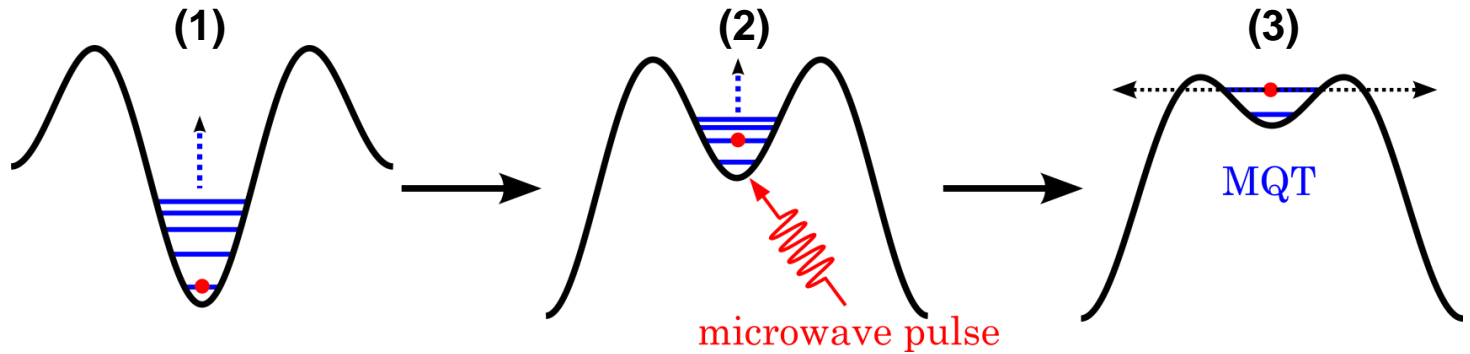
$$E_J = 17\text{K}$$

$$E_C = 7\text{mK}$$

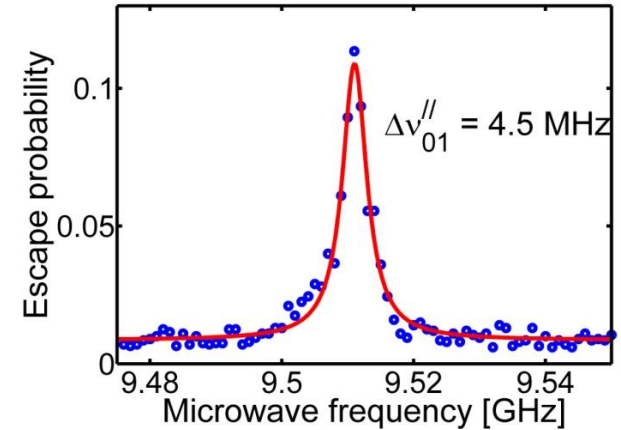


Nanosecond flux pulse and switching current measurement

Hoskinson, Lecocq et al, *PRL* (2009)



The probability of escape increases when the system is excited



F. Lecocq

Ph.D. Defense
May 11th 2011

1. Quantum dynamics in a dcSQUID

-Th description

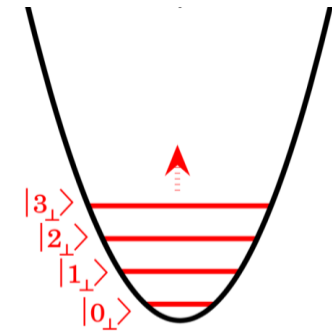
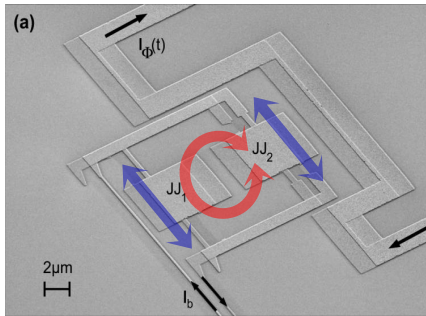
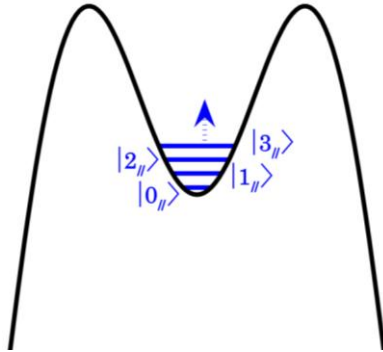
- Spectroscopy

- Coherent control

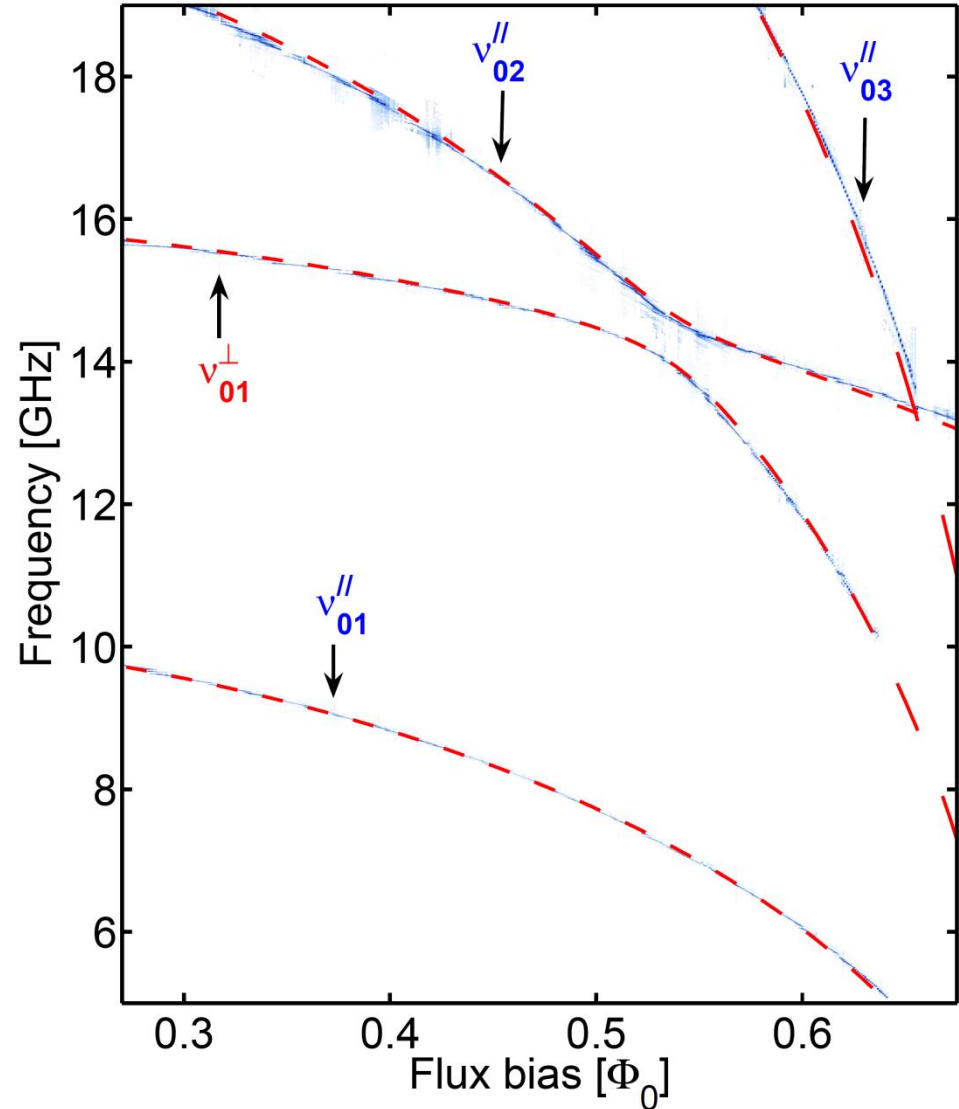
2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

Longitudinal mode



Transverse mode



Large anti-crossing at the resonance between ν_{02}^{\parallel} and ν_{01}^{\perp}

