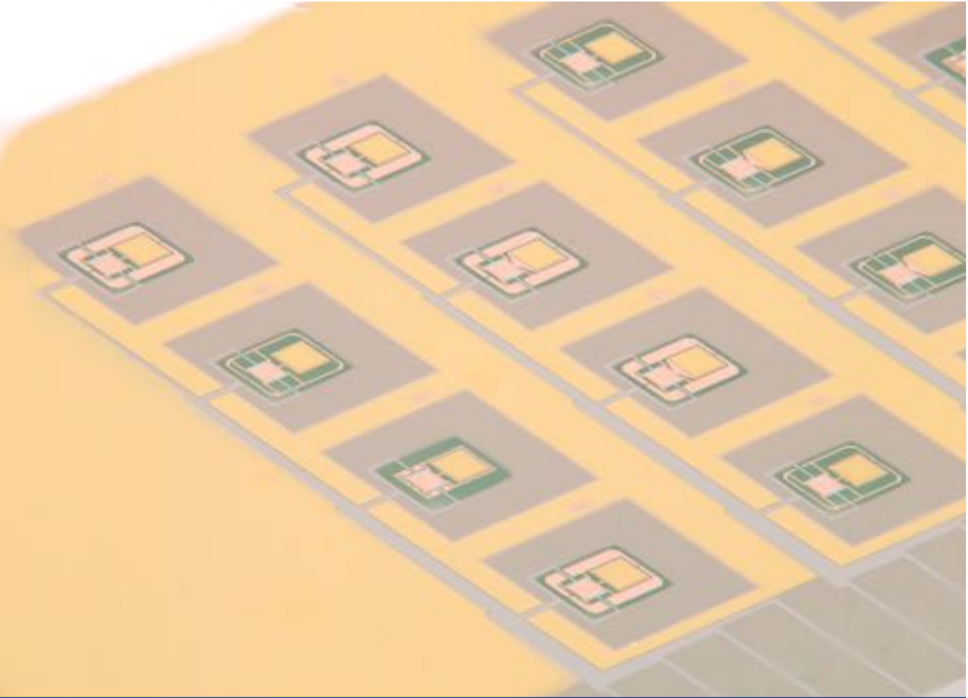

Pixel Design for HOLMES

motivation, design, and performance

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Angelo Nucciotti,[†] Daniel Swetz,[*] Joel Ullom[*]

[†] *INFN Sezione di Milano-Bicocca*

[*] *National Institute of Standards and Technology*

HOLMES

- TES embedded with ^{163}Ho
- Measure total energy, *Q*, of decay
- Spectrum endpoint sensitive to neutrino mass

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- 1000 pixels
- 300 cps/pixel
- Microwave Multiplexed

Demands of the HOLMES Pixel

- high count rate
- multiplexable
- implanted ions

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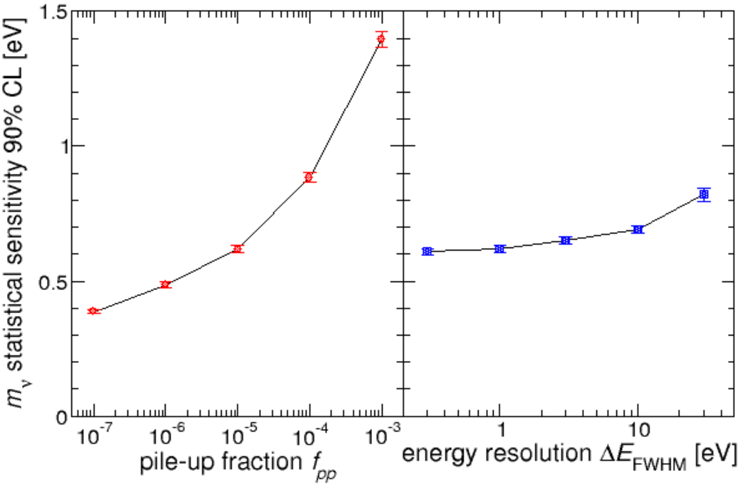
Compatibility with High Count Rate



