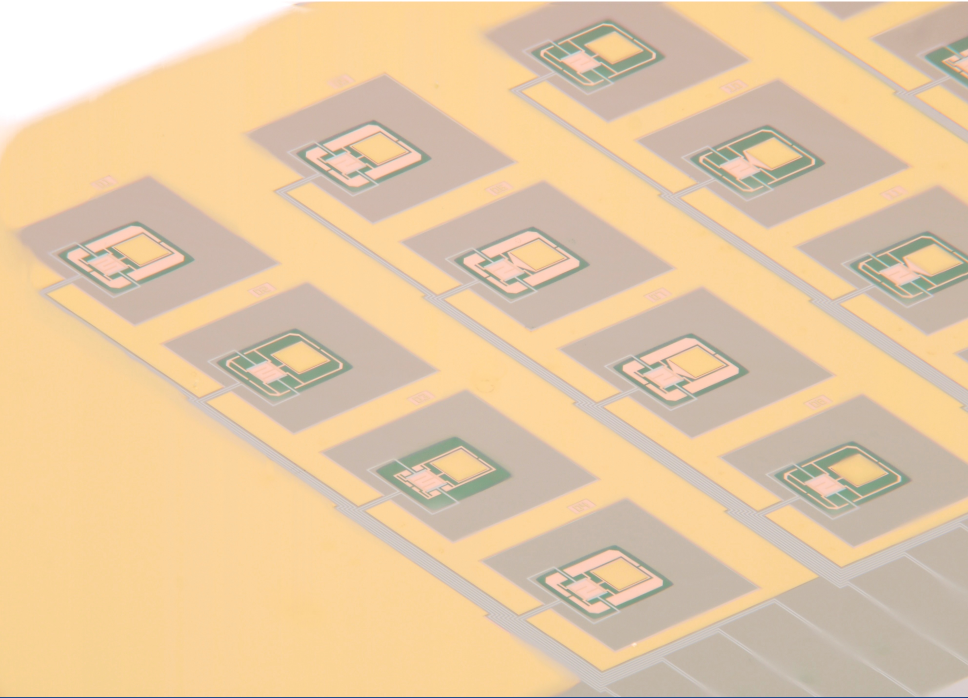


Pixel Design for HOLMES

motivation, design, and performance

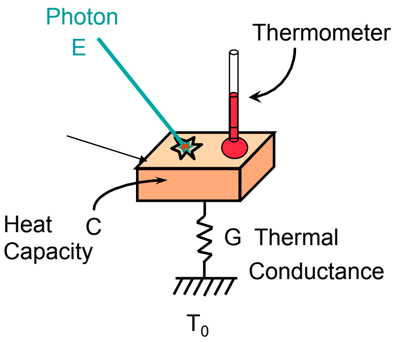
James Hays-Wehle

INFN Sezione di Milano-Bicocca

National Institute of Standards and Technology

Contents

The microcalorimeter



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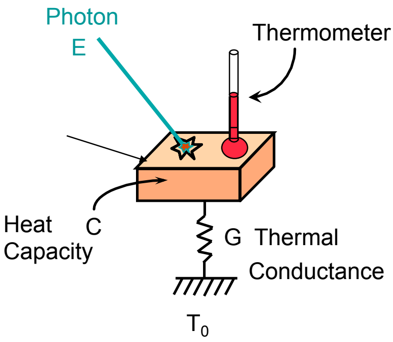
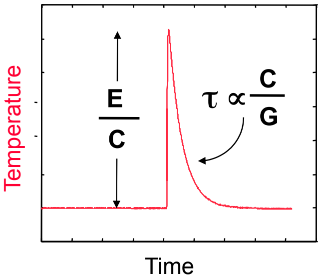


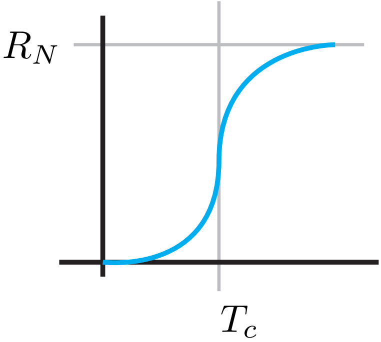


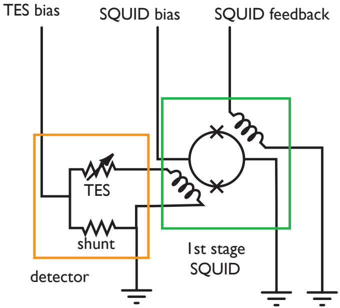
Microcalorimeter

- bulk absorbs energy, converts to heat
- thermometer reads increase in temperature
- pulse shape determined by thermal properties

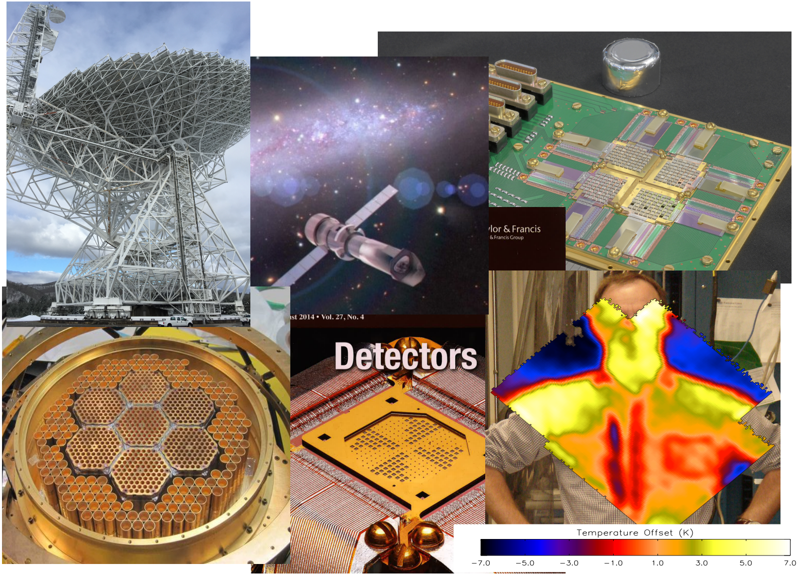
The Transition Edge Sensor

- superconductor at its transition temperature, T_C typically $\sim$100 mK
- within the transition, small temperature excursions result in large resistance change
- current change read out by SQUID