Non linear coupling

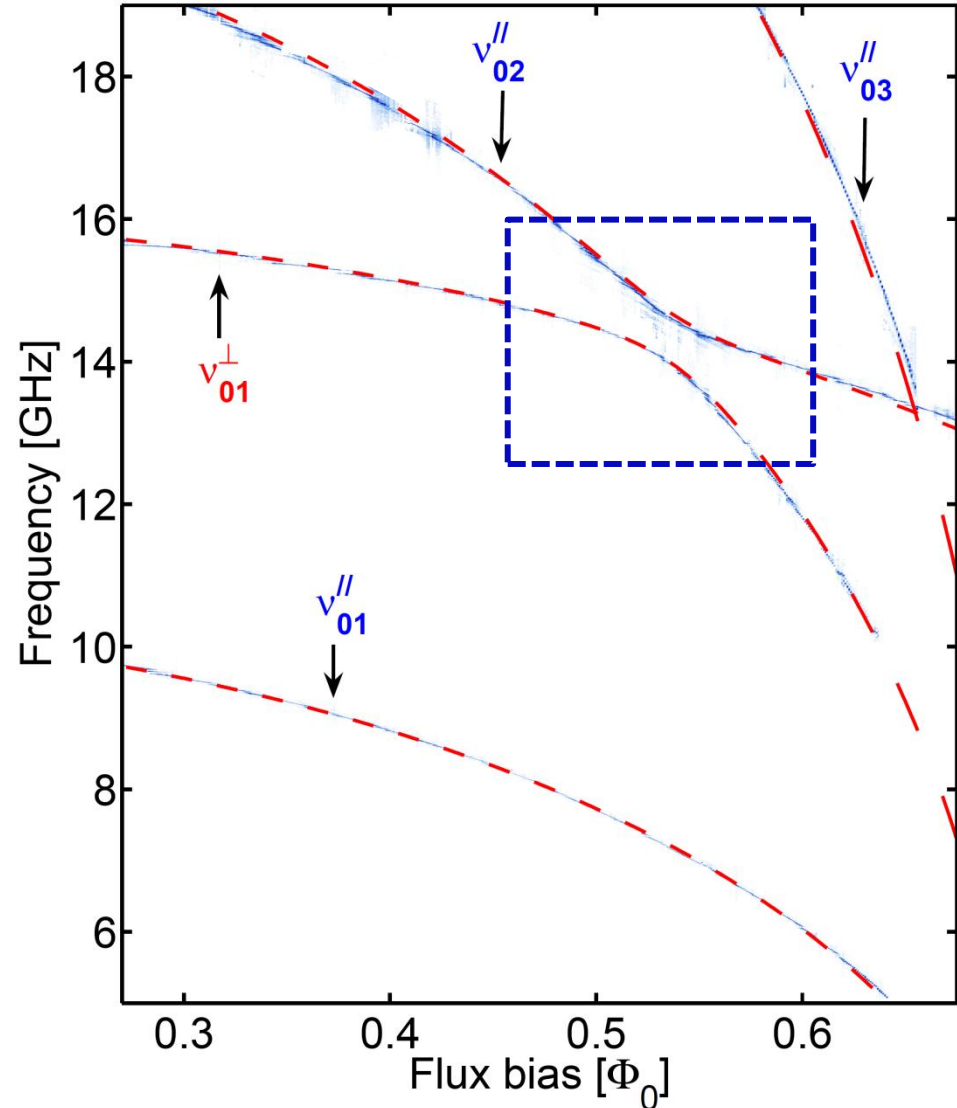
$$\hat{C}_{\parallel\perp} = h\nu_{21}^c \hat{X}_{\parallel}^2 \hat{Y}_{\perp}$$

Also discussed in quantum optics and ion traps

Bertet et al, PRL (2002)
Vogel and Dematos, PRA (1995)

Strong coupling regime

$$\nu_{21}^c = 700\text{MHz}$$



1. Quantum dynamics in a dcSQUID

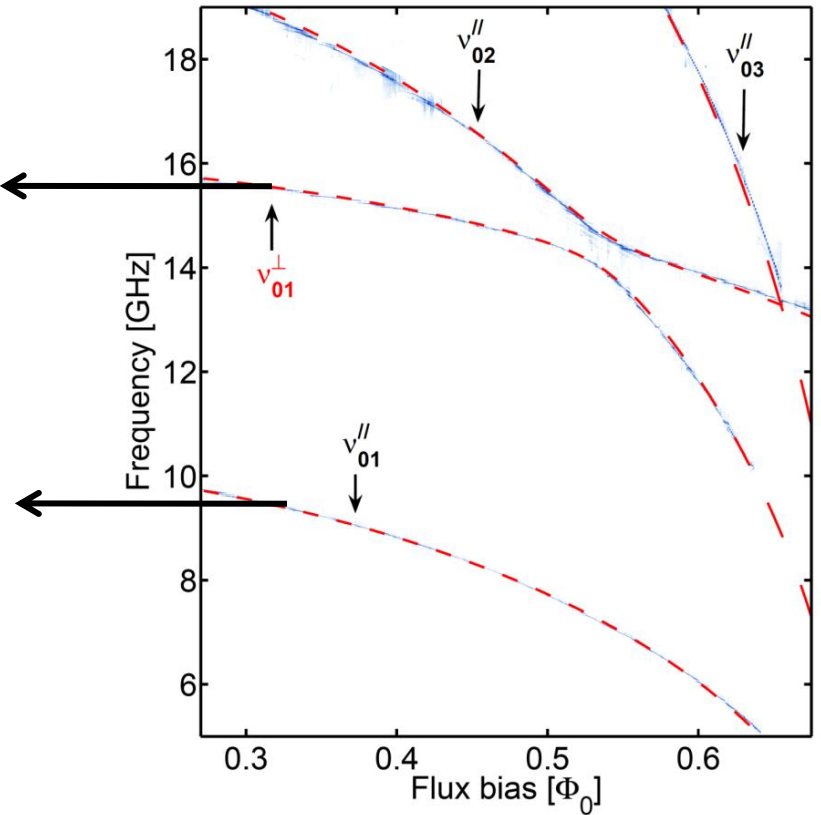
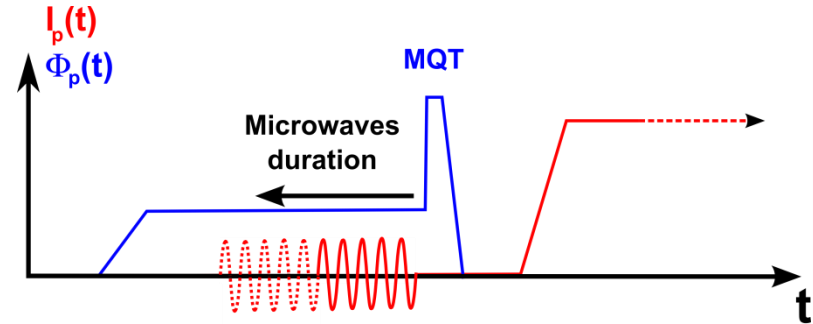
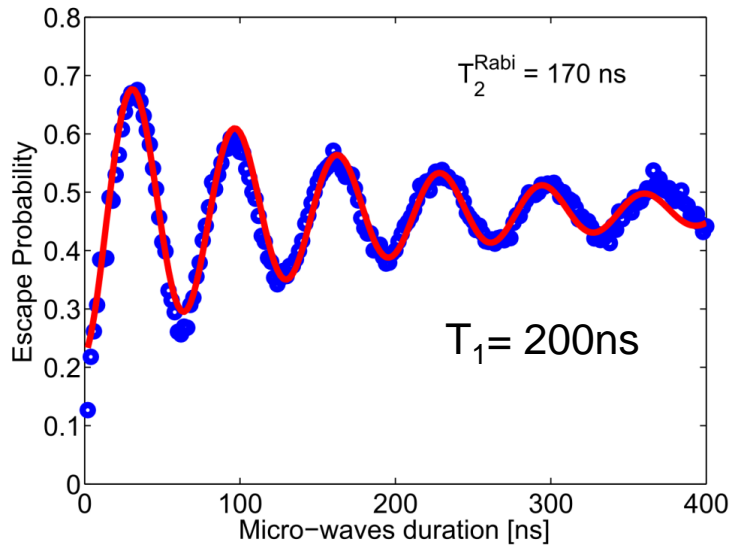
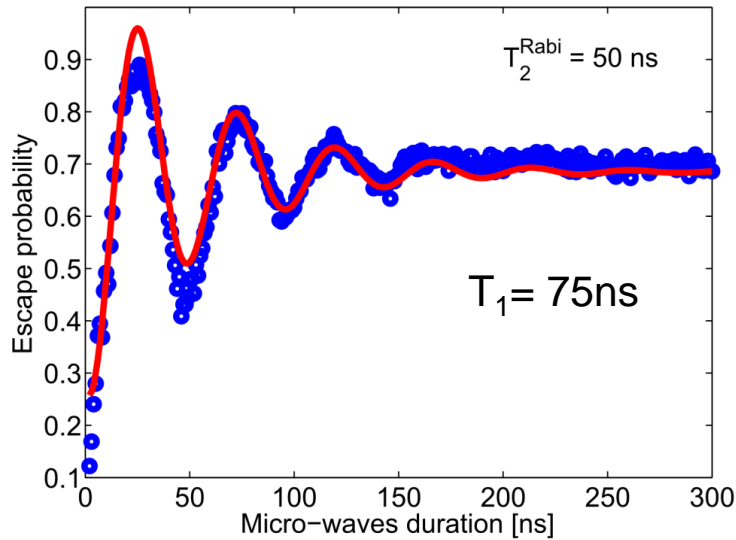
-Th description

- Spectroscopy

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2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID





