Development of antenna-coupled bolometers for mm-wave astronomy

Aurélien BIDEAUD

Supervisors: A. Benoit (I. Néel) and X. Désert (LAOG)
In team with: P. Camus, C. Hoffmann, A. Monfardini

• Within the DCMB collaboration (I. NEEL, IEF, CSNSM, CESR, IAS, APC, LPN, LPSC, LAOG)
Introduction: mm-wave astronomy and bolometers

I. Antenna-coupled bolometers
1. Design
2. Electrical characterisation
3. Optical characterisation
4. Alternative design

II. Multiplexed readout for high impedance thermometers
1. Principle
2. 216 pixels prototype
3. Preliminary results
Interest for (sub)mm-wave detectors

T = 2,725 K
+/- 0.002 K

λ = 1.87 mm
f = 160 GHz
E_{ph} = 660 µeV

Interstellar dust:
- enveloping young stars
- highly present in galaxies clusters

Distance
We measure: $\Delta R \propto \Delta T$

$\Delta T = \frac{E}{C} = \tau \cdot \frac{P_{\text{rad}}}{C}$

and $\tau \approx \frac{C}{G}$

**Signal**: $\Delta T = \frac{P_{\text{rad}}}{G}$
Development of antenna-coupled bolometers for mm-wave astronomy

Aurélien BIDEAUD

Introduction: mm-wave astronomy and bolometers

I. Antenna-coupled bolometers
   1. Design
   2. Electrical characterisation
   3. Optical characterisation
   4. Alternative design

II. Multiplexed readout for high impedance thermometers
   1. Principle
   2. 216 pixels prototype
   3. Preliminary results
Interest for full sampled focal plan

Horn-coupled detectors are used in many instruments.

1. High **optical coupling** efficiency (within the lobe).
2. Progress have been made for **use with arrays of detectors**.

But they have a limited filling factor.

1. Limits the **number of detectors** for a given filed of view.
2. Limits the (static) **sampling** of the filed of view (under Shannon criteria).
3. **Photometric measurement** is uncertain from Earth, due to anomalous refraction generated by atmosphere instabilities.
Antenna-coupled bolometers

Alternative optical coupling

1. Dissociated from the absorber
   => free geometry for absorber / thermometer / thermal link.
   => allows band defining with electrical filters.

2. **Full coverage** of the pixel area.
   => better filling factor than horns.

3. Sensitive to **polarization** (if needed).

4. Control of the lobe.
Single bow-tie antenna

1. Suspended stress compensated membrane (500 nm SiO$_2$ - Si$_3$N$_4$ - SiO$_2$)
2. Dissipative shunt (7 nm Pd)
3. Superconducting bow-tie antenna (40 nm Al)
4. Insulating layer (50 nm Si$_3$N$_4$)

5. Thermometer (100 nm NbSi)
6. Superconducting wires (50 nm Nb) terminated with contact pads (200 nm Au)
7. Opening in the (300 μm Si) Wafer
Single bow-tie antenna

1. Suspended stress compensated membrane (500 nm Si$_2$O$_2$ - Si$_3$N$_4$ - Si$_2$O$_2$)
2. Dissipative shunt (7 nm Pd)
3. Superconducting bow-tie antenna (40 nm Al)
4. Insulating layer (50 nm Si$_3$N$_4$)
5. Thermometer (100 nm NbSi)
6. Superconducting wires (50 nm Nb) terminated with contact pads (200 nm Au)
7. Opening in the (300 μm Si) Wafer
Electrical characterization

1. Voltage measurement:
   - for different current bias
   - for different bath temperature
2. Working in R(P) domain:
bolometer resistance without bias
3. Construction of the $R(T)$ law

$$R(T) = R_0 \exp \left(\frac{T_0}{T}\right)^n$$

**Good homogeneity:**

- $R_0 = 2150 \ \Omega \pm 2\%$
- $T_0 = 4.6 \ \text{K} \pm 5\%$
  (with $n = 0.5$)

$R @ 100 \ \text{mK} \sim 1 \ \text{M}\Omega$
Electrical characterization

\[ T_e = f\left(P_{el}, G, P_{e-ph}, T_{bath}\right) \]

Thermal conductance
\[ G = 0.2 \, \text{nW.K}^{-1} \]
Response and noise

for typical $I_{\text{bias}} = 1$ nA,

- Electrical response of $1.5 \times 10^8$ V.W$^{-1}$
- Excess noise observed: $N \sim 100$ nV.Hz$^{-1/2}$
- Due to the thermometer and proportional to its responsivity

Local heating

Redistribution of the current

Local cooling
Optical measurements

Modulated source

Constant source

Optical response.

Noise.
1. See light.

