Fabrication of superconducting detectors for studying the Universe

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What we can learn by using far-infrared (FIR) astronomical observatories

The age and origins of the Universe.
The presence of water in extra-solar planets.
Stellar formation and evolution.
Searches for dark matter.
What we can learn by using x-ray astronomical observatories

Look for the presence of hot dark matter around metallic ions.

Study regions around and locate massive black holes.
Means of making these measurements: Focal plane detector arrays

- Light is focused onto the focal plane detector arrays via optics.

- Individual detector elements populate the focal plane -> good spatial resolution.

- A focal plane detector has a very small form factor, which allows for low hardware mass.

- A focal plane geometry facilitates integration with other components (e.g., antireflection coatings and backshorts).

- Focal plane array realization is highly dependent on advances in fabrication and packaging.
Why use superconducting detectors?

- Operate at cryogenic temperature => Good signal to-noise
- High heat capacity => Large dynamic range
- Somewhat easy/inexpensive to set relevant parameters
Transition edge sensors (TES)

- Bias a superconductor so that it is in the transition region of its R vs T curve.

- A small change in the TES temperature will cause its resistance to increase.

- This will cause the current flowing through the TES to decrease.

- The change in current is detected by a SQUID.
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After absorption of energy
TES for x-ray instrumentation

World-record breaking energy resolution for high quantum efficiency x-ray detectors!
TES for FIR

- Radiation couples to antenna.
- Resistive absorber heats TES.
- Electron/phonon temperature difference dominates noise.
- The noise equivalent power (NEP) of these sensors is approaching the background-limited noise of the cosmic microwave background.
Break a superconducting detector’s Cooper pairs with incoming (sub-mm, FIR) radiation.

• This increases in the detector’s kinetic inductance $L_k$ and surface resistance $R_s$.

When the detector is integrated as part of a resonant circuit, the change in $L_k$, $R_s$ results in:

• A decrease in resonant frequency
• A decrease in power absorbed by the resonator

Microwave kinetic inductance detectors (MKIDs)

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MKIDs as far-infrared detectors

**Antenna-coupled**

Incident power is coupled to antenna, which is then absorbed by a resistive (at that $f$) KID.

**Absorber-coupled**

Incident power is coupled to broadband absorber which acts simultaneously as KID.
Device Fabrication
Fabrication Tools Inside Cleanroom

Physical vapor deposition systems

For depositing thin dielectric and metal films on Si wafers
Fabrication Tools Inside Cleanroom

Photoresist spinners and mask aligners

For creating masks to pattern the thin films
Fabrication Tools Inside Cleanroom

Plasma etchers and corrosive chemicals

To etch the thin films as well as the silicon substrates
Fabrication Tools Inside Cleanroom

Wafer bonders

To bond Si wafers together
Fabrication Tools Inside Cleanroom

Wire bonders

To integrate detectors with readout electronics and/or amplifiers
Example of an MKID Fabrication Process

- **SOI Wafer**:
  - Buried Oxide
  - Si Handle

- **Etch AMs**

- **Pattern front metal**
  - Pyrex or Si
  - Wafer wax

- **Bond backing wafer**

- **Remove handle, BOX**

- **Pattern back metal, streets**

- **Bond frame to device**
  - Si frame
  - Epotek-301

- **Membrane release**

- **Flip Devices**
Architecture of x-ray TES
Fabrication developments for x-ray TES: Cantilevered “mushroom” absorbers

<table>
<thead>
<tr>
<th>Absorber Material</th>
<th>Grain Size</th>
<th>Heat Capacity (at 0.1 K)</th>
<th>Energy Resolution (at 5.9 keV)</th>
<th>Time Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroplated Au</td>
<td>~ 1 µm</td>
<td>1.4 pJ/K</td>
<td>2.4 eV</td>
<td>2 ms</td>
</tr>
<tr>
<td>Electroplated Au/Bi</td>
<td>2-5 µm</td>
<td>0.4 pJ/K</td>
<td>2.1 eV</td>
<td>400 µs</td>
</tr>
<tr>
<td>Evaporated Au/Bi</td>
<td>0.2-0.5 µm</td>
<td>0.4 pJ/K</td>
<td>4.0 eV</td>
<td>1 ms</td>
</tr>
</tbody>
</table>

Architecture of FIR TES

1 THz Antenna-Coupled Bolometric Transition-Edge Sensor (TES)

Slot Antenna (ground plane cut)

Voltage Bias Lines

TES

Termination Resistor

Bias Chokes

Microstrip Line

$\lambda/4n$ stub

Ground Plane (below)

10 $\mu$m
Fabrication developments for FIR TES: Novel ground plane and absorber materials

Novel microstructured Au thin films as ground plane material

Our Au films act very similar to perfect electrical conductors.

Novel microstructured Bi thin films as THz absorbers

Our Bi films act like purely resistive elements over a broad frequency range.

Architecture of Absorber-Coupled MKID

- Superconducting Al KIDs/resonators
- Single crystal Si membranes
- Low impedance Nb traces
- Nb microstrip feedline
Fabrication developments for Absorber-Coupled MKID: Novel fabrication methodology in which...

An entire camera can be fabricated on a single 1.5 micron thick Si membrane.

There is a very small front-to-back misalignment, which results in low transmission line loss, without having to use front-to-back lithographic techniques.

Architecture of Antenna-Coupled MKID

Antenna

Coupling capacitor (to readout)

KID/termination resistor (underneath)

Coupling capacitor (to antenna)

Tuning capacitor

Thin silicon membranes are never roughened.
Fabrication developments for Absorber-Coupled MKID: Keep Si membrane smooth throughout fabrication

Roughening of Si during fabrication can introduce noise in the detectors.

Solution: Develop many different liftoff techniques in order to avoid having to etch the metals (Nb).

Liftoff involves:
1. Depositing liftoff material(s).
2. Patterning that material with a negative image of what is desired.
3. Depositing the desired material.
4. Selectively removing the liftoff material.

Novel liftoff process to pattern the Nb thin films used for the capacitors and transmission lines.
Ancillary devices: Filters

Boxed microstrip lowpass filter

Needed for ultrahigh sensitivity detector operation.

Bandpass grill filter

Needed for rejecting out-of-band thermal noise.
Summary

• Superconducting detectors offer unparalleled means of making astronomical/cosmological observations.

• Fabrication of these detectors is somewhat unconventional; however, a lot of novel condensed matter physics/materials scientific discoveries and semiconductor fabrication processes can be generated in making these devices.
Acknowledgments

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