F. Lecocq

Ph.D. Defense
May 11th 2011

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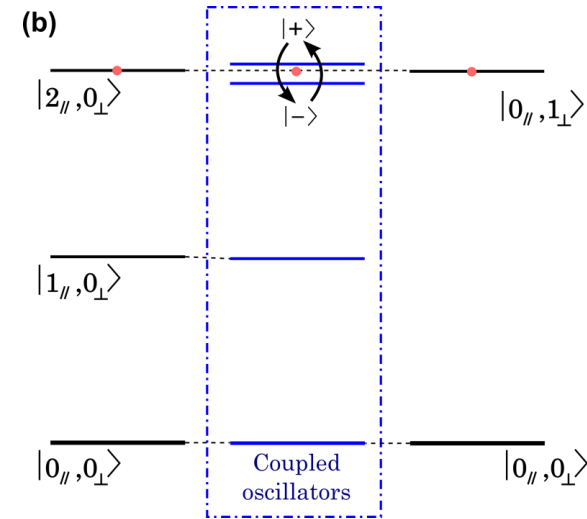
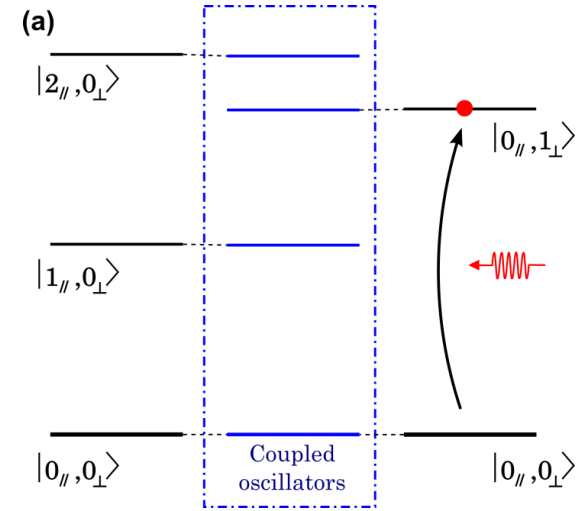
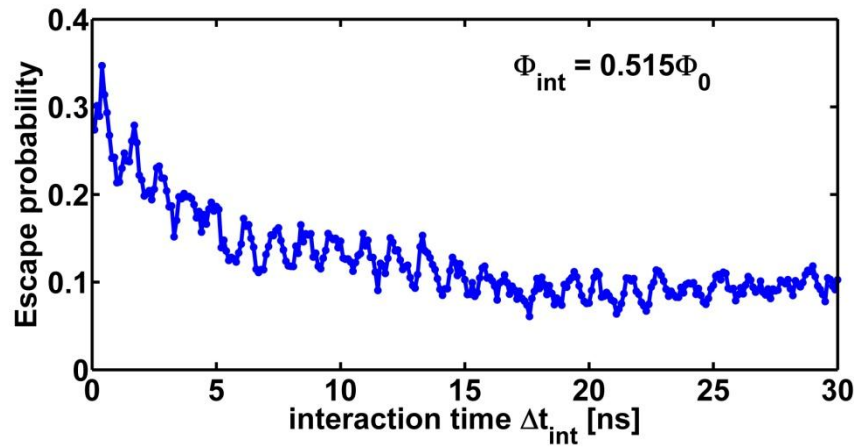
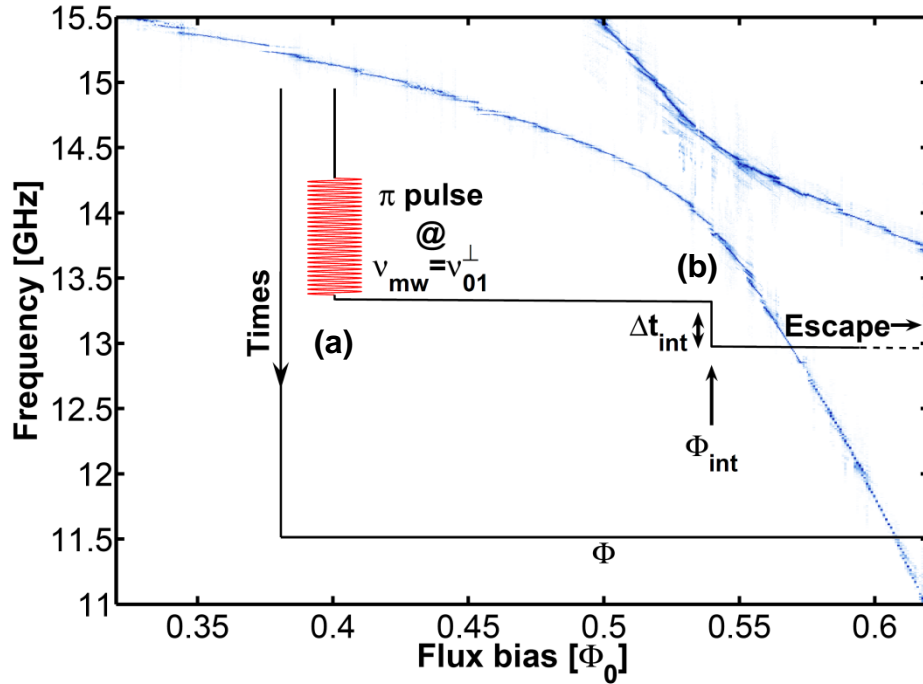
-Th description

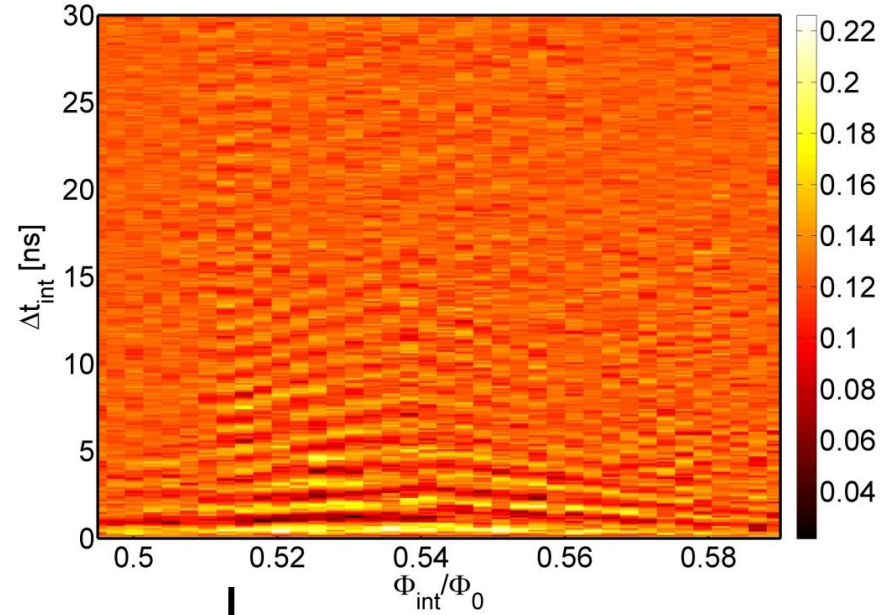
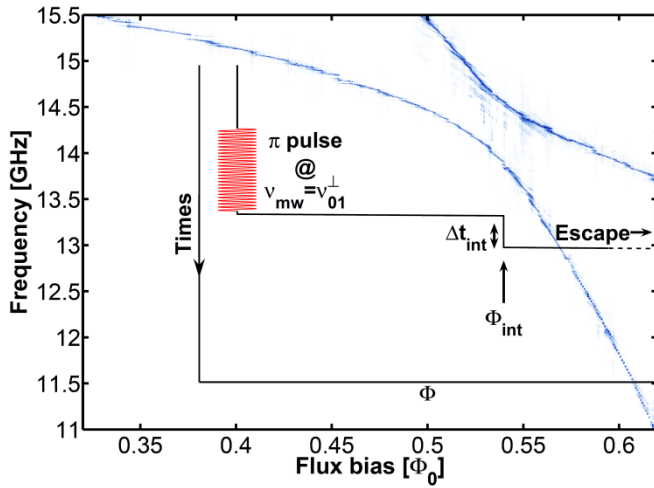
- Spectroscopy

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2. Bridge-Free Nanofabrication Technique

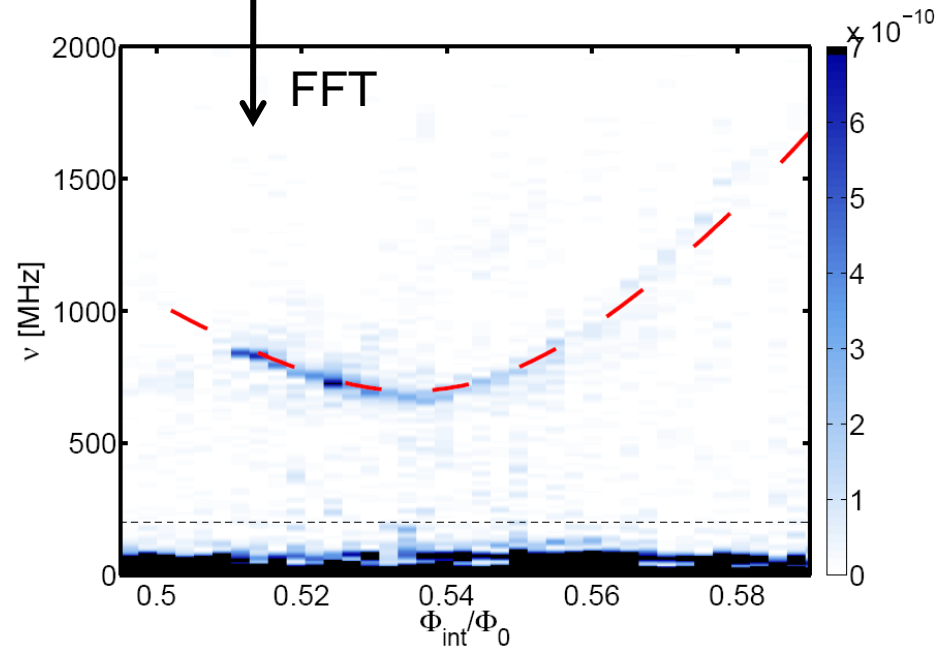
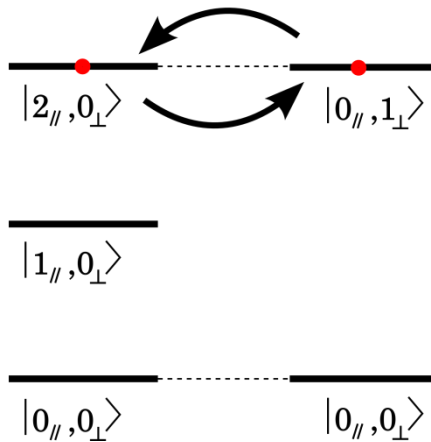
3. Sequential junction cooling in dcSQUID