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

Two issues with pile-up

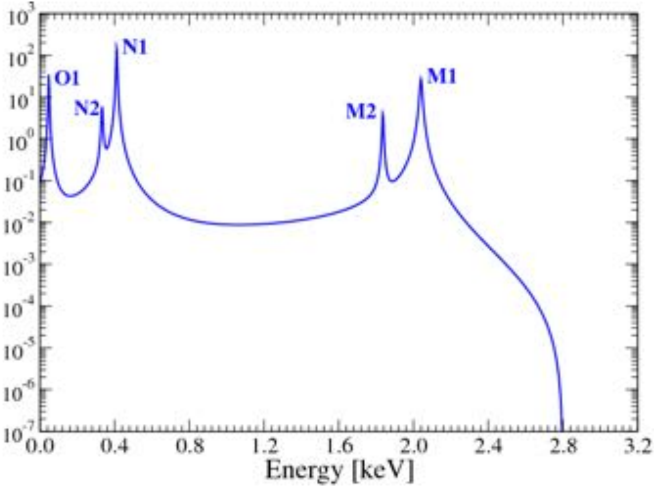
Identifying Pile-up

- Coincident pulses that could distort spectra can be cut

Preventing Pile-up

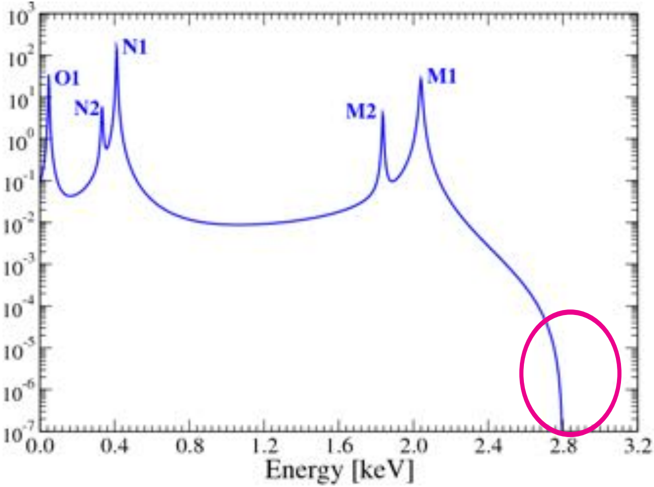
- Need to integrate many events in a few years
- 300 Hz/pixel planned
- Piled-up pulses are difficult to analyze

Pile-up in HOLMES



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

Pile-up in HOLMES



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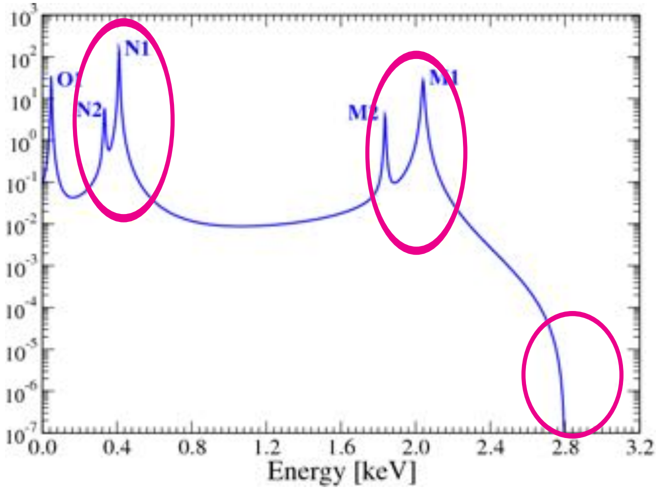

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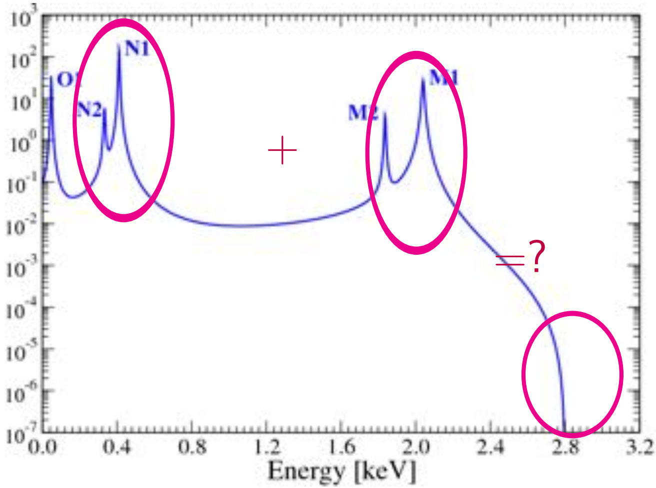
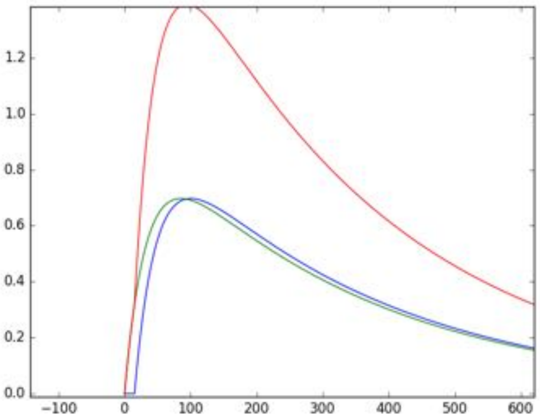
Pile-up in HOLMES



- Two common events could be coincident enough to fake a rare one.
- Identification depends on both sampling and rise time.