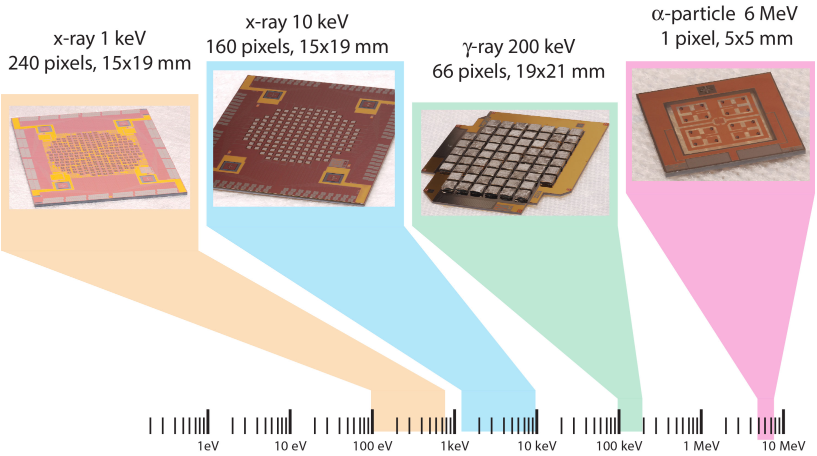
Uses for TESs



Deployed TES spectrometers

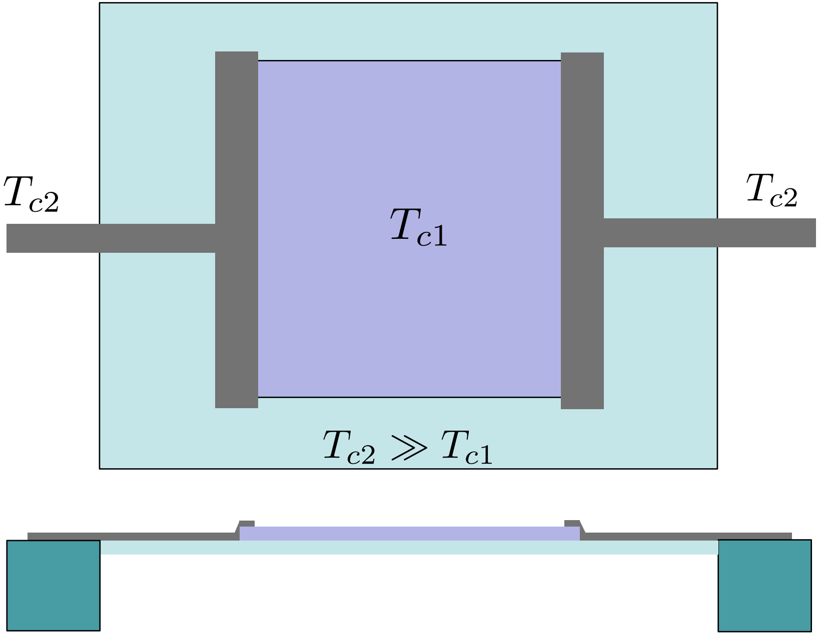
NIST TES spectrometers with worldwide collaborators

Energy Range of TES microcalorimeters



Many arrays of pixels used for all sorts of spectrometers.

Basic TES design



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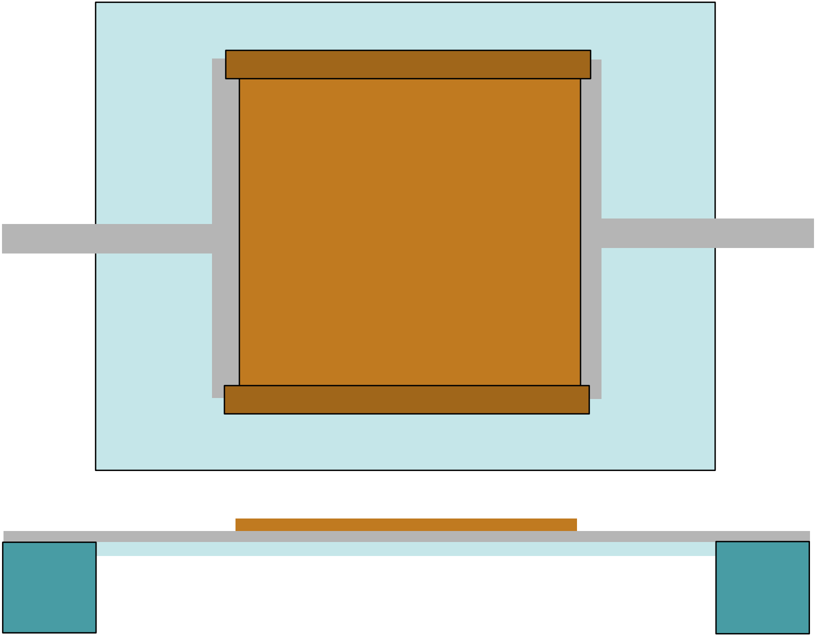
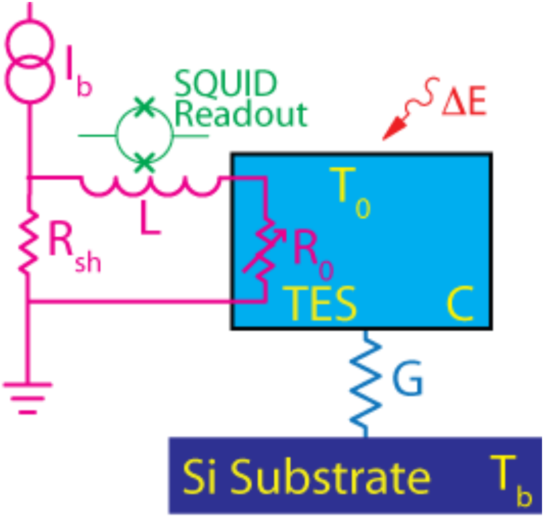
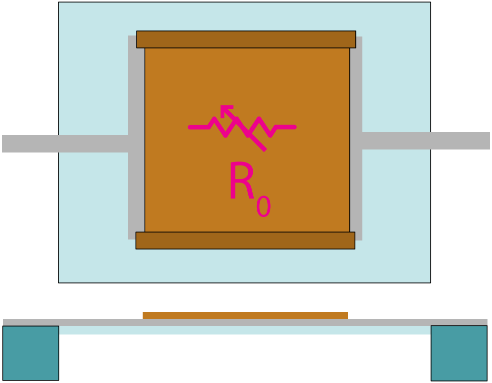
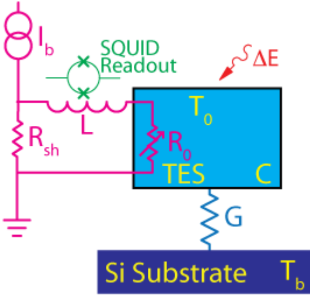


Schematic representation of TES microcalorimeter



Correspondence to Schematic





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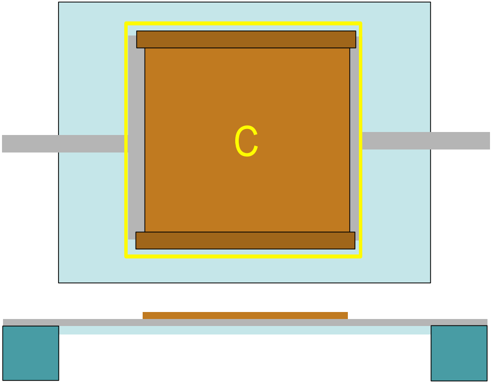

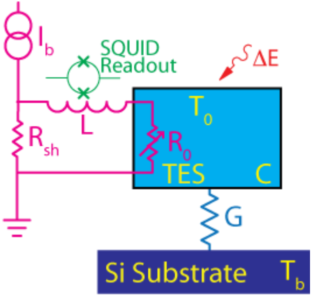

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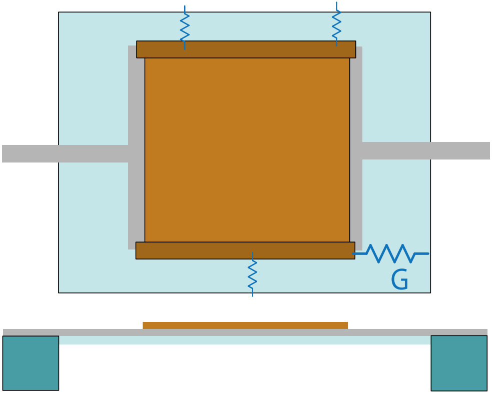
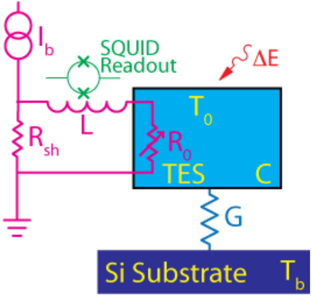
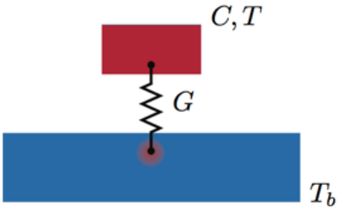
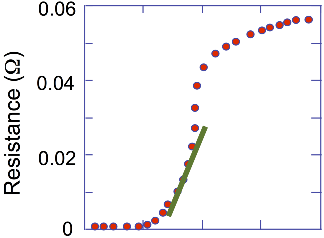