Coherent exchange of quanta between the modes

Frequency conversion back and forth



1. Quantum dynamics in a dcSQUID

- Th description

- Spectroscopy

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3. Sequential junction cooling in dcSQUID

1. Quantum dynamics in a dcSQUID

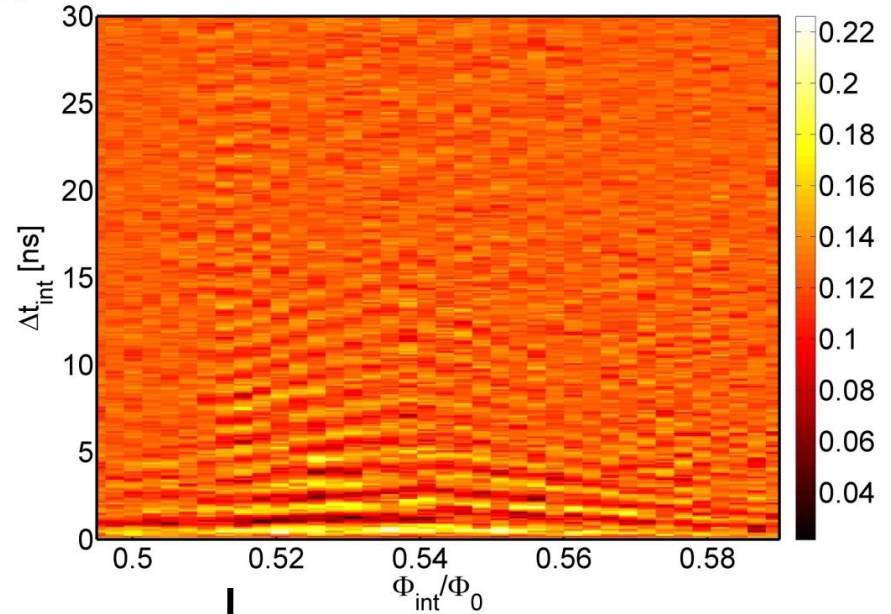
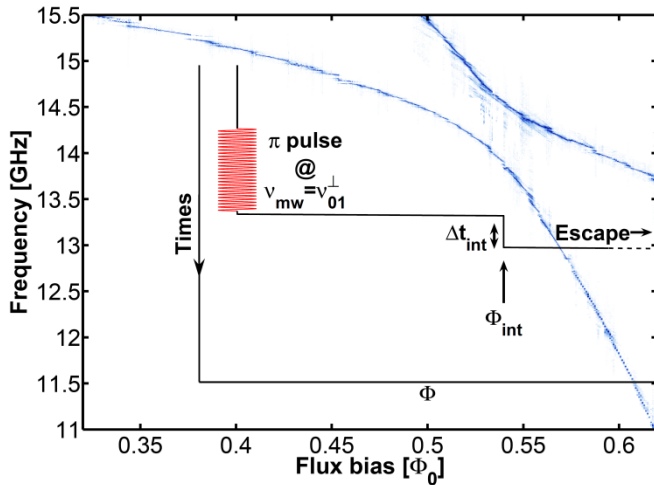
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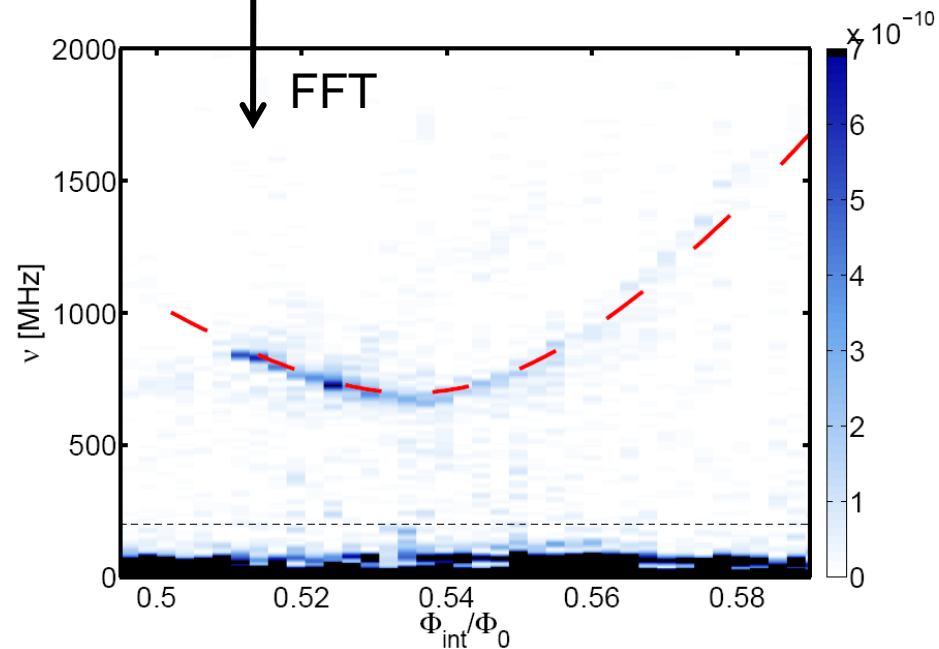
Low contrast :

Slow microwave π pulse

Readout

Non perfect adiabatic flux pulse

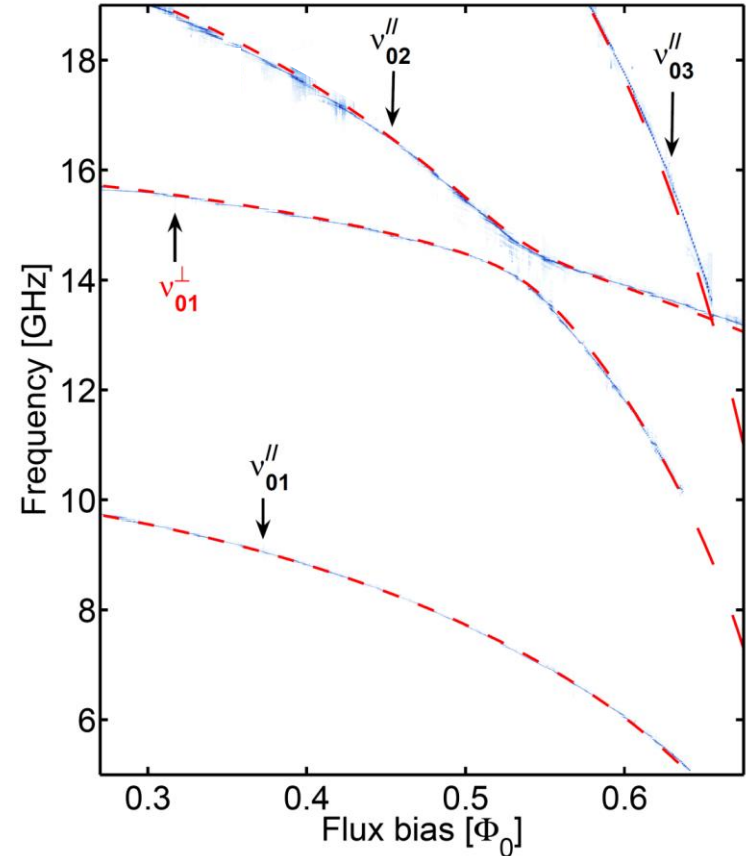
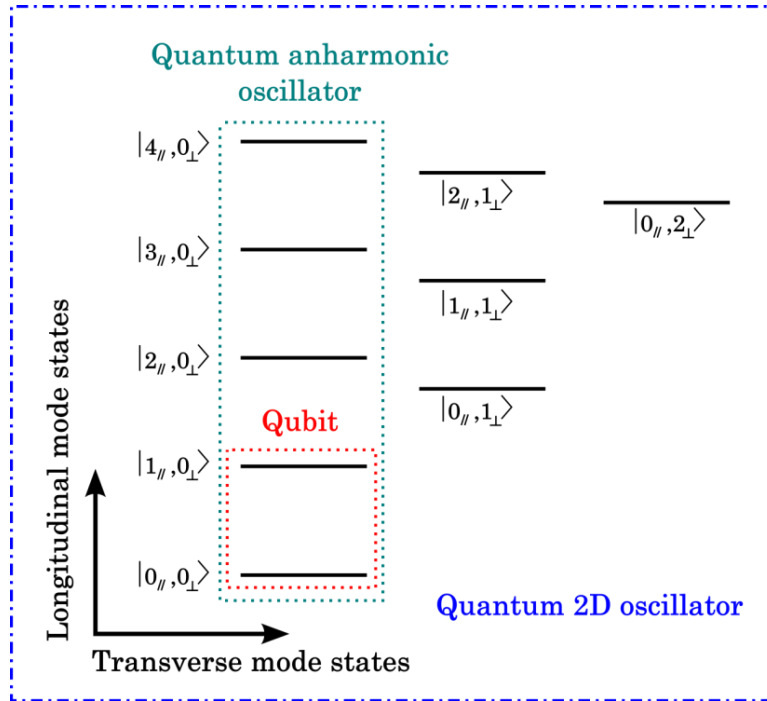
Parasitic TLS