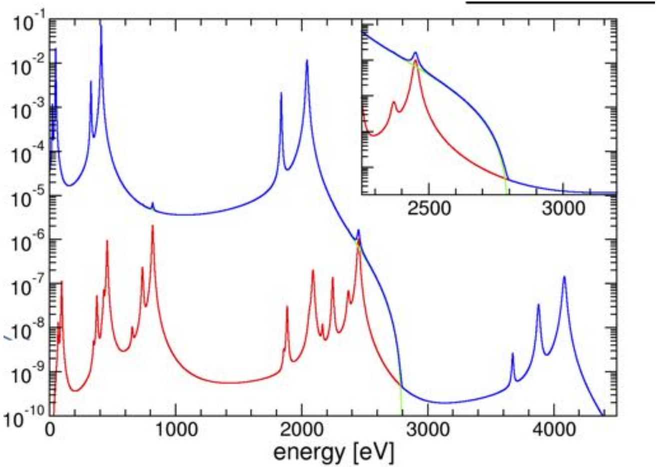
Coincident Pulses



Two pulses, green and blue, arrive separated by ΔT
Measured sum has kink

For a given ΔT, detectability of kink depends on rise time, τ_+

Simulated Pile-Up



true spectrum and pileup spectrum sum to measured spectrum.

Two issues with pileup

Identifying Pile-up

Want pulse with short **rise time**

Two issues with pileup

Identifying Pile-up

Want pulse with short **rise time**

Preventing Pile-up

Want pulse with short **duration** (fall time)

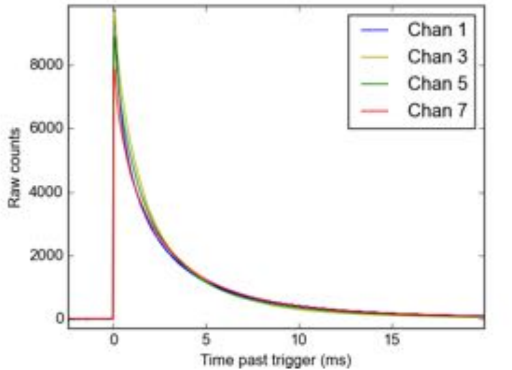
Control of fall time

TES parameters

- C, and α set by targeted energy range. (For HOLMES, ~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

Control of fall time

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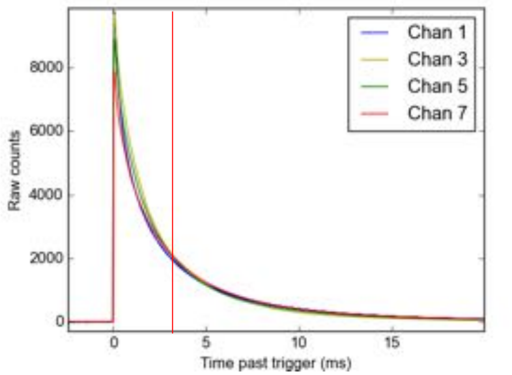
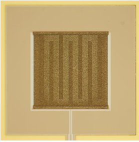


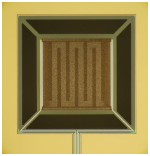
Pulses from non-HOLMES X-ray pixels. $\tau > 1$ms

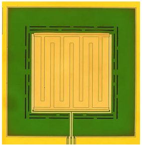
Historical control of G

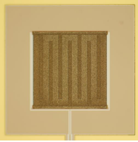


- TES thermally isolated on a SiN_x membrane.

Historical control of G

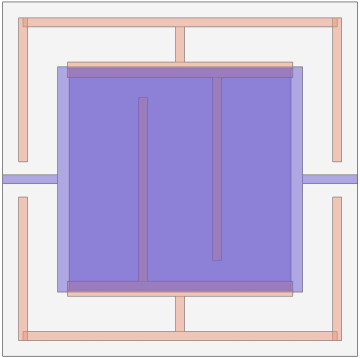


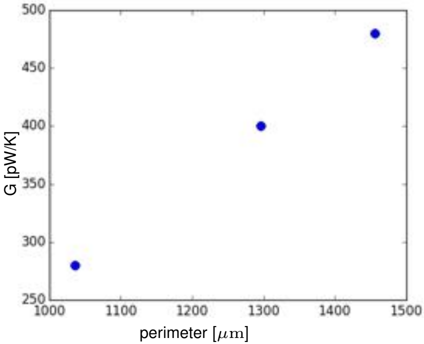




- TES thermally isolated on a SiN_x membrane.
- Perforated membranes used for *smaller G* to meet bandwidth constraints.
- Bare silicon G too much, fixed.

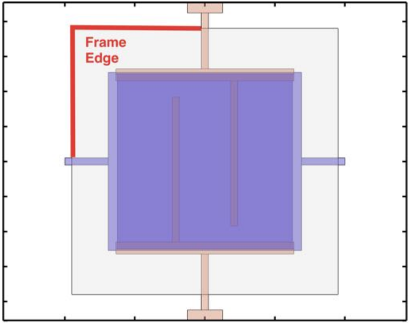
G increasing feature: perimeter

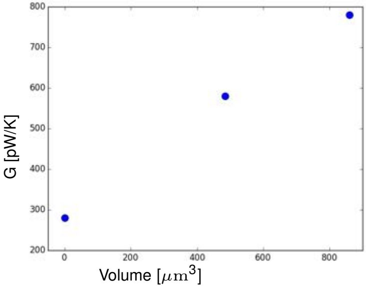




- On a membrane, *G* scales with perimeter.
  - Understood from 2-D ballistic phonon transport
- Test design doubles *G* relative to baseline device