Characterization





Important Parameters

- C, heat capacity

$$C \equiv \frac{\partial E}{\partial T}$$

- G, thermal conductivity

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- α, temperature sensitivity

$$\alpha \equiv \frac{T}{R}\frac{\partial R}{\partial T}$$

- β, current sensitivity

$$\beta \equiv \frac{I}{R}\frac{\partial R}{\partial I}$$

Characterization

Parameters determine behavior of device:

- Resolution

$$\Delta E \propto \sqrt{\frac{4k_B T^2 C(1+\beta)}{\alpha}}$$

- Rise Time

$$\tau_+ \approx \frac{L}{R_L + R_0(1+\beta)}$$

- Fall Time

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(In low inductance, high gain limit)

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- Compatibility with ion implantation
- Compatibility with multiplexing
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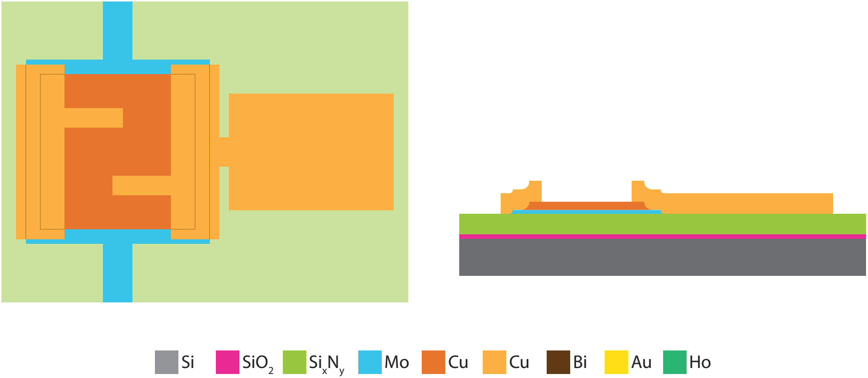
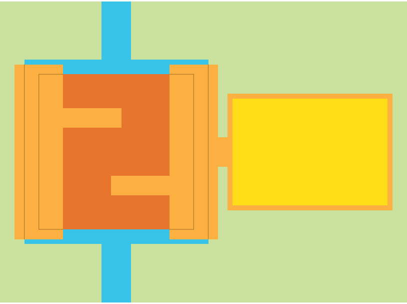
Implanting Scheme



“Sidecar” design

- Ion absorber pad to the side
- Thermal link is integrated copper structure
- 1 μm layer of gold
- Implanted holmium capped with more gold

Implanting Scheme



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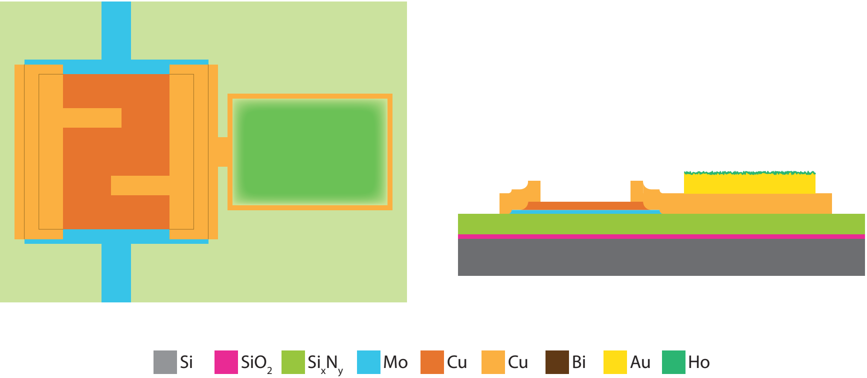

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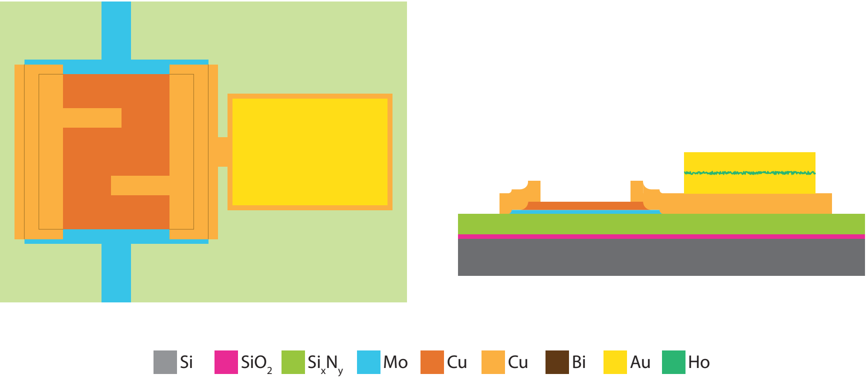

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Given a fixed amount of time, bandwidth, and ^{163}Ho, one could:

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HOLMES has picked the middle path:

- 1000 pixels
- 300 Hz activity
- 500 kHz sampling rate

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See E. Ferri talk next!

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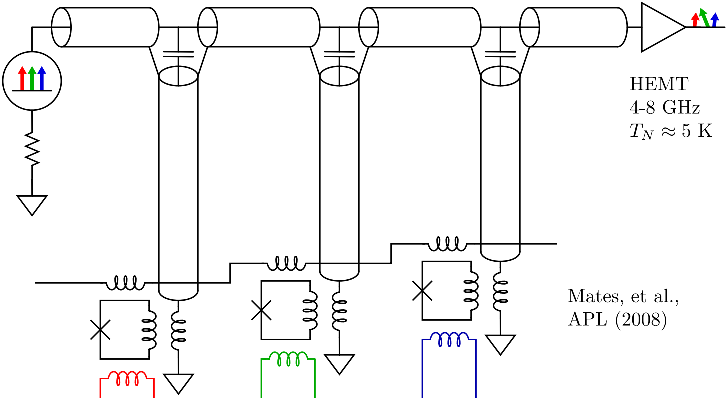
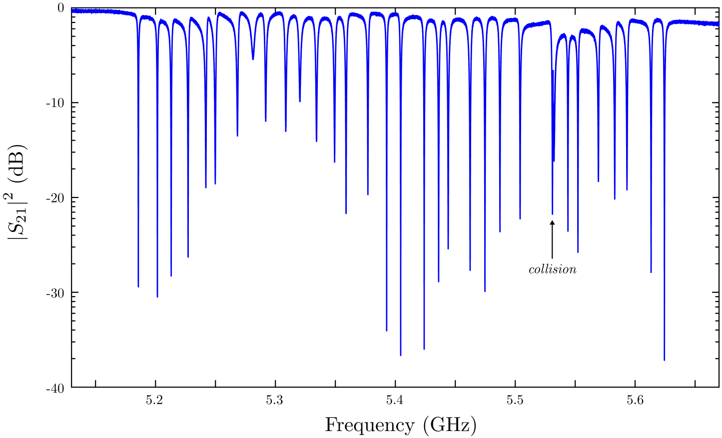