1. Quantum dynamics in a dcSQUID

2. Bridge-Free Nanofabrication Technique

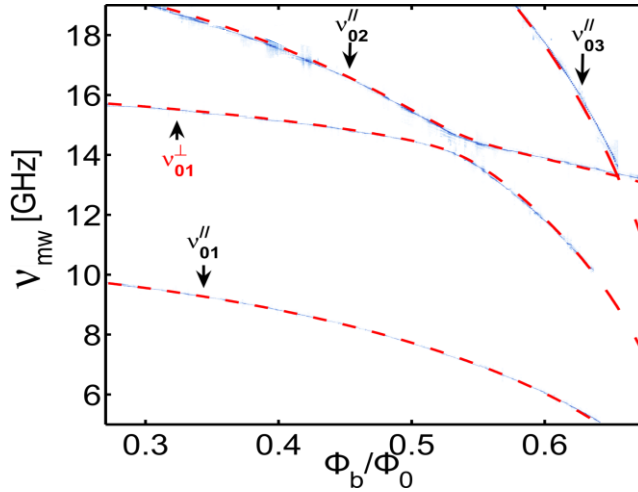
3. Sequential junction cooling in dcSQUID



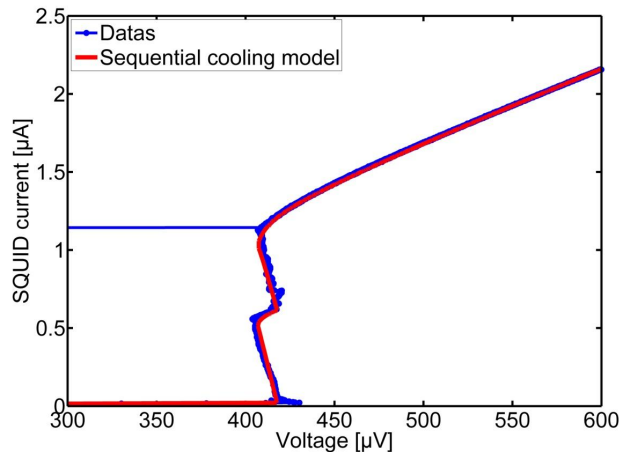
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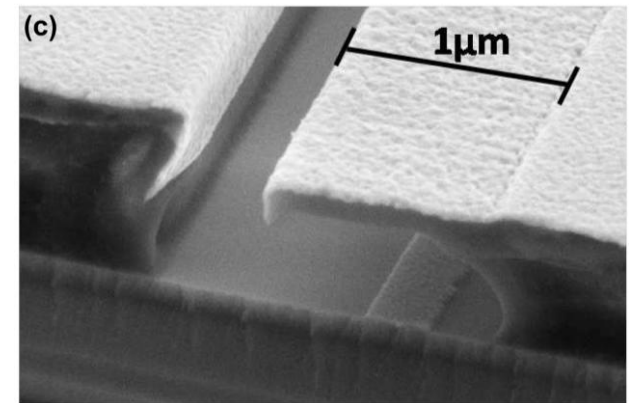


Part 2 Nano-Fabrication: Bridge-Free Technique



Part 1

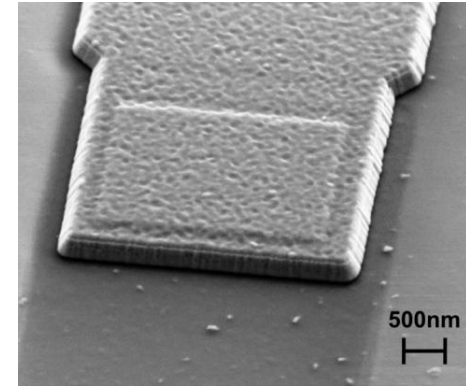
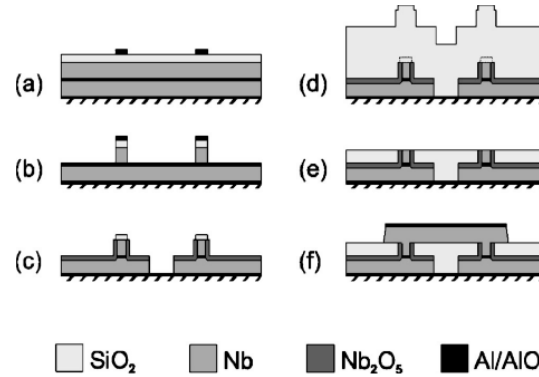
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Part 3 Sequential junction cooling In a dcSQUID

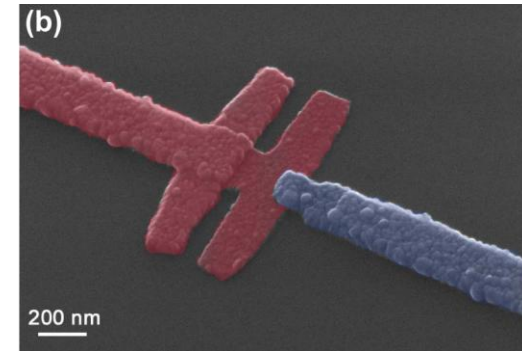
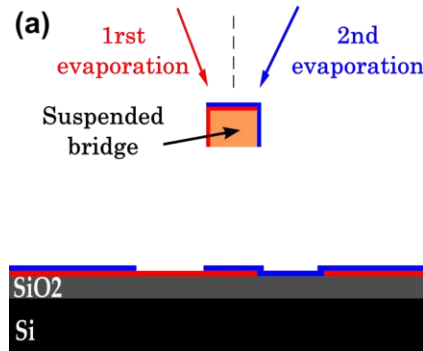
Trilayer Technique

Dolata et al, *J. Appl. Phys* (2005)



Standard shadow evaporation Dolan Bridge Technique

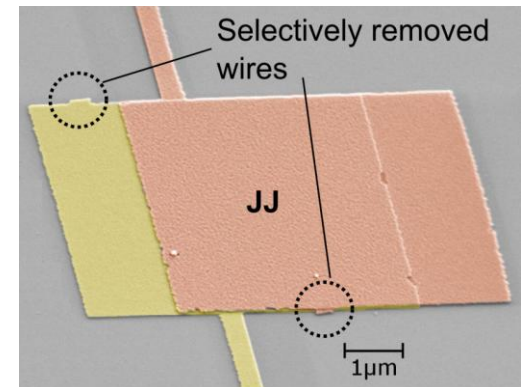
Dolan, *Appl. Phys. Lett.* (1977)



Courtesy of I.M.Pop

Bridge-Free shadow evaporation technique (BFT)