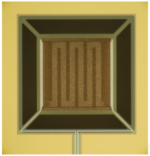
G increasing feature: patches

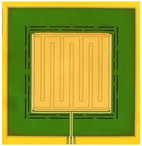


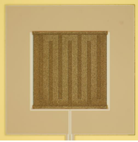


- Copper patches create thermal link directly to the frame
- Added G increases linearly with metal volume on frame
  - Understood from e-p coupling theory
- Test design trebles G of baseline device

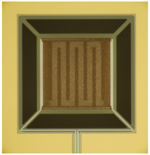
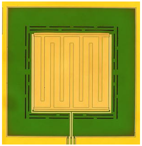
Control of *G*

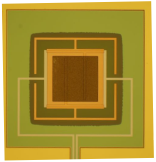
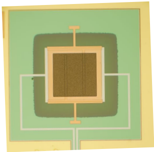






Control of *G*

10 pW/K 1 nW/K

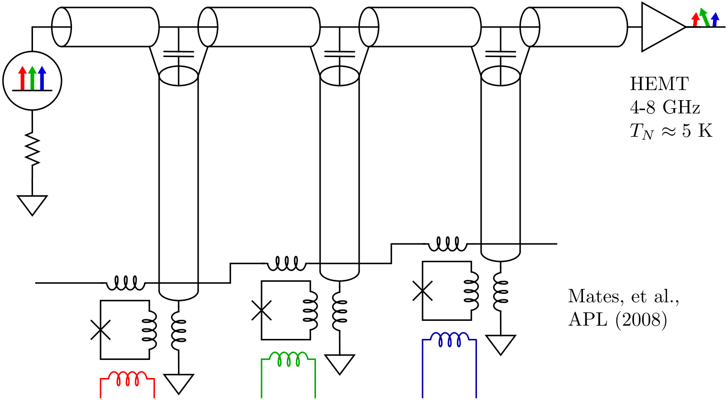
Predictable lithographic control of *G* over an order magnitude.

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

Demands of the HOLMES Pixel

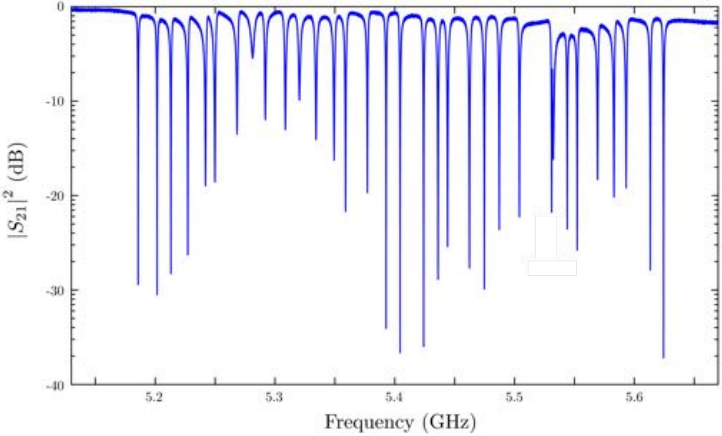
- high count rate
- **multiplexable**
- implanted ions

Multiplexing Scheme



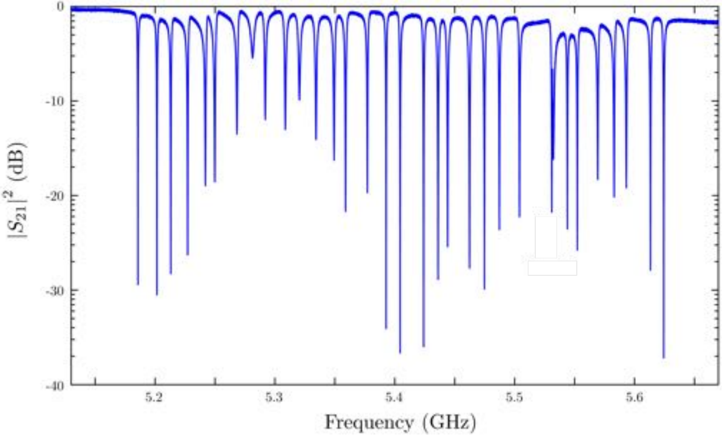
Mates, et al.,
APL (2008)

Multiplexer



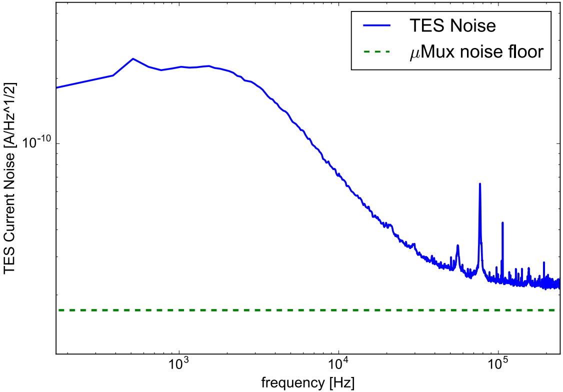
- 2 MHz per channel full bandwidth
- 33 channels per 550 MHz ROACH2 ADC

