Read out electronics for low-temperature detector arrays

Kent Irwin, NIST

- Characterizing noise in amplifiers
  - Matching to resistive thermometers
  - Quantum limit
- Noise properties of FETs, SETs, SQUIDs
- Multiplexing – time & frequency division
Amplifier noise model

- Neglect feedback
- Correlations \( (S_{IV}) \) important
- \( Z_{in} \), \( I_n \), and \( V_n \) are frequency dependent
- For high impedance amplifiers (FETs, SETs…) the current noise \( S_I \) is the back action. For low impedance amplifiers (SQUIDs…) \( S_V \) is the back action.
To resolve the Johnson noise of a resistive thermometer, you need a noise temperature << bias temperature.

\[ 4k_B T_n R = S_V + S_I R^2 \]

**Matching impedance** – optimizes noise temperature

\[ R_{\text{match}} = \sqrt{\frac{S_V}{S_I}} \]

Often it isn’t possible to match.

**Noise energy & quantum limit**

\[ E_n = k_B T_n = \frac{\sqrt{S_I S_V}}{2} \quad E_n \geq \frac{\hbar \omega}{2} \]

**Additional complexities**

- Amplifier input impedance
- Source reactance
- Correlations \((S_{IV})\)

\[ E_n = \frac{\sqrt{S_I S_V - \text{Im}(S_{IV})^2}}{2} \]
A zoology of amplifiers

**Semiconductor amplifiers**

- **Bipolar transistors**
  
  noise impedance $<\sim 100\ \text{k}\Omega$

- **Field-effect transistors (Si JFETs)**
  
  noise impedance $>\sim 100\ \text{k}\Omega$

- **Microwave amplifiers (i.e. HEMTs)**
  
  impedance matched to transmission line

**Quantum amplifiers**

- **Single-electron transistor (charge quantum)**
  
  noise impedance $\sim 100\ \text{G}\Omega$

- **Superconducting quantum interference device (flux quantum)**
  
  SQUID noise impedance $\sim \omega L \sim 1\ \text{m}\Omega$
Non-dissipative thermometers

**Microwave kinetic inductance**

The measurement of small shifts in frequency with a high Q resonance circuit gives high effective gain. These low-temperature detectors can be efficiently read out with high-noise-temperature HEMTs.

Talks A02 and Y02

**Magnetic calorimeter**

Needs extremely low noise SQUID to simultaneously optimize resolution and speed – will eventually push up against quantum limits.

Talk Y03, Posters A07, A08, A09
Multiplexing

• Bandwidth-limiting filter
  L/R or RC
  LC tuned resonance for frequency-division multiplexing

• Signal Modulation
  Switch (time division) or sinusoid bias (frequency division)

• Signal addition
  Add signals inductively, or add voltages or currents

• Demultiplexing at room temperature

Reviews on SQUID MUX (both TDM and FDM)
Time and frequency division

Time-division signal modulation: L/R filter and SQUID at each pixel.

Frequency-division signal modulation: L/R filter and LC resonator at each pixel.
FET readout of thermistors: XRS II

- 10 MΩ thermistor impedance
- InterFET SNJ14AL16

\[ V_n \sim 3 \text{ nV Hz}^{-1/2} \text{ at 100 Hz} \]
\[ I_n < 5 \times 10^{-17} \text{ A Hz}^{-1/2} \]

- Not impedance matched.
- Noise temperature at 40 MΩ, 200 Hz: 4 mK (10^6 times quantum limit at that frequency.)
Single electron transistors

- Typically: $C < 1 \text{ fF}$
  $V_n \sim 30 \text{ nV Hz}^{-1/2}$

- Impedance set by feedback resistor $R_{FB} \sim 100 \text{ M} \Omega$
- Not impedance matched ($R_{\text{match}} \sim 100 \text{ G} \Omega$ at 1.6 kHz)
- Noise temperature at 100 MΩ, 1.6 kHz: 150 mK (4 x 10⁶ times quantum limit at that frequency.)

Multiplexed RFSETs

HEMTs are microwave amplifiers operated at \( \sim 4 \) K with \( T_n \sim 10 \) K, >10 GHz bandwidth.
A bit noisy to couple directly to 100 mK resistors...

