LTD-10

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_1 is the back action. For low impedance amplifiers (SQUIDs...) S_V is the back action.

Noise temperature, matching, quantum limit

To resolve the Johnson noise of a resistive thermometer, you need a noise temperature << bias temperature

$$4k_BT_nR = S_V + S_IR^2$$



Matching impedance – optimizes noise temperature

R _{match}	= ,		S_V
		\mathbb{V}	$\overline{S_I}$

Often it isn't possible to match

Noise energy & quantum limit

$$E_n = k_B T_n = \frac{\sqrt{S_I S_V}}{2}$$

$$E_n \ge \frac{\hbar\omega}{2}$$

Additional complexities

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

$$E_n = \frac{\sqrt{S_I S_V - \operatorname{Im}(S_{IV})^2}}{2}$$

A zoology of amplifiers

Semiconductor amplifiers

- Bipolar transistors
 - noise impedance <~ 100 k Ω
- Field-effect transistors (Si JFETs)
 - noise impedance >~ 100 k Ω
- Microwave amplifiers (i.e. HEMTs)
 - impedance matched to transmission line
- Quantum amplifiers
- Single-electron transistor (charge quantum) noise impedance ~ 100 G Ω
- Superconducting quantum interference device (flux quantum) SQUID noise impedance $\sim \omega L \sim 1 \ m\Omega$



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

<u>Reviews on SQUID MUX (both TDM and FDM)</u> K. D. Irwin, Physica C 368 (2002) 203-210. M. Kiviranta *et. al.,* AIP 605 (2002) 295-300.

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 $M\Omega$ thermistor impedance
- InterFET SNJ14AL16



- $V_n \sim 3 \text{ nV Hz}^{-1/2} \text{ at } 100 \text{ Hz}^{-1/2}$
 - $I_n < 5 \times 10^{-17} \text{ A Hz}^{-1/2}$
- Not impedance matched.
- Noise temperature at 40 M Ω , 200 Hz: **4 mK** (10⁶ times quantum limit at that frequency.)

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16-channel pulse processing electronics

Single electron transistors





Electron-beam lithography

Aluminum tunnel junctions

Schoelkopf et. al.

- Typically: C < 1 fF
 V_n ~ 30 nV Hz^{-1/2}
- Impedance set by feedback resistor $R_{FB} \sim 100 \text{ M}\Omega$
- Not impedance matched ($R_{match} \sim 100 \text{ G}\Omega$ at 1.6 kHz)
- Noise temperature at 100 M Ω , 1.6 kHz: **150 mK** (4 x 10⁶ times quantum limit at that frequency.) Devoret and Schoelkopf, *Nature* **406** (2000) 1039 calculates the limits

on S_I , S_V , S_{IV} , $E_n \sim 4 x$ quantum limit (impedance matched).





Multiplexed RFSETs



HEMTs are microwave amplifiers operated at ~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







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

• TES bias resistance R_{bias} ~ 5 mΩ, not too far from impedance matched • Noise temperature at 5 mΩ, 10 kHz: **90** µK (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



Need an L/R low-pass filter and switch at each pixel

Frequency-Division SQUID MUX



Need an LC tank filter at each pixel



Multiplexed γ -ray calorimeters



multiplexing does not degrade sensor performance

J.N.Ullom, Livermore, Berkeley

Berkeley LC Filters



Resonant Filter Chip





Capacitors

Nb₂O₅ capacitors

1 cm



Time-division MUX cast of thousands

NIST

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RE: a multiplexed 8-pixel TES bolometer

Presented at LTD-9

atomited

- 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 TES bolometer array



The 8-Channel TDM chip

32-Channel MUX Chip



Multiplexes up to 32 channels in one column.

A kilopixel array requires 32 chips, power dissipation ~ 100 nW total.



Column

output



Input channels

100 mK ADR Test Facility





MUX chip







Results: Randy Doriese's poster E05

SCUBA-2 MUX pixel







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

Hot-Electron Switches



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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