Multiplexer



- 2 MHz per channel full bandwidth
- 33 channels per 550 MHz ROACH2 ADC
- $2\Phi_0$ ramp $\rightarrow$ corresponds to a sampling rate of 500 kHz
- imposes speed limit on rise time <1 A/s or $\tau_+ > 20\mu$s

Expectations for μMux

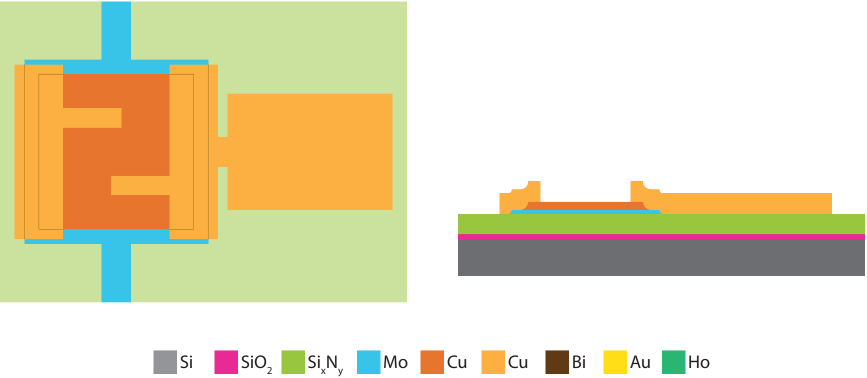


- TES Johnson noise dominates signal to noise, readout a non-issue
- Tested μMux device has low enough noise
- ($\approx$ 27 pA/$\sqrt{\mathrm{Hz}}$)

Demands of the HOLMES Pixel

- high count rate
- multiplexable
- **implanted ions**

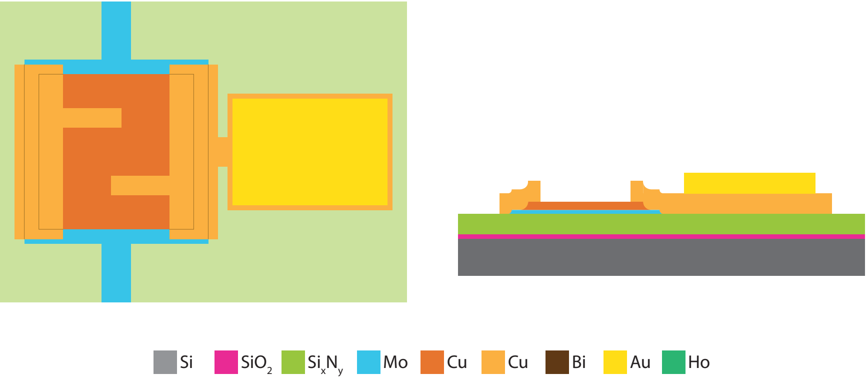
Implanting Scheme



“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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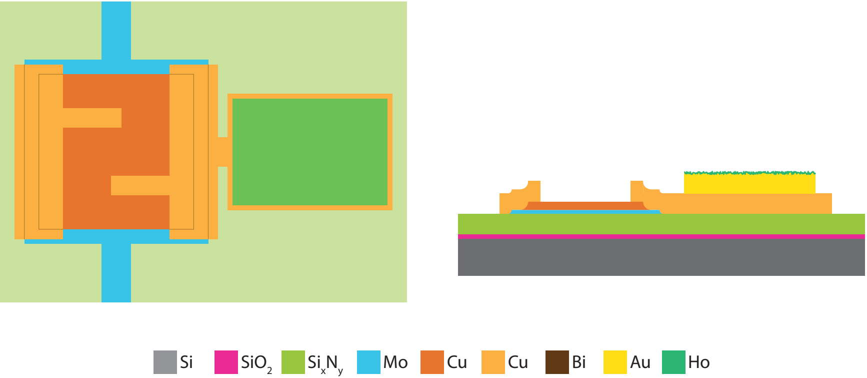

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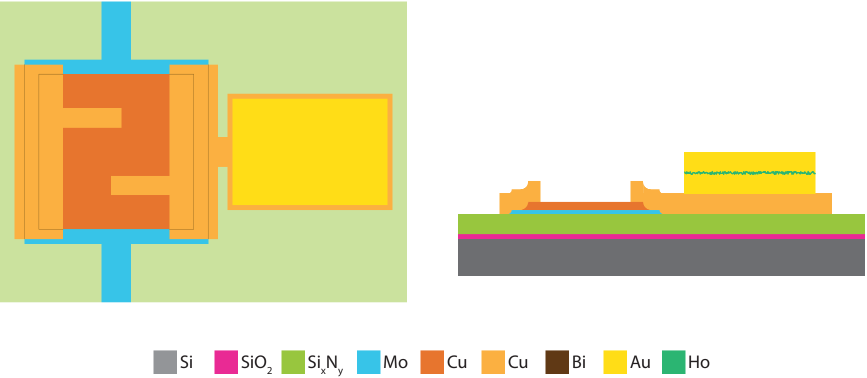