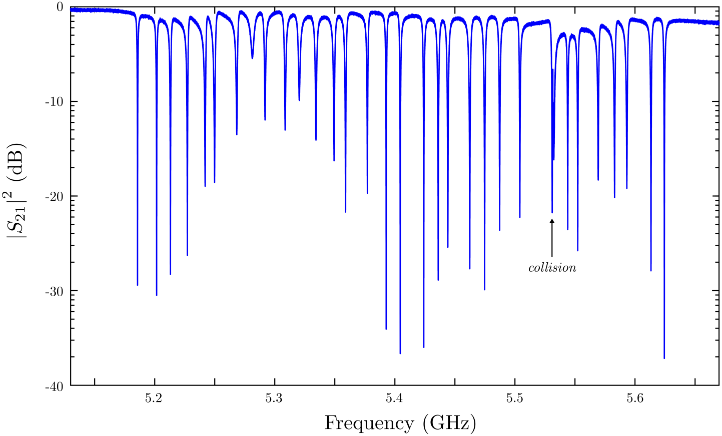
Mates, et al., APL (2008)

Multiplexer



- 2 MHz per channel full bandwidth
- allows ∼ 30 channels to fit onto a 550 MHz ROACH2 ADC

Multiplexer



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- imposes speed limit on rise time <1 A/s or $\tau_+ > 40\mu$s

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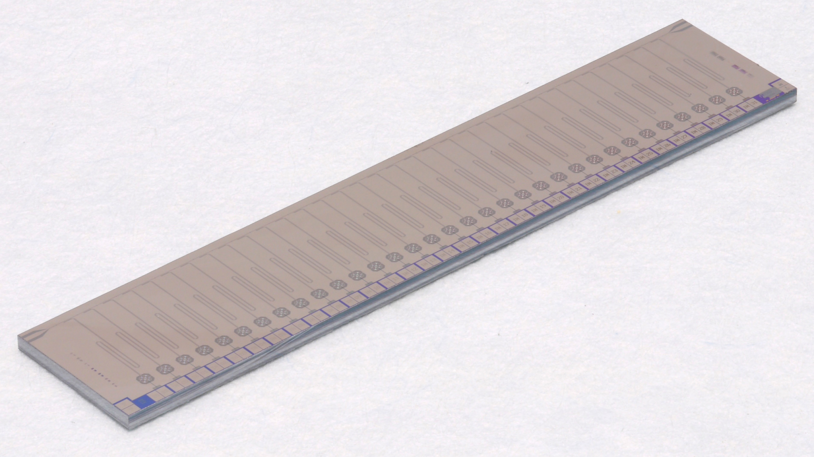

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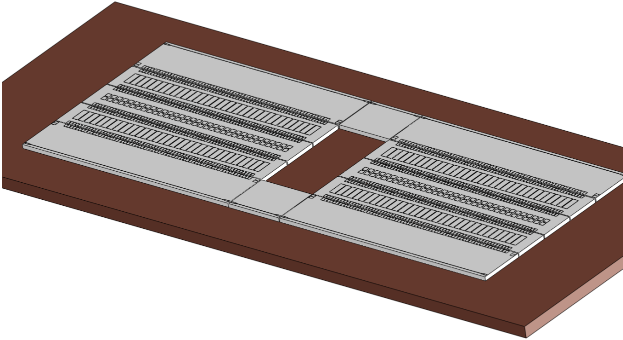
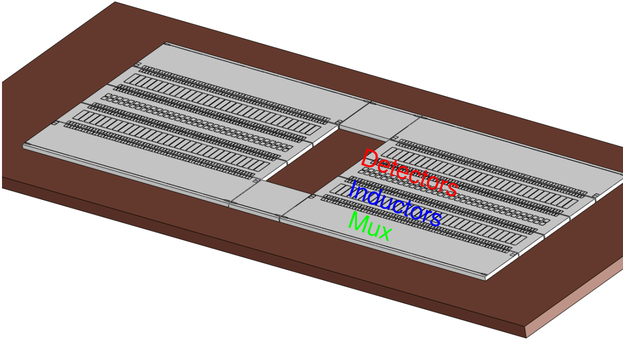


- Modular design allows for separate development of constituent parts.

Multiplexing integration



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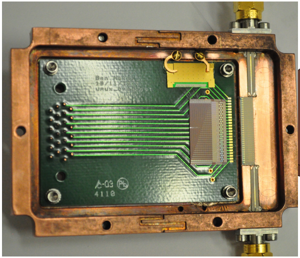

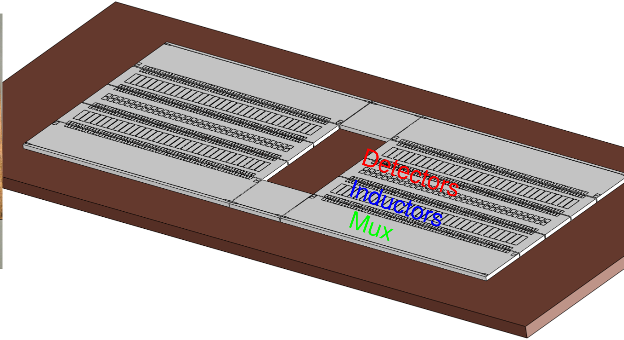

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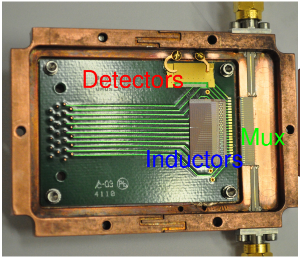
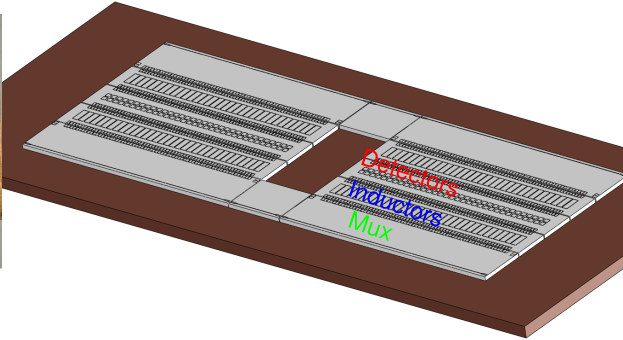
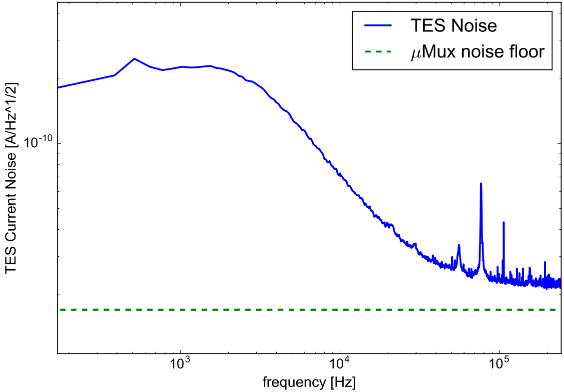




- Modular design allows for separate development of constituent parts.
- Inductance selectable for altering rise time

Expectations for μMux



- TES Johnson noise dominates signal to noise, readout a non-issue
- Tested μMux device has noise comparable to TDM system
- ($\approx$ 23 pA/$\sqrt{\mathrm{Hz}}$)

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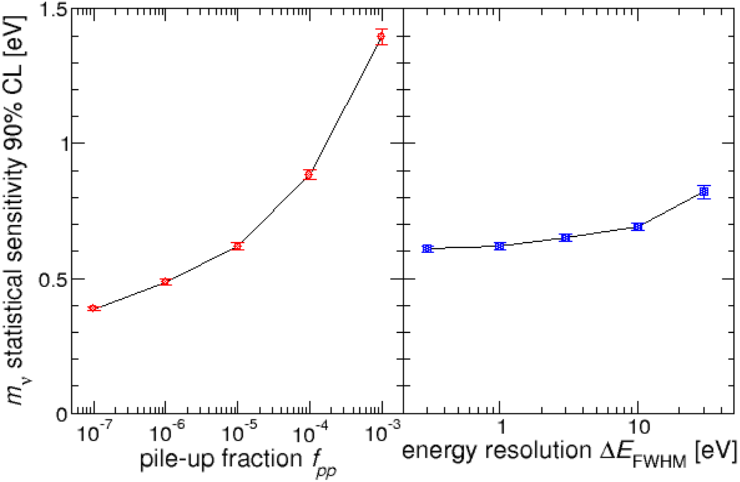
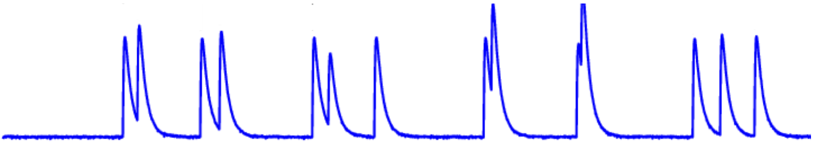
Compatibility with High Count Rate



Final sensitivity on m_{ν_e} depends mostly on statistics and pileup.
Energy resolution only a slight concern.