Lecocq et al, *ArXiv* (2010) submitted to *Nanotechnology*

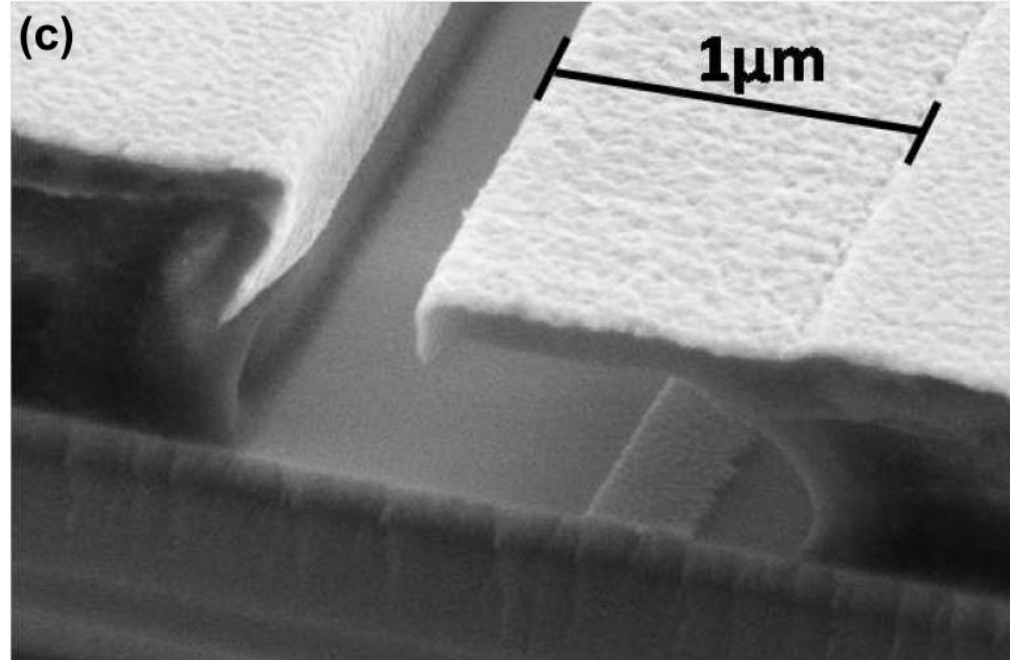
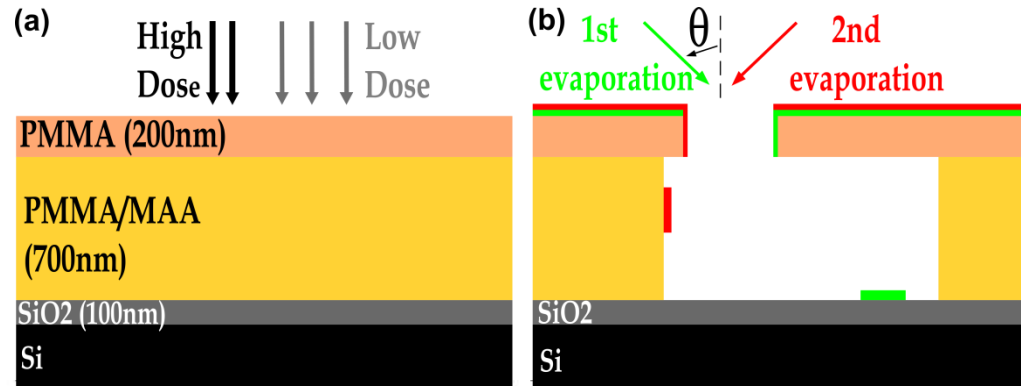


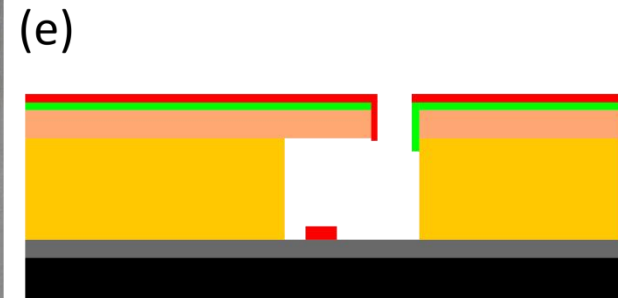
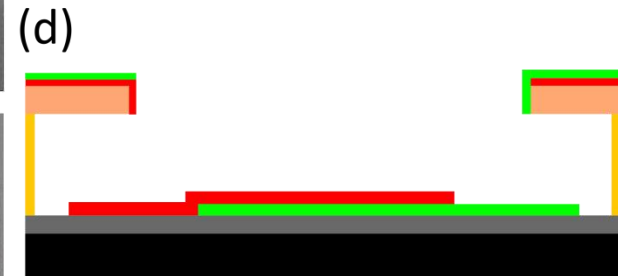
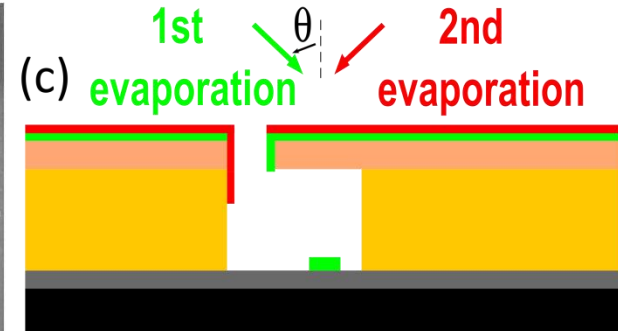
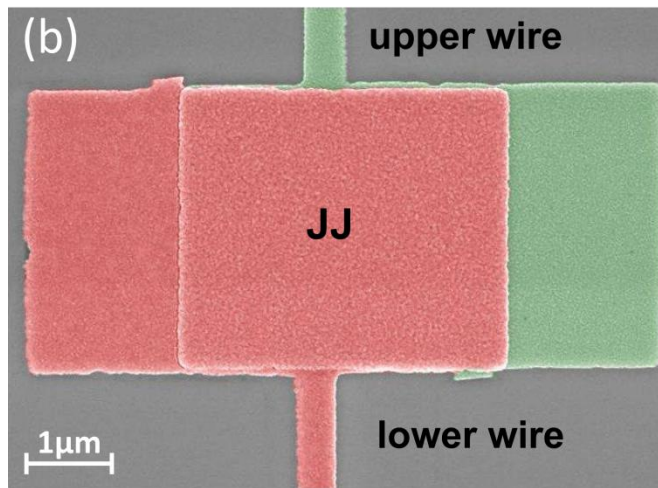
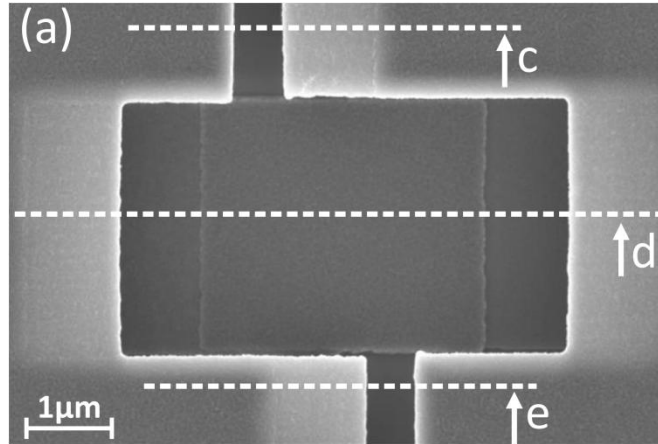
1. Design of strongly asymmetric undercut :

- e-beam lithography @ 100kV
- “double exposure” technique
Cord et al, JVST B (2006)

2. Deposition :

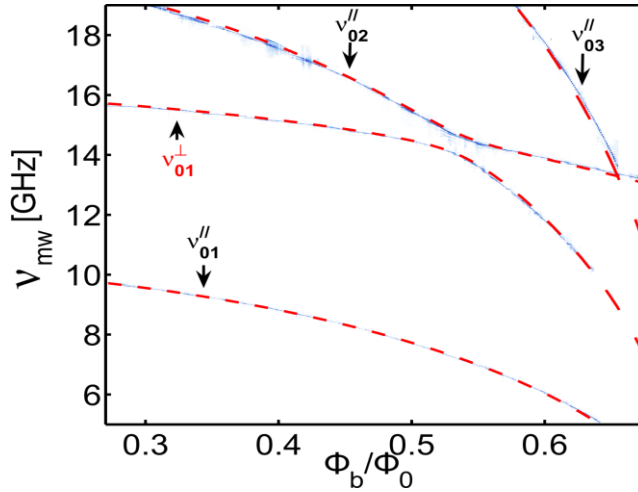
deposition on substrate depends on the undercut position and the angle



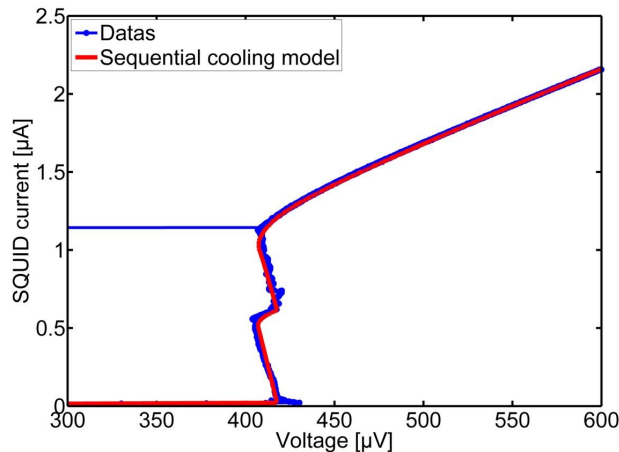


No suspended bridge

- Less mechanical issues
- Junction size from 10^{-2} to $10^4 \mu\text{m}^2$
- Easy cleaning of resist residues (RIE, IBE)