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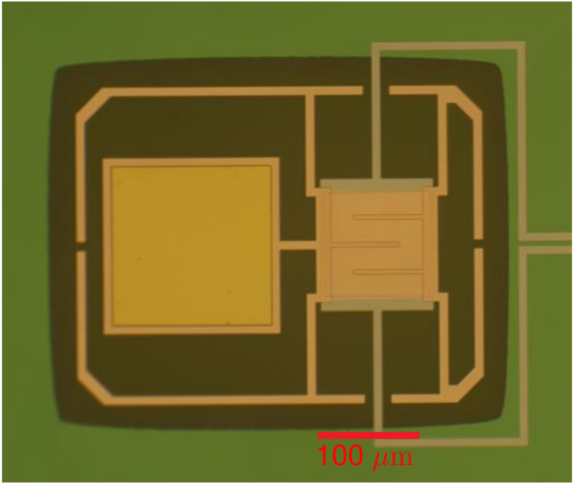
Device features



Device has sidecar absorber AND enhanced perimeter

Performance requirements

We want:

- Total pulse duration < 3 ms

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- $20\mu\text{s} < \tau_+ < 50\mu\text{s}$
- (faster for pile-up, slower for multiplexing)

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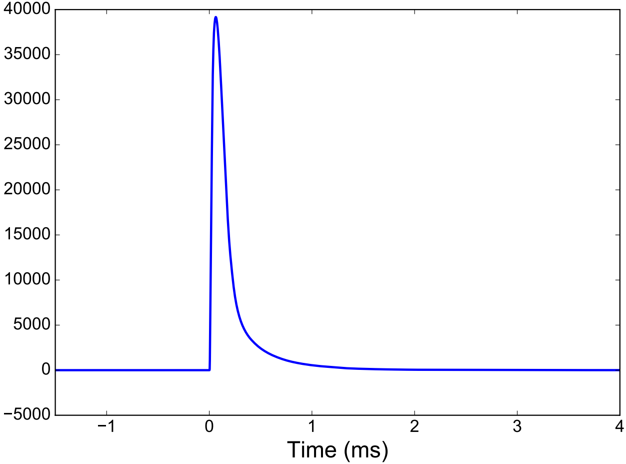
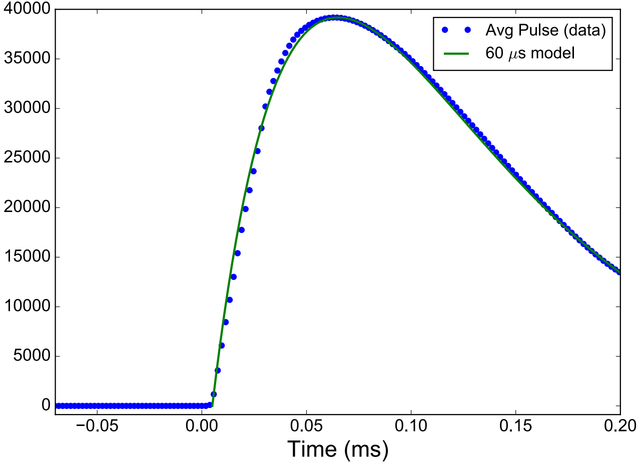
- Total pulse duration < 3 ms
- 20μs $< \tau_+ <$ 50μs
- (faster for pile-up, slower for multiplexing)
- And $\Delta E < 10$ eV

Prototype speed



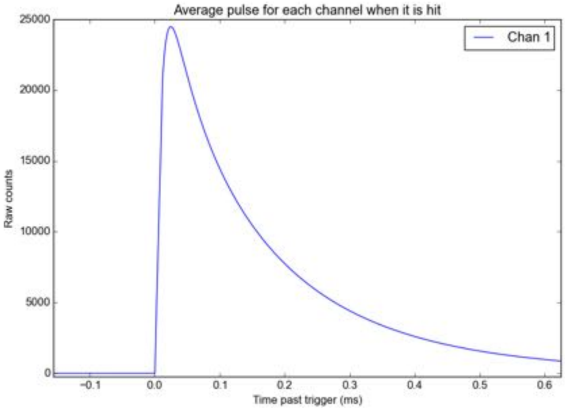
- G increased $\sim$6x (580 pW/K from $\sim$100 pW/K)
- Total pulse duration $<$ 1 ms

Prototype speed (high *L*)



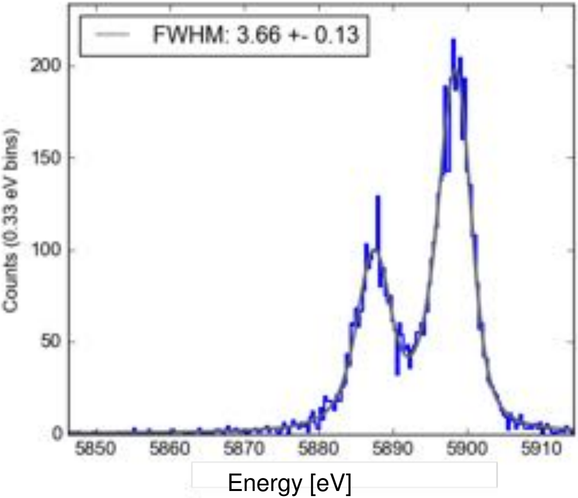
- *G* increased to 570 pW/K (from ∼100 pW/K)
- $\tau_+ \approx \tau_- \approx 60\mu\mathrm{s}$ (Critically damped)
- At target sample rate (500 kHz) sufficient points on rising edge