Two issues with pile-up



Identifying Pile-up

- Coincident pulses that could distort spectra can be cut

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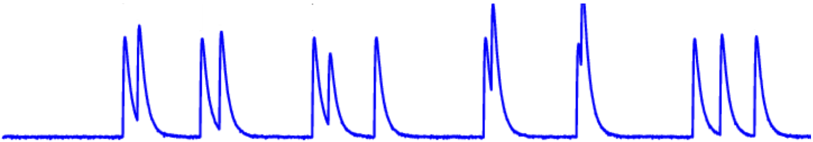


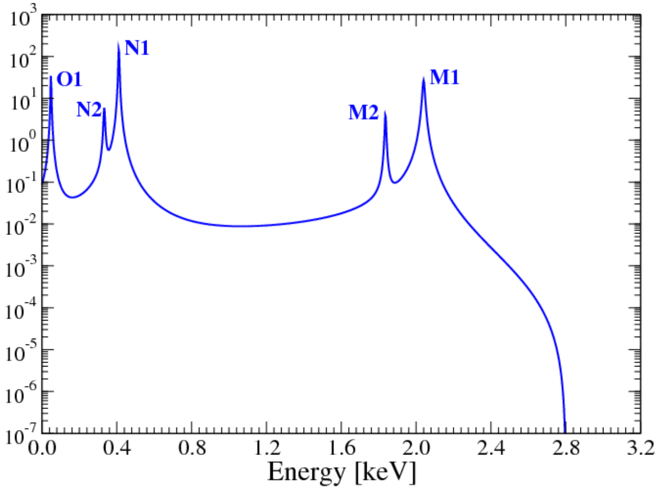
Identifying Pile-up

- Coincident pulses that could distort spectra can be cut

Preventing Pile-up

- Need to integrate many events in a few years
- 300 Hz/pixel planned
- Piled-up pulses are difficult to analyze

Pile-up in HOLMES



- Two common events could be coincident enough to fake a rare one.

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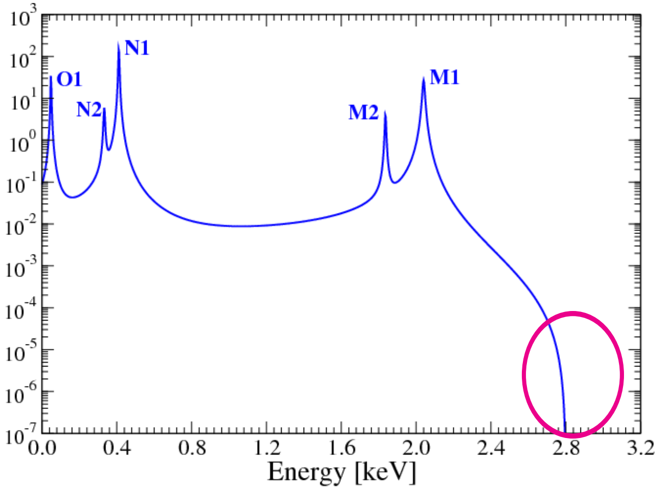

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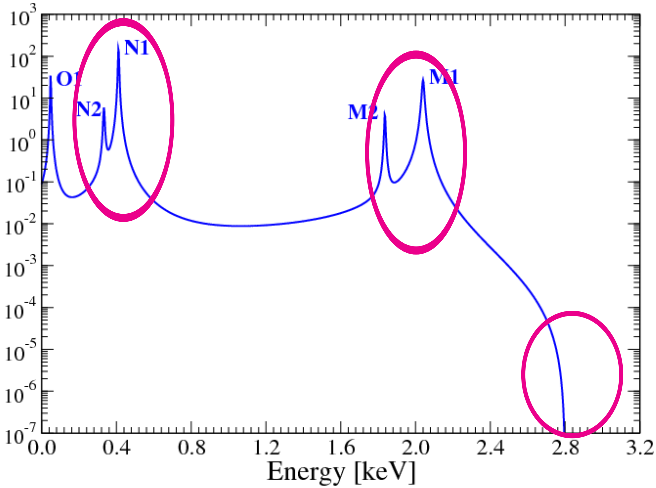

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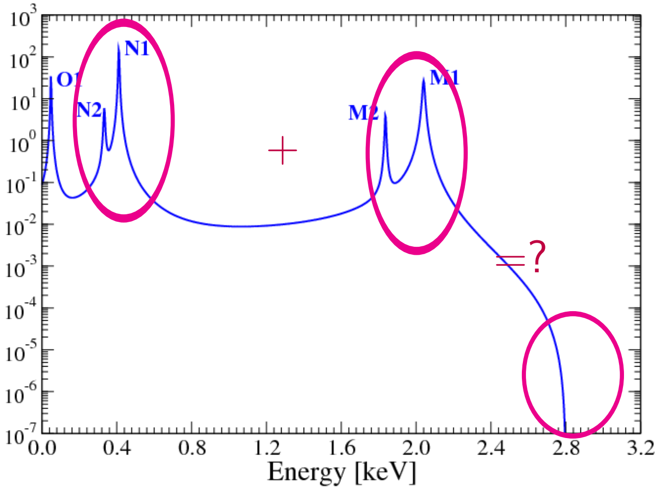
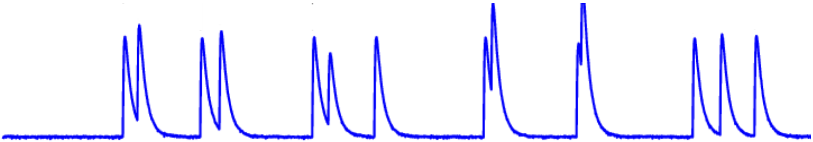


- Two common events could be coincident enough to fake a rare one.
- Identification depends on both sampling and rise time.
- See E. Ferri, next and B. Alpert, 16:30 Today

Two issues with pileup



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Want pulse with short **rise time**

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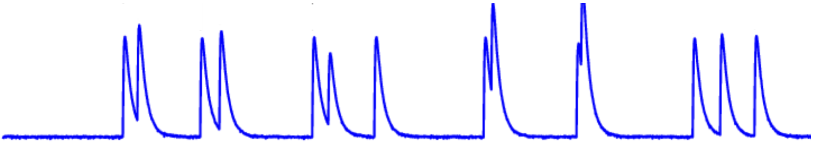

Identifying Pile-up

Want pulse with short **rise time**

Preventing Pile-up

Want pulse with short **duration**

Summary thus far

We want:

- Total pulse duration < 3 ms

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- $\tau_+ <\sim 20\mu s$ (for pileup)

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Summary thus far

We want:

- Total pulse duration < 3 ms
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- $\tau_+ >\sim 40\mu s$ (for multiplexing)
- And $\Delta E < 10$ eV