2. Antennas are working well.

3. Optical efficiency of ~30%

4. NEP limited by the excess noise:
   \[ \text{NEP} \approx 8 \times 10^{-15} \text{W.Hz}^{-1/2} \]
**Alternative design**

1. Absorbing trough silicon
   => smaller antennas

2. Dissociating optical coupling and thermal dissipation
   => smaller membranes and thermometers

3. Incoherent co-addition of the signals from each antenna.
Preliminary optical results

1. See light.

2. Low efficiency and irregular response to polarization.

<table>
<thead>
<tr>
<th>Pixel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Theta_0 , (^\circ)$</td>
<td>-12.75</td>
<td>-149.32</td>
<td>51.81</td>
<td>45.78</td>
<td>-19.08</td>
<td>55.04</td>
</tr>
<tr>
<td>$\eta , (%)$</td>
<td>78</td>
<td>58</td>
<td>78</td>
<td>60</td>
<td>61</td>
<td>66</td>
</tr>
</tbody>
</table>
1. Lowering the noise by increasing the thermometer section.

2. Understand the absorption of the 6 antennas design.
Introduction: mm-wave astronomy and bolometers

I. Antenna-coupled bolometers
   1. Design
   2. Electrical characterisation
   3. Optical characterisation
   4. Alternative design

II. Multiplexed readout for high impedance thermometers
   1. Principle
   2. 216 pixels prototype
   3. Preliminary results
Time domain multiplexing

Quantum Point Contact (QPC) Transistors

Single QPC characteristic curve

(Y. Jin – IEF, Orsay)
12-fold readout prototype

15 wires / 72 pixels + 15 addressing wires

=> 60 wires for 216 pixels
First light with multiplexer

Moving a small source in focal plan.

=> imaging the Point Spread Function of each pixel

No cross-talk between pixels.
Other projects concerning detectors

Small arrays of **horn-coupled high impedance bolometers** for the balloon-born experience OLIMPO.

Arrays of **Kinetic Inductance Detectors** (KIDs)
Demonstrated on the 30 meter IRAM telescope.

(NIKA projet)

Arrays of **high-impedance TES** (Transition Edge Sensors),
using **electron-phonon decoupling** as the thermal leak.

(S.Marnieros,
CSNSM, Orasy)
Thank you for your attention.
Testing QPC-HEMT chips

Grid voltage (mV)

1-13 : closing-voltage ($V_{on}$)
14 : opening-voltage ($V_{off}$)
Time domain multiplexing high impedance bolometers

- Multiplexing of 216 high impedance bolometers.
- Connections to hot stages divided by more than 4.
- Noise less than 2nV/√Hz
- Adaptative solution for a future 1000 pixels array with less than 200 connections.

Quantum Point Contact (QPC) Transistors

Single QPC transistor response

High impedance bolometers
The optical cryostat

- $^4$He reserve
- $^4$He – $^3$He dilution
- optical entrance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Temperature</td>
<td>100 mK</td>
</tr>
<tr>
<td>Cooling Power at 100 mK</td>
<td>10-100 µW</td>
</tr>
<tr>
<td>Frequency of cooldown</td>
<td>up to 2 per week</td>
</tr>
<tr>
<td>To close and start pumping</td>
<td>1 hour</td>
</tr>
<tr>
<td>Pumping time (small pump)</td>
<td>3-6 hours</td>
</tr>
<tr>
<td>From 300K to 4K</td>
<td>6-7 hours</td>
</tr>
<tr>
<td>From 4K to 100mK</td>
<td>4-6 hours</td>
</tr>
<tr>
<td>Helium to cool down and refill once</td>
<td>$\approx$ 100 liters</td>
</tr>
<tr>
<td>Helium consumption at base T</td>
<td>1 liter/h</td>
</tr>
<tr>
<td>Total Cool-down time</td>
<td>14-18h</td>
</tr>
</tbody>
</table>

(also used for measuring bolometers)
(pulse-tube version to be tested)
For “thick” films, like the ones we normally utilise (t = 100nm), \( \text{Nb}_x\text{Si}_{1-x} \) behaves as following:

- **Insulator** \( x < 9\% \) \( \Rightarrow \lim_{T \to 0} R(T) = \infty \)

- **Transition Insulator – Metal** (MIT) at \( x_{\text{MIT}} = 9\% \)

- **Metal** \( 9\% < x < 12\% \) \( \Rightarrow \lim_{T \to 0} R(T) = R_0 \)

- **Transition Metal – Superconductor** (MST) at \( x_{\text{MST}} = 12\% \)

- **Superconductor** \( x > 12\% \) \( \Rightarrow \) \( \lim_{T \to 0} R(T) = 0 \)

Other parameters influencing the behaviours (e.g. \( x_{\text{MIT}}, x_{\text{MST}}, T_c \)):

- film thickness, thermal treatments, irradiation.
Response time

Mechanical chopping
\[ \tau = \frac{C}{G} \leq 10 \text{ ms} \]

\[ G \approx 0.2 \text{ nW/K} \]

\[ \Rightarrow C < 2 \text{ pJ/K} \]

**Calculation**

\[ C = 0.2 \text{ pJ/K} \]

\[ \Rightarrow \tau \approx 1 \text{ ms} \]