Prototype speed (low L)



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

Prototype Resolution



- 3.7 eV FWHM resolution demonstrated at 5.9 keV
- No low energy tail
- 3 eV at 1.5 keV

Conclusions

- Pixel requirements similar to that for FAST x-ray device
- Rise and fall times are tuned with L and G to match requirements

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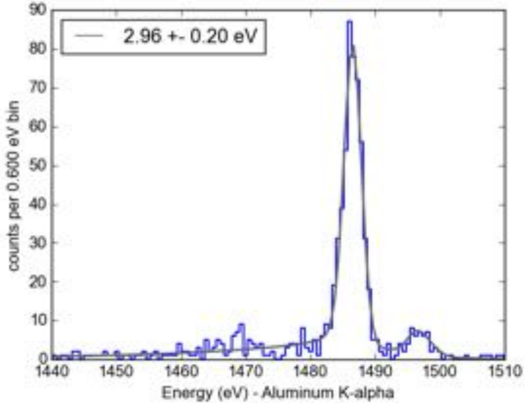
- Pixel requirements similar to that for FAST x-ray device
- Rise and fall times are tuned with L and G to match requirements

- Can be tuned again for future upgrades
- Prototype design soon to be used in implanted production arrays

Thank You!

resolution at 1.5 keV



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

Performance Metrics

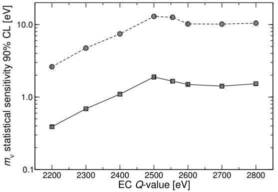


Fig. 4 Monte Carlo estimate of HOLMES neutrino mass statistical sensitivity for $N_{ev} = 3 \times 10^{13}$ (lower) or 10^{10} (upper) and with $f_{pp} = 3 \times 10^{-4}$, $\Delta E_{\rm FWHM} = 1\,\rm eV$, and no background.

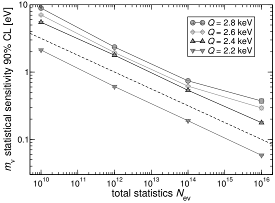
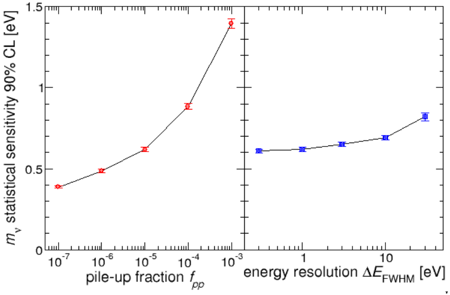
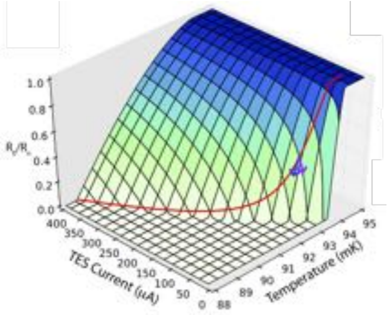


Fig. 3 ^{163}Ho decay experiments statistical sensitivity dependence on the total statistics N_{ev} for $\Delta E_{\rm FWHM} = 1\,\rm eV$, $f_{pp} = 10^{-5}$, and no background.

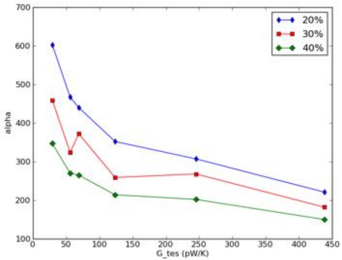


Final sensitivity on m_{ν_e} depends mostly on statistics and pileup.

Bonus Challenge



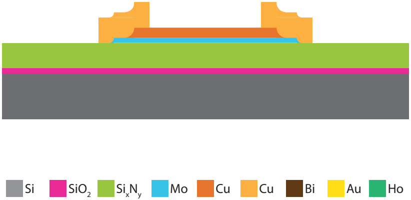
$R(I, T)$ surface in the 2-fluid model.
D. Bennett et al DOI:10.1007/s10909-011-0431-4



Previous experiments show a decreasing trend of α with G.

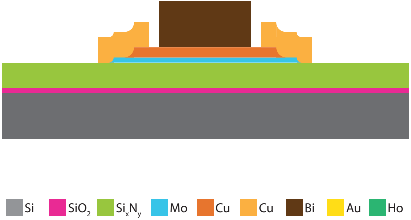
The two fluid model predicts that α is inversely proportional to I/I_C.
Increasing G means increasing the bias current, which in turn suppresses α.
We are exploring devices with higher resistances and fewer bars to compensate for this effect.