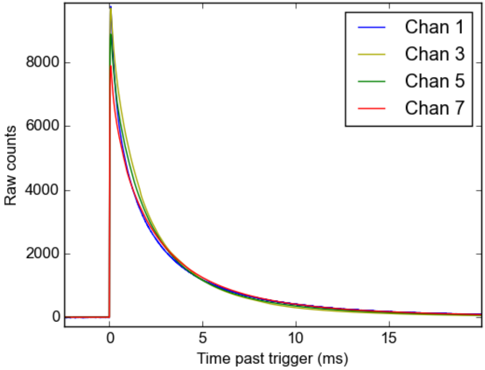
Control of fall time

TES parameters

- C, and α set by targeted energy range. (For HOLMES, $\sim$3 keV)
- $E_{\max} \propto C/\alpha$
- Pulse speed chiefly determined by thermal conductance
- $\tau_{-} \propto C/G$

Goal

Increase G to improve pixel speed



Pulses from non-HOLMES X-ray pixels. $\tau > 1$ms

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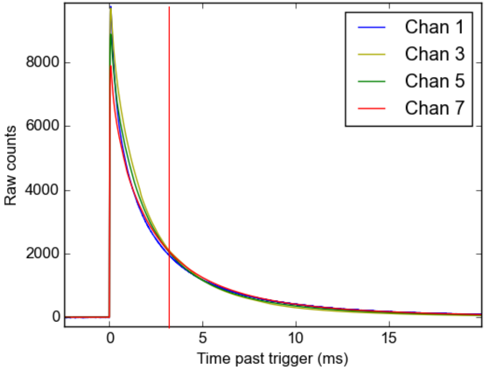

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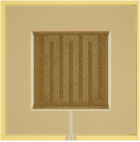
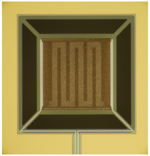
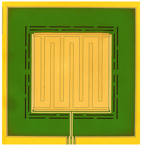
Historical control of G

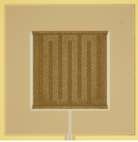


- TES thermally isolated on a SiN_x membrane.

Historical control of G

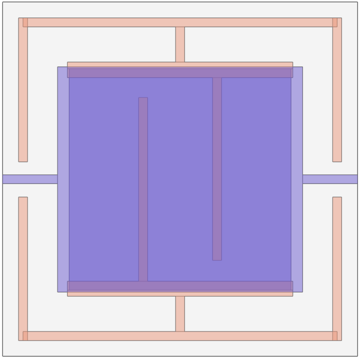


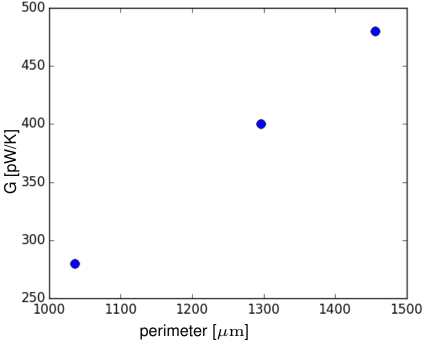




- TES thermally isolated on a SiN_x membrane.
- Perforated membranes used for *smaller G* to meet bandwidth constraints.
- Bare silicon G too much, fixed.

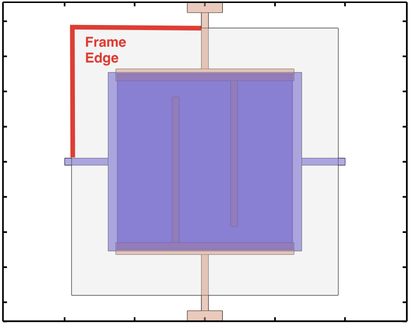
G increasing feature: perimeter

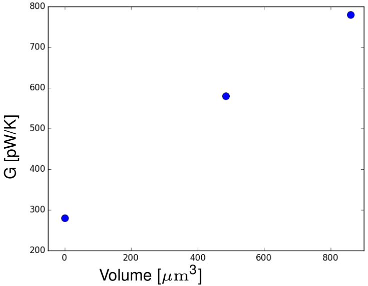




- On a membrane, *G* scales with perimeter.
  - Understood from 2-D ballistic phonon transport
- Test design doubles *G* relative to baseline device

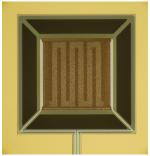
G increasing feature: patches

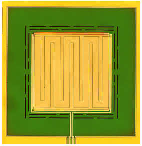


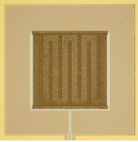


- Copper patches create thermal link directly to the frame
- Added G increases linearly with metal volume on frame
    - Understood from e-p coupling theory
- Test design trebles G of baseline device

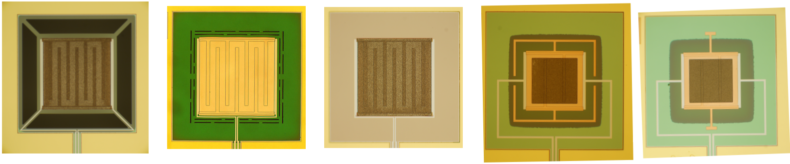
Control of G







Control of *G*

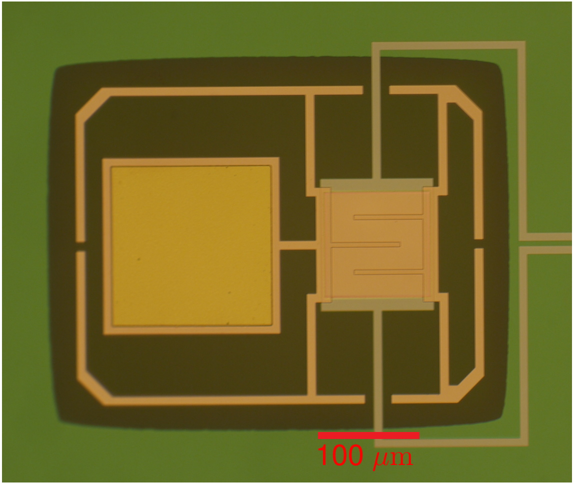


10 pW/K 1 nW/K

Predictable lithographic control of *G* over an order magnitude.

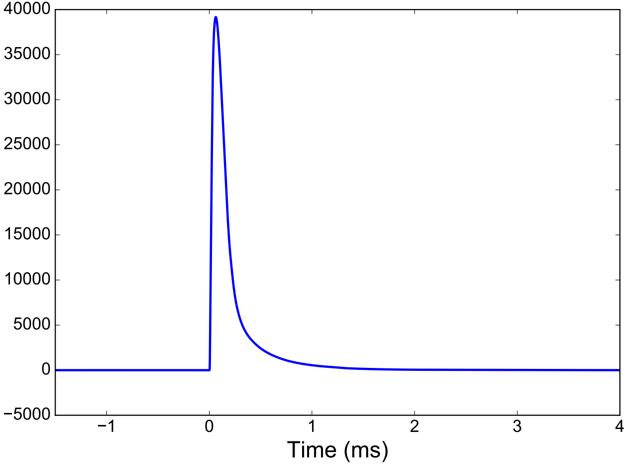
Hays-Wehle *et al.*, "Thermal Conductance Engineering for High-Speed TES Microcalorimeters"
J. Low Temp. Phys. 2016 doi:10.1007/s10909-015-1416-5