- Frequency-division multiplexing with microwave tank circuit demonstrated.
- RFSET can be integrated on-chip with cryogenic detectors and small microwave filter elements.
- See poster S08 – photon-counting STJ with RFSET MUX
SQUIDs

- Typically: $L \sim 100 \text{ nH}$ in cryogenic detector use
  $I_n \sim 1 \text{ pA Hz}^{-1/2}$

- TES bias resistance $R_{\text{bias}} \sim 5 \text{ m}\Omega$, not too far from impedance matched

- Noise temperature at $5 \text{ m}\Omega$, 10 kHz: $90 \mu\text{K}$ (400 x quantum limit at that frequency). Coupled SQUIDs can be made within a factor of 10 of the quantum limit. There is no present need to improve the noise temperature.

*Clarke, Tesche, Giffard, JLTP 37 (1979) 405* calculates the limits on $S_I$, $S_V$, $S_{IV}$, $E_n$. 
Time Division SQUID MUX

Boxcar Modulation Functions

\[ I_1(t) \]

\[ I_2(t) \]

\[ I_{M}(t) \]

Need an L/R low-pass filter and switch at each pixel
Frequency-Division SQUID MUX

Sinusoidal Modulation Functions

I_1(t) vs time
I_2(t) vs time
I_M(t) vs time

Need an LC tank filter at each pixel

Talks E02, E03
Posters E07, E08, E11
Multiplexed $\gamma$-ray calorimeters

Measured Spectral Density

FWHM at 60 keV

<table>
<thead>
<tr>
<th>$^{2}\text{E}_{\text{FWHM}}$</th>
<th>device #1</th>
<th>device #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>only recipient of bias</td>
<td>65 eV</td>
<td>62 eV</td>
</tr>
<tr>
<td>both sensors biased</td>
<td>63 eV</td>
<td>65 eV</td>
</tr>
<tr>
<td>both biased, coincident pulses</td>
<td>64 eV</td>
<td>63 eV</td>
</tr>
</tbody>
</table>

resolving power $\sim$ 940

multiplexing does not degrade sensor performance

J.N. Ullom, Livermore, Berkeley
Resonant Filter Chip

Berkeley LC Filters

Capacitors
Inductors

$\text{Nb}_2\text{O}_5$ capacitors

1 cm
Time-division MUX cast of thousands

**NIST**
- James Beall
- Steve Deiker
- Randy Dorisee
- Erich Grossman
- Gene Hilton
- Martin Huber (CU Denver)
- Kent Irwin
- John Martinis
- Sae Woo Nam
- Carl Reintsema
- Joel Ullom
- Leila Vale
- Yizi Xu

**NASA/GSFC**
- Simon Bandler
- Dominic Benford
- Kevin Boyce
- Jay Chervenak
- Rich Kelley
- Mark Lindeman
- Harvey Moseley
- Umesh Patel
- Rick Shafer
- Johannes Staguhn
- Caroline Stahle

**UK ATC**
- Damian Audley
- William Duncan
- Wayne Holland
- Mike MacIntosh

**SRON**
- Piet de Korte

**PTB Berlin**
- Joern Beyer
The TES bolometer array

- Presented at LTD-9
- Instrument development by NASA/GSFC in collaboration with NIST, IAS Paris, and Caltech
- The TES bolometer and SQUID MUX were fabricated at NIST
- Tunable Fabry-Perot Interferometer
- 8 pixel TES array with SQUID MUX
- Upgraded array (with stripes) should return to the CSO soon

The 8-Channel TDM chip
Multiplexes up to 32 channels in one column.

A kilopixel array requires 32 chips, power dissipation ~ 100 nW total.
100 mK ADR Test Facility

Results: Randy Doriese’s poster E05
The readout will degrade the noise of the SCUBA-2 850 µm array by 1.6% (due to aliased amplifier and detector noise).

- 32 × 41 MUX subarray to be tested in August
When address current flows through the normal-metal, hot electrons diffuse into the superconductor, driving it normal. When the heat is turned off, they escape into the phonon system.

- Simple, small, linear, and low power.
- HEBs operate at $>> 1$ GHz
- With simple, high-yield optical lithography, HESs can be made with $> 20$ MHz bandwidth and $< 1$ nW power dissipation.
- Initial design complete, fabrication starting
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