Simple scheme for ion implanting



- Begin with TES with Bismuth absorber

Simple scheme for ion implanting



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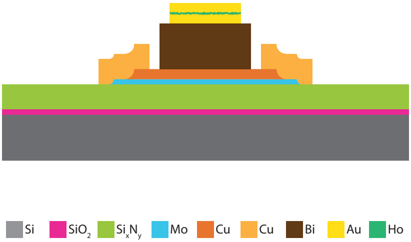
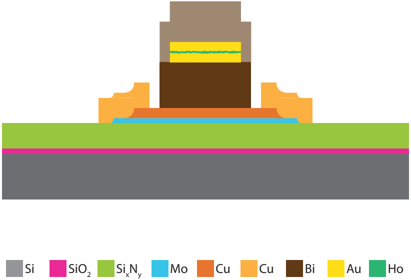


- Begin with TES with Bismuth absorber
- Ho ions implanted in gold above TES

Simple scheme for ion implanting



- Begin with TES with Bismuth absorber
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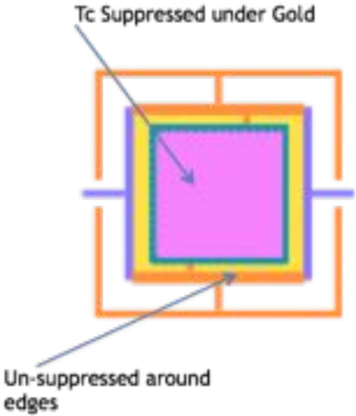
- Capped off with extra Bismuth

Simple scheme for ion implanting



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- Gold suppresses T_C of area beneath.

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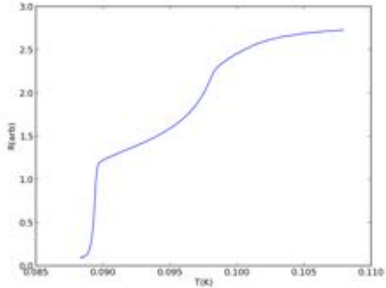
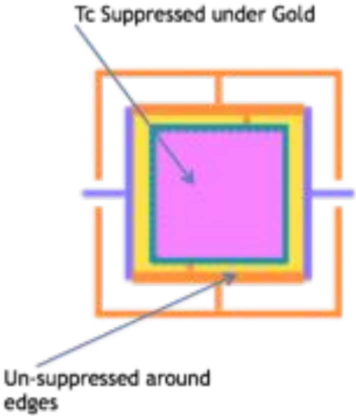
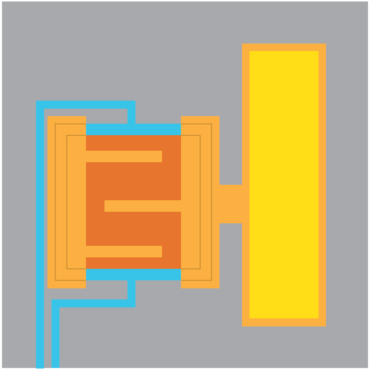
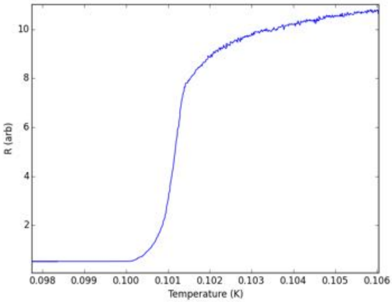




- Begin with TES with Bismuth absorber
- Ho ions implanted in gold above TES
- Gold suppresses T_C of area beneath.
- Double T_C observed.

NEW scheme

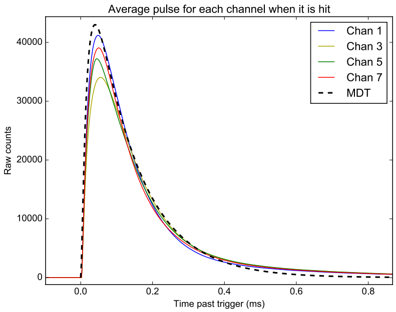


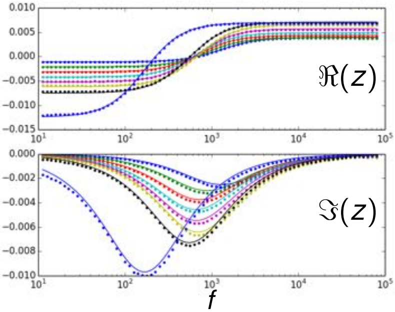


"Sidecar" design

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

Two-Body effects

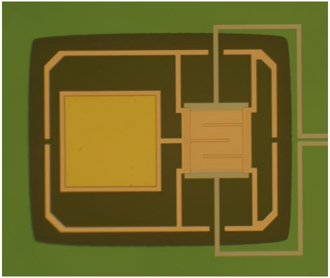


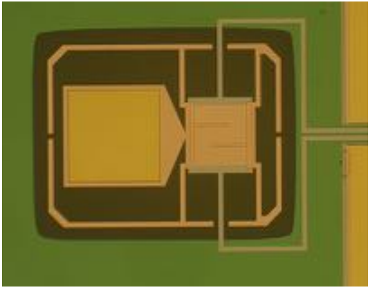


Dark testing

- 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