Microcalorimeters for X-ray Detection

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Plus close collaboration with U. Wisconsin, Stanford/SLAC, NIST/Boulder, Northwestern, Yale
Power of X-ray Microcalorimeters

Non-Dispersive Imaging Spectroscopy!
- high resolving power at diagnostically rich 6 keV (Fe K-shell)
- spectroscopy of extended sources
- unity QE and photon counting
Outline

• Intro to our X-ray microcalorimeters & sensors
• Two technical challenges
• Reduced heat capacity devices

Note: $\Delta E_{\text{FWHM}} = 2.355 \sigma$
Energy resolution is limited by thermodynamics:

\[ \Delta E \propto T \, C(T)^{0.5} \]

Operate at cryogenic temperatures (~50 mK)

Thermal detection of individual X-ray photons

- High spectral resolution
- High intrinsic quantum efficiency

Signal:

\[ \delta T \propto \frac{E}{C_{\text{tot}}} \]

Decay:

\[ \tau \propto \frac{C_{\text{tot}}}{G} \]

\( C_{\text{tot}} = \) total heat capacity
\( G = \) thermal conductance
Several sensor approaches:

1. **Semiconductor Thermometer** (Doped Ge or Si)

   - Graph showing resistance decreasing with increasing temperature.

2. **Superconducting Transition Edge Sensor (TES) Thermometer**

   - Narrow transition $T_c \sim 100\,\text{mK}$.

   - Graph showing resistance increasing with increasing temperature.

Approach used for:
- XQC Sounding Rocket
- Astro-H Soft X-ray Spectrometer (SXS)

Also, magnetic calorimeters.

Large Arrays, Best $E/\Delta E$
Semiconductor Thermistors

- Ion-implanted Si
  (or Neutron Transmutation Doped Ge)
- High resistance, read out with JFET

\[ R = R_0 \exp \sqrt{\frac{T_0}{T}} \]

\[ \Delta E_{\text{FWHM}} \sim 4 \text{ eV (R~1500 at 6 keV)} \]

arrays of \( \sim 36 \) pixels
Mo/Au bilayer TES

Mo (45 nm) / Au (225 nm); $T_c = 0.1$ K

microcalorimeter array (0.1 –12 keV, $\Delta E_{\text{FWHM}} \sim 2$ eV)

- Si removed beneath pixels to leave TES sitting on SiN membrane
- Overhanging absorbers are several microns thick (made of Au or Au/Bi), to provide high QE and appropriate C; even thicker absorbers used for high-energy x-ray or gamma-ray detectors
Recent TES X-ray Microcalorimeter Array Development:
Energy Resolution and Device Optimization

\[ \Delta E \propto T (C/\alpha)^{0.5} \]

\[ \alpha = \frac{\partial \ln(R)}{\partial \ln(T)} \quad \beta = \frac{\partial \ln(R)}{\partial \ln(I)} \]

- \( \Delta E \) is independent of \( E \) in small temperature excursion around \( T_c \)
- Optimize detector design for best resolution with a certain \( E_{\text{max}} \)
  - make heat capacity as small as possible and \( \alpha \) as high as possible without saturating detector, taking into account noise scaling

\[ \Delta E \propto (T E_{\text{max}})^{0.5} \quad E_{\text{max}} \propto C T/\alpha \]
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\[ \Delta E = \sqrt{4 k_b T^2 C \frac{C}{\alpha}} \sqrt{2(1 + 2 \beta)(1 + M^2)} \]

\[ \beta \text{ scales with } \alpha \quad M^2 \text{ depends on } \alpha \quad \text{high } \alpha (>100) \rightarrow \text{high } M^2 \]

- Use matched “optimal” filter for standard event processing for best \( \Delta E \)
- alternative analysis approaches are in development for non-linear devices and high count-rate applications
Energy Threshold (example, using $\Delta E_{\text{FWHM}} \sim 4 \text{ eV}$ silicon thermistor SXS array)

High-frequency noise can have large effect on trigger threshold, but little impact on energy resolution.

Low instrument collecting area at low energy so not a driving requirement; we trigger as low as possible to reduce background and avoid contamination/pile-up.
Technical Challenges (1)

Thermalization
Insufficient thermalization can lead to degraded resolution and/or distorted line shape.

- Want rapid energy downconversion following photon absorption, where device thermalization is complete prior to sensor response (measuring a single $\Delta T$)

- If thermalization is not rapid or complete or there are other energy loss mechanisms, signal size can depend on absorption position, degrading resolution and distorting line shape
  - Silicon thermistor devices: use separate absorber to avoid absorbing in Si, controlled/reproducible absorber attachment process
  - TES devices: use separate absorber; Au layer in absorbers for thermalization, electroplated Bi