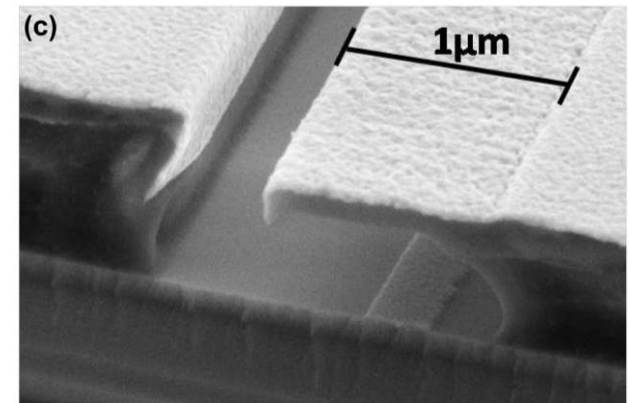


Part 2 Nano-Fabrication: Bridge-Free Technique

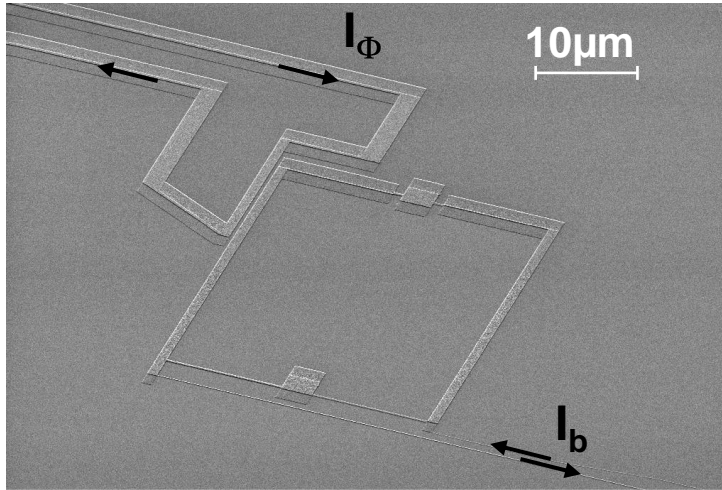


Part 1

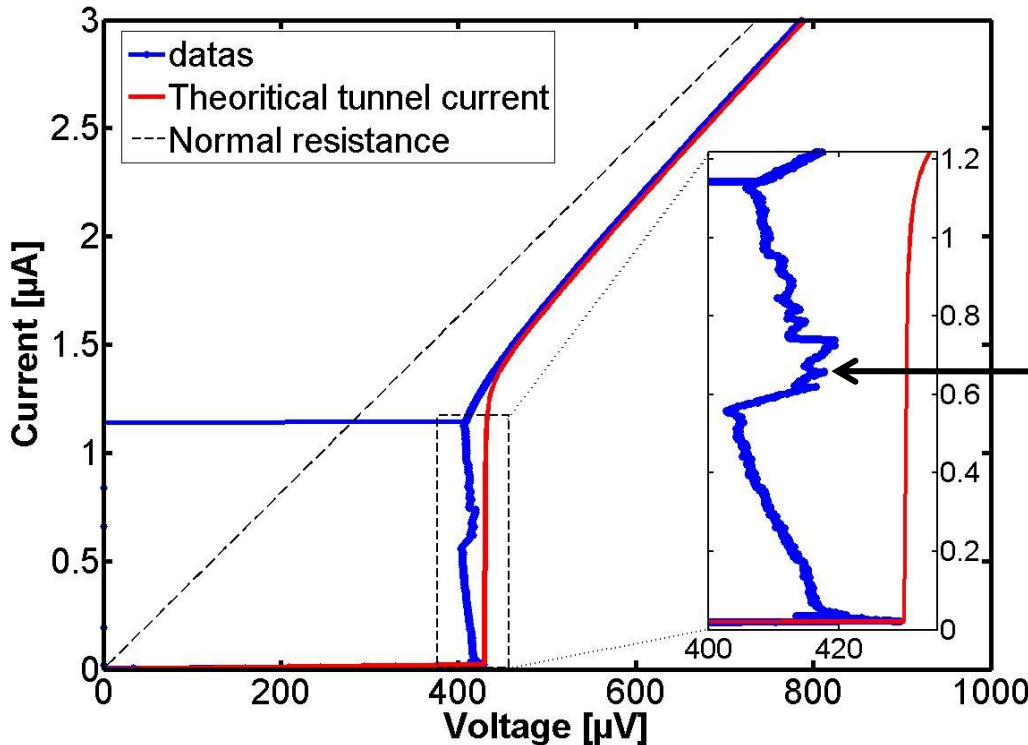
Quantum dynamics in a dcSQUID
From a phase Qubit to a 2D oscillator



Part 3 Sequential junction cooling in a dcSQUID



Theoretical prediction for the tunnel current fails to describe experimental results accurately



Anomaly @ $I_c/2$

1. Quantum dynamics in a dcSQUID

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

- Anomaly

- Sequential cooling

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Ph.D. Defense
May 11th 2011

Exemple of anomaly in Aluminium dcSQUID:

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May 11th 2011

1. Quantum dynamics in a dcSQUID

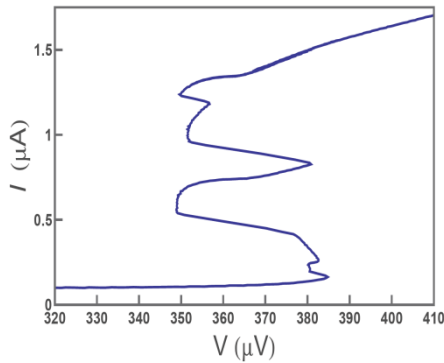
2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

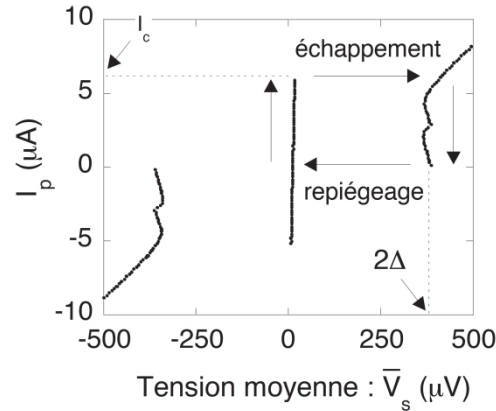
- Anomaly

- Sequential cooling

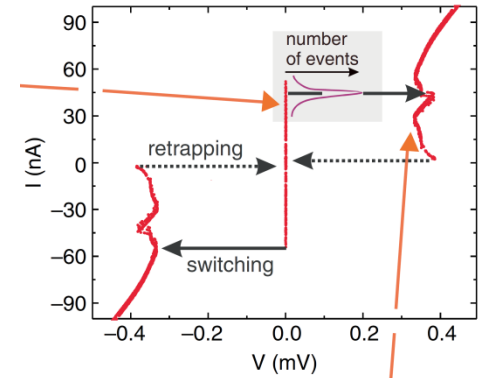
LeMasne, *PhD thesis* (2009)



Claudon, *PhD thesis* (2005)

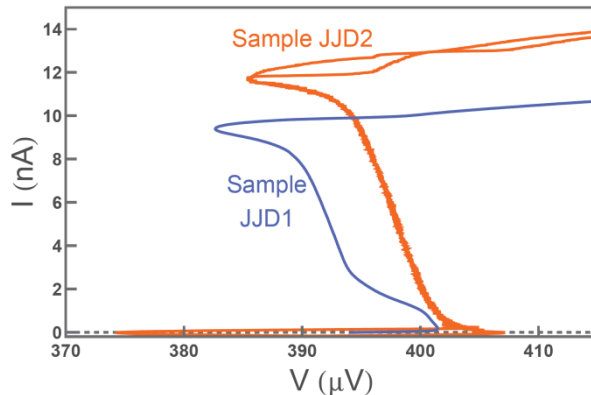


Kivioja et al, *New. J. of Phys.* (2005)

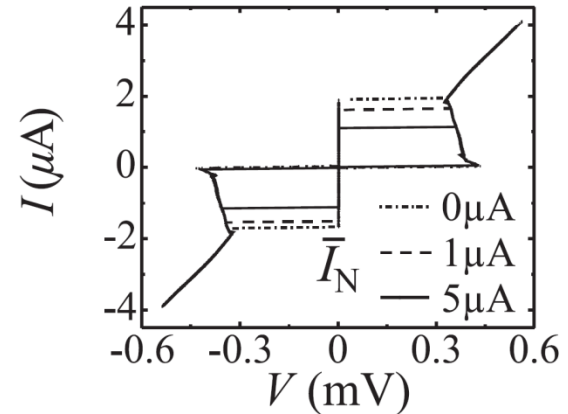


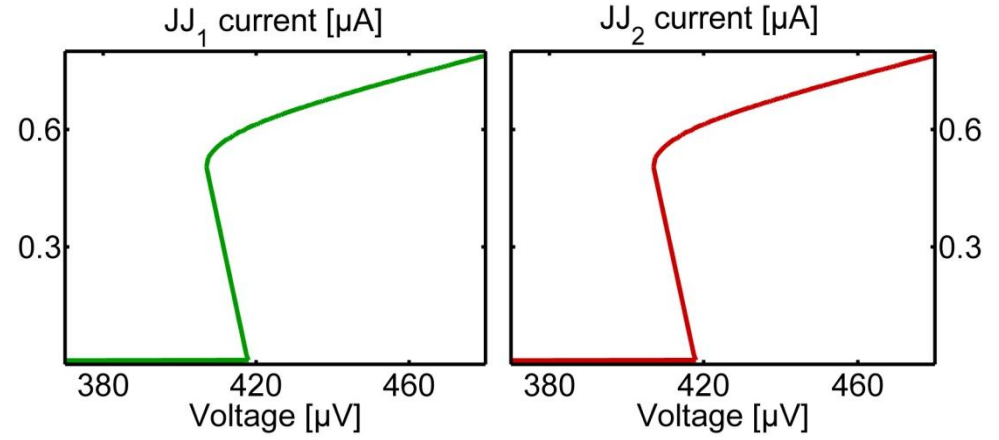
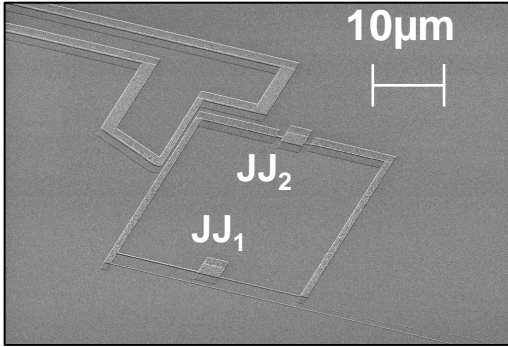
Correlated with “back-bending” in single Aluminium JJ:

