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
Scientific context

Quantum integrated circuits

- **Ultra-low dissipation**: superconductivity

- **Ultra-low noise**: low temperature

- **Non-linear, non-dissipative element**: Josephson junction

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

\[ E_C = \frac{(2e)^2}{2C} \]
**Scientific context**

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)*
Scientific context

Engineering quantum mechanics

- Coherence
- Optimal point

- Coupling
- Gates
- Algorithm

- Readout
- Memory
- Bus

T₂ ~ 30µs inside
“3D” transmon

Yale, *APS Meeting* (2011)


Motivations: multiple degrees of freedom

Trapped ion

NV centers in diamond


High fidelity readout & Electromagnetically Induced Transparency

Superconducting artificial atom with multiple degrees of freedom?
Part 1
Quantum dynamics in a dcSQUID
From a phase Qubit to a 2D oscillator

Part 2
Nano-Fabrication: Bridge-Free Technique

Part 3
Sequential junction cooling in a dcSQUID
Modes of oscillations

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

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

where

\[ x = \frac{\phi_1 + \phi_2}{2} \]

\[ b = \frac{L_J}{L} = \frac{\Phi_0}{2\pi L I_c} \]
Modes of oscillations

1. Quantum dynamics in a dcSQUID
   - The description
   - Spectroscopy
   - Coherent control

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

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

\[ \hat{H}_{2D} = \hat{H}_\parallel + \hat{H}_\perp \]

\[ \hat{C}_{\parallel \perp} = h \nu_{21} \hat{X}^2 \hat{Y} + h \nu_{12} \hat{X} \hat{Y}^2 + h \nu_{22} \hat{X}^2 \hat{Y}^2 \]
From a phase qubit...

**L < \( L_{josephson} \)**

- Transverse mode high in energy
- Considered in the ground state
- 1D dynamics

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

**Circuit insensitive to current noise @ zero current bias**
... to a 2D oscillator

Longitudinal mode states

Transverse mode states

Quantum 2D oscillator

Quantum anharmonic oscillator

Qubit

2D oscillator = large loop inductance + dcSQUID

$\frac{U}{U_0}$

$\frac{\phi}{\phi_0}$

$\phi_0 = 0.49\phi_0$

$\phi = 0.7\phi_0$

Transverse mode energy decreased

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

F. Lecocq
Ph.D. Defense
May 1st, 2011
Experimental setup

1. Quantum dynamics in a dcSQUID
   - Th description - Spectroscopy - Coherent control

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical current per JJ</td>
<td>0.713 μA</td>
</tr>
<tr>
<td>Capacitance per JJ</td>
<td>510 fF</td>
</tr>
<tr>
<td>loop inductance</td>
<td>629.8 pH</td>
</tr>
<tr>
<td>JJ’s surface</td>
<td>10μm²</td>
</tr>
<tr>
<td>SQUID’s surface</td>
<td>900μm²</td>
</tr>
</tbody>
</table>

\[ b = \frac{L_J}{L} = 0.733 \]

\[ E_J = 17K \]

\[ E_C = 7mK \]
**Experimental setup**

The probability of escape increases when the system is excited.

**Nanosecond flux pulse and switching current measurement**

_Hoskinson, Lecocq et al, PRL (2009)_
Spectroscopy

1. Quantum dynamics in a dcSQUID
   - Description
   - Spectroscopy
   - Coherent control
2. Bridge-Free Nanofabrication Technique
3. Sequential junction cooling in dcSQUID

Longitudinal mode

Transverse mode

Frequency [GHz]

Flux bias [$\Phi_0$]

$|2\rangle$, $|3\rangle$, $|0\rangle$, $|1\rangle$

$\nu_{02}$, $\nu_{03}$, $\nu_{01}$
Large anti-crossing at the resonance between $\nu_{02}^{\parallel}$ and $\nu_{01}^{\perp}$

Non linear coupling

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

Also discussed in quantum optics and ion traps

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

Strong coupling regime

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

1. Quantum dynamics in a dcSQUID
   - Theory description
   - Spectroscopy
   - Coherent control

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID
Coherent oscillation between modes

1. Quantum dynamics in a dcSQUID
   - Theory description
   - Spectroscopy
   - Coherent control

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID
Coherent oscillation between modes

Coherent exchange of quanta between the modes

Frequency conversion back and forth

| 2₂,0₀ ⟩ \[\rightarrow\] | 0₂,1₀ ⟩

| 1₁,0₀ ⟩

| 0₂,0₀ ⟩ \[\rightarrow\] | 0₂,0₀ ⟩

1. Quantum dynamics in a dcSQUID
- Th description
- Spectroscopy
- Coherent control

2. Bridge-Free Nanofabrication Technique

3. Sequential junction cooling in dcSQUID
Coherent oscillation between modes

Low contrast:

- Slow microwave $\pi$ pulse
- Readout
- Non perfect adiabatic flux pulse
- Parasitic TLS

1. Quantum dynamics in a dcSQUID
   - Th description
   - Spectroscopy
   - Coherent control
2. Bridge-Free Nanofabrication Technique
3. Sequential junction cooling in dcSQUID
A superconducting 2D artificial atom

1. Quantum dynamics in a dcSQUID
2. Bridge-Free Nanofabrication Technique
3. Sequential junction cooling in dcSQUID
Presentation outline

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

Part 2
Nano-Fabrication:
Bridge-Free Technique

Part 3
Sequential junction cooling
In a dcSQUID

Graphs and images are not transcribed, but they likely contain data and illustrations relevant to the topics presented.
Standards techniques and BFT

Trilayer Technique


Standard shadow evaporation
Dolan Bridge Technique


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
     \[\text{Cord et al, JVST B (2006)}\]

2. Deposition:
   deposition on substrate depends on the undercut position and the angle
Bridge Free Technique

No suspended bridge

Less mechanical issues
Junction size from $10^{-2}$ to $10^{4}$ $\mu$m²
Easy cleaning of resist residues (RIE, IBE)

Pop et al., submitted to APL (2011)
Presentation outline

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

Part 2
Nano-Fabrication: Bridge-Free Technique

Part 3
Sequential junction cooling in a dcSQUID
IV characteristics of dcSQUID in Al

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

Anomaly @ $I_c/2$
A recurrent anomaly

Exemple of anomaly in Aluminium dcSQUID:

LeMasne, PhD thesis (2009)

Claudon, PhD thesis (2005)


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

LeMasne, PhD thesis (2009)

Timofeev et al, PRL (2007)
“back-bending” and bifurcation

@ anomaly:

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

**JJ 2**: current higher than critical current ("hot junction")

Sequential junction cooling in dcSQUID
Conclusions

✓ 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
Outlooks

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**

Thank you for your attention

And thanks to:

<table>
<thead>
<tr>
<th>Services of Institut Néel</th>
<th>Experimental team</th>
<th>Theoretical support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanofab and PTA Electronics Cryogénie Liquéfacteur Administration</td>
<td>Olivier Buisson Wiebke Guichard Bernard Pannetier Ioan M. Pop Iulian Matei Thomas Weissl Etienne Dumur Alexey Feofanov</td>
<td>Franck Hekking Nicolas Didier Perola Milman PTB Alexander Zorin Ralf Dolata</td>
</tr>
</tbody>
</table>

And all the “Quantum Coherence” group !!

Best wishes for Cecile and Julie