Device features



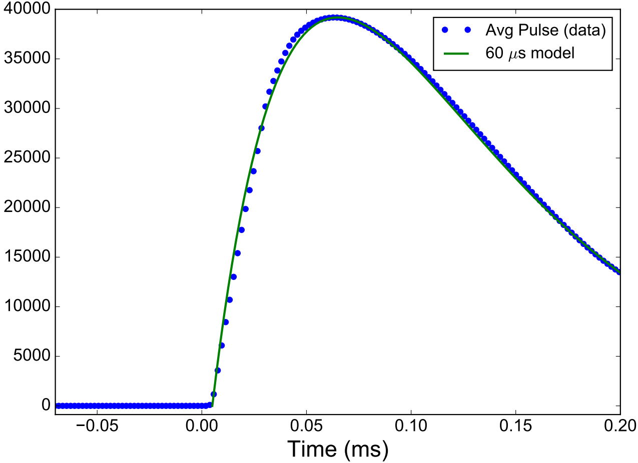
Device has sidecar absorber AND enhanced perimeter

Prototype speed



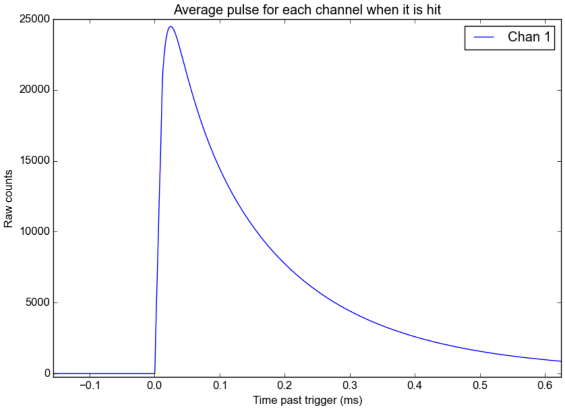
- *G* increased ∼6x (570 pW/K from ∼100 pW/K)
- Total pulse duration $<$ 1 ms

Prototype speed (high L)



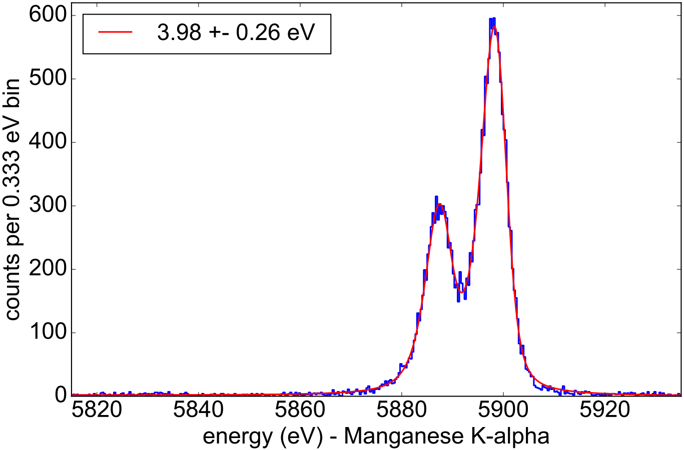
- G increased to 570 pW/K (from ∼100 pW/K)
- $\tau_+ \approx \tau_- \approx 60\mu\text{s}$ (Critically damped)
- At target sample rate (500 kHz) sufficient points on rising edge
- Sparser sampling introduces distortions

Prototype speed (low L)



- Different choice of inductance gives faster rise time
- $\tau_+ \approx 10\mu\mathrm{s}$ shown above, but also $\tau_- \approx 130\mu\mathrm{s}$
- Requires > MHz sampling rate

Prototype Resolution



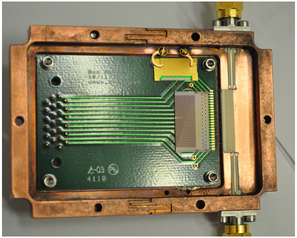
- 4 eV FWHM resolution demonstrated at 5.9 keV with TDM
- $\sim$3 eV expected at 2.8 keV

Conclusions

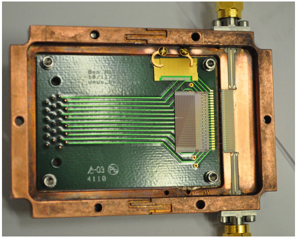
- HOLMES has unique requirements for its sensors
- Rise and fall times are tuned with L and G to match requirements
- Can be tuned again for future upgrades
- Prototype design soon to be used in implanted production arrays

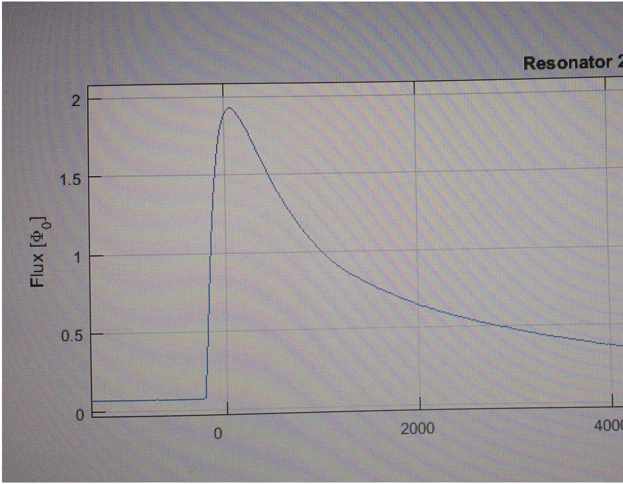
Thank You!

Latest News



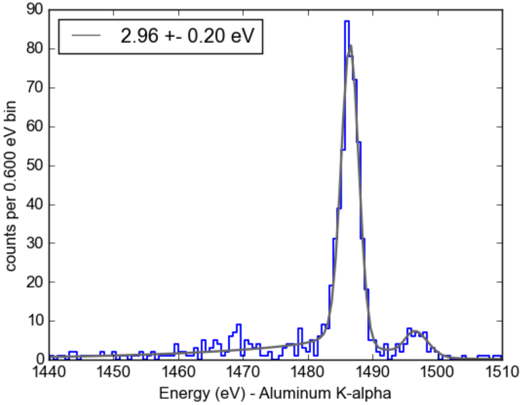
Latest News





On our way to validating this configuration in Milano!

resolution at 1.5 keV



3 eV shown at 1.5 keV, closer to 2.8 keV than 5.9 keV is.

Performance Metrics

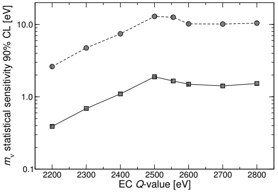


Fig. 4 Monte Carlo estimate of HOLMES neutrino mass statistical sensitivity for $N_{ev} = 3 \times 10^{13}$ (lower) or 10^{10} (upper) and with $f_{pp} = 3 \times 10^{-4}$, $\Delta E_{\mathrm{FWHM}} = 1\,\mathrm{eV}$, and no background.

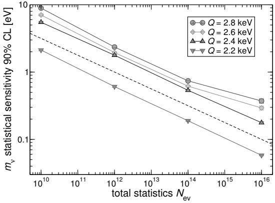
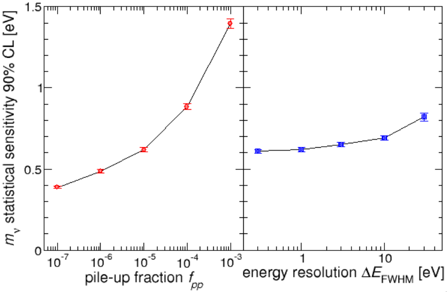
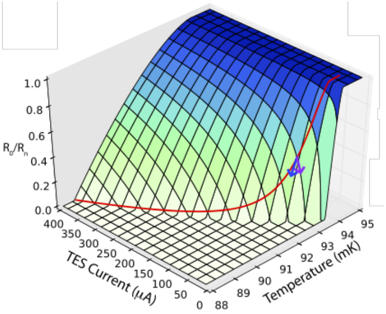


Fig. 3 ^{163}Ho decay experiments statistical sensitivity dependence on the total statistics N_{ev} for $\Delta E_{\mathrm{FWHM}} = 1\,\mathrm{eV}$, $f_{pp} = 10^{-5}$, and no background.