LeMasne, *PhD thesis* (2009)



Timofeev et al, *PRL* (2007)



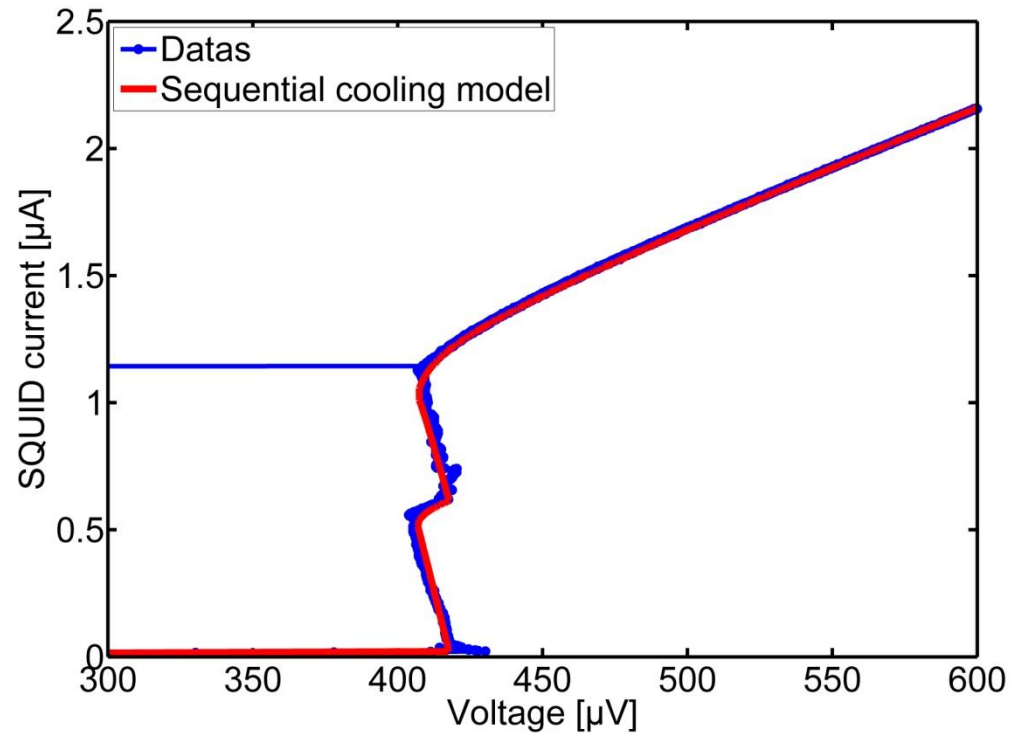


@ anomaly :

JJ 1 : almost no current
("cold junction")

JJ2 : current higher than critical current
("hot junction")

Sequential junction cooling



1. Quantum dynamics in a dcSQUID

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

- Anomaly

- Sequential cooling

✓ Optimal current bias for current noise insensitive dcSQUID phase qubit

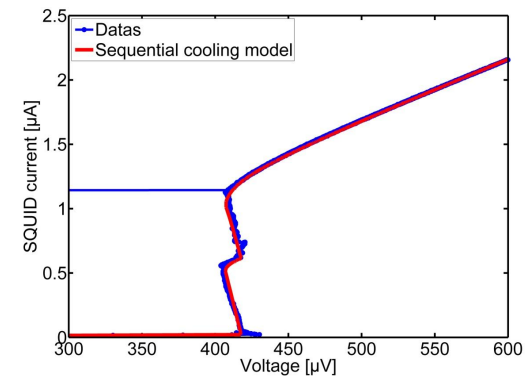
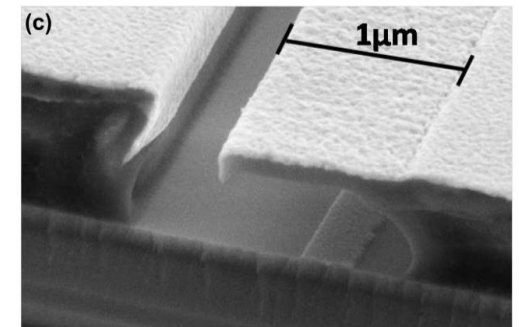
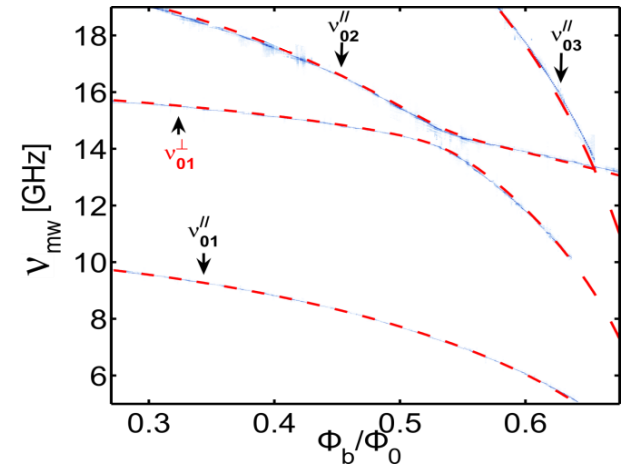
Hoskinson, Lecocq et al, PRL (2009)

✓ Measurement of a 2D superconducting artificial atom : a dcSQUID with a large inductance

✓ Bridge-free shadow evaporation technique for JJ nanofabrication

Lecocq et al, ArXiv (2010) submitted to Nanotechnology

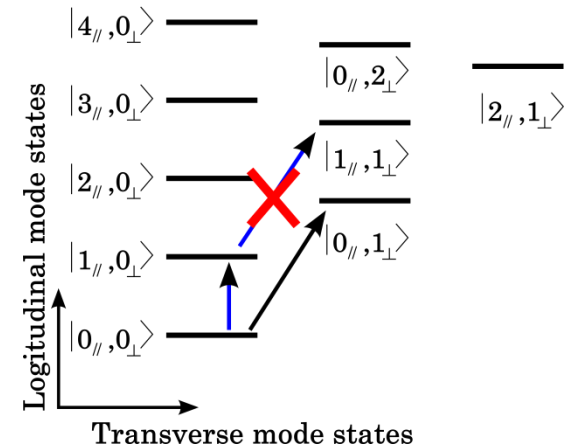
✓ First explanation of the recurrent anomaly in IV characteristic of dcSQUID



Light / matter interaction with a 2D artificial atom

Include this device in a circuit QED architecture

“Electromagnetically Induced Transparency” ?



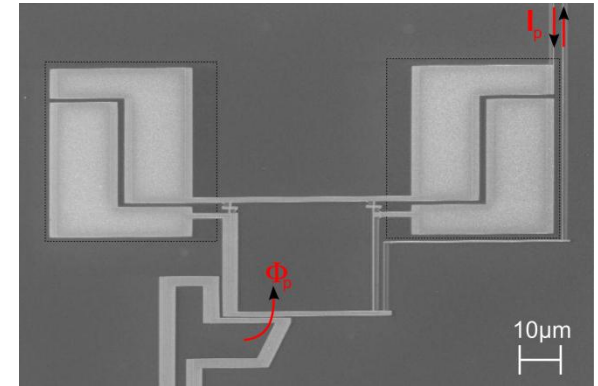
Reduce TLS density

Reduce junction size

Good dielectric (a-SiH)

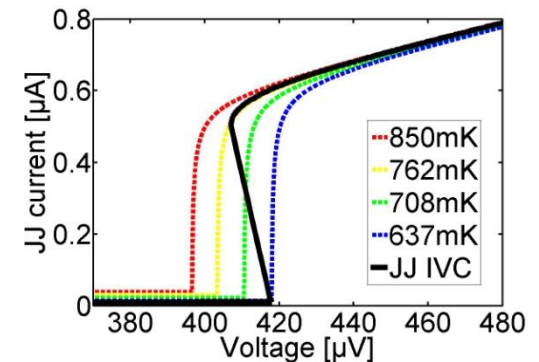
Martinis et al, PRL (2005)

Steffen et al, PRL (2006)



Origin of back bending ?

Thermal model
(including q.p diffusion and recombination)





Acknowledgements



F. Lecocq

Ph.D. Defense
May 11th 2011

1. *Quantum dynamics in a dcSQUID*

2. *Bridge-Free Nanofabrication Technique*

3. *Sequential junction cooling in dcSQUID*

Thank you for your attention

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Best wishes for Cecile and Julie