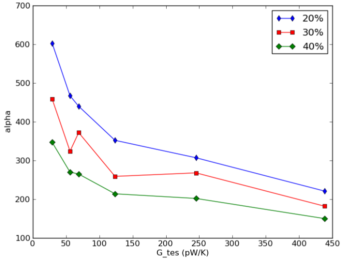


Final sensitivity on m_{ν_e} depends mostly on statistics and pileup.

Bonus Challenge



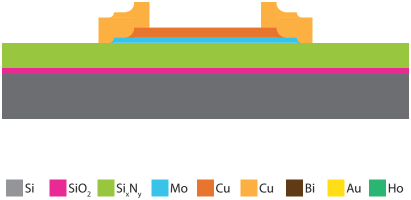
$R(I, T)$ surface in the 2-fluid model.
D. Bennett et al DOI:10.1007/s10909-011-0431-4



Previous experiments show a decreasing trend of α with G.

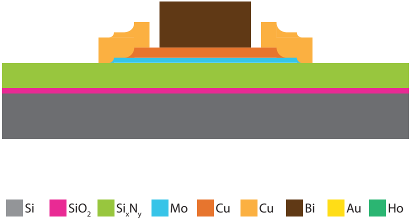
The two fluid model predicts that α is inversely proportional to I/I_C.
Increasing G means increasing the bias current, which in turn suppresses α.
We are exploring devices with higher resistances and fewer bars to compensate for this effect.

Simple scheme for ion implanting



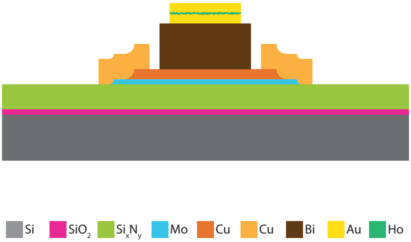
- Begin with TES with Bismuth absorber

Simple scheme for ion implanting



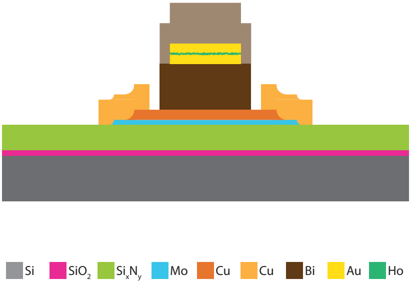
- Begin with TES with Bismuth absorber

Simple scheme for ion implanting



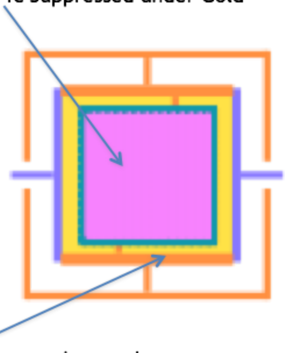
- Begin with TES with Bismuth absorber
- Ho ions implanted in gold above TES

Simple scheme for ion implanting



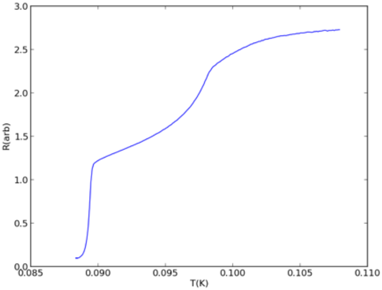
- Begin with TES with Bismuth absorber
- Ho ions implanted in gold above TES
- Capped off with extra Bismuth

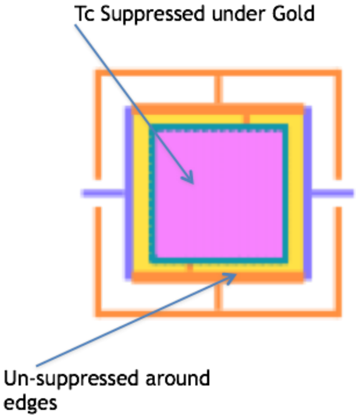
Simple scheme for ion implanting



- Begin with TES with Bismuth absorber
- Ho ions implanted in gold above TES
- Capped off with extra Bismuth
- Gold suppresses T_C of area beneath.

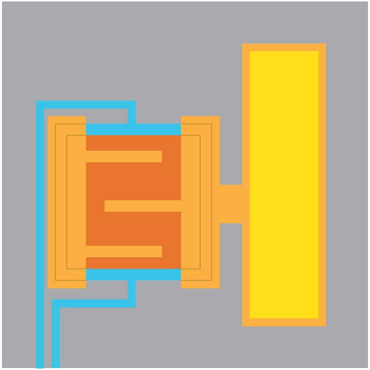
Simple scheme for ion implanting

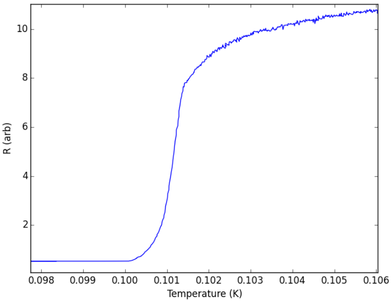




- Begin with TES with Bismuth absorber
- Ho ions implanted in gold above TES
- Gold suppresses T_C of area beneath.
- Double T_C observed.

NEW scheme

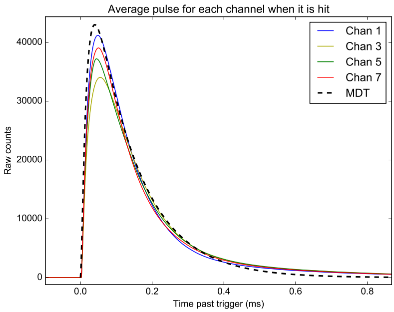


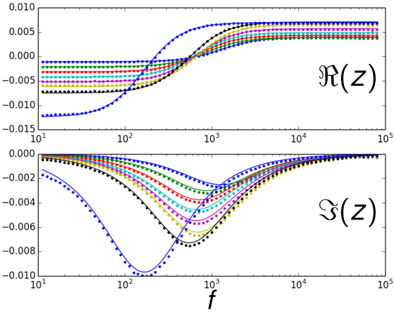


“Sidecar” design

- Moves ion absorber pad to the side
- Thermal link is integrated copper structure
- Superconducting transition is restored
- Eliminates bismuth layer

Two-Body effects

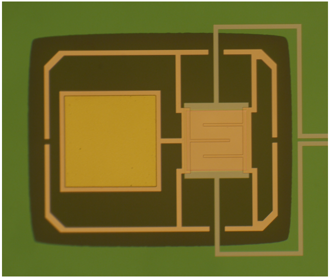


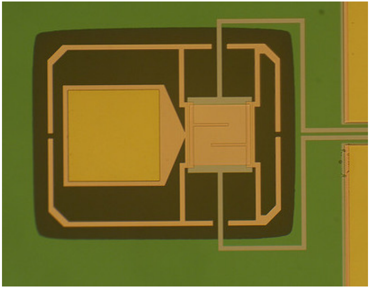


Dark testing

- Impedance and noise suggest two body structure:
- $C_1 \approx 0.2$ pJ/K (TES), $C_2 \approx 0.5$ pJ/K (Absorber)
- and $G_2 \approx 70$ nW/K
- Born out by pulse shape

Two-Body effects II





Dark testing

- G_2 4x lower than predicted by Wiedemann-Franz
- And shows no variation between connection designs
- Possibly connection between metal layers?
- However, $G_2 >> G$, so $G_2 \to \infty$ makes only marginal difference to noise, fall time
- New fabrication run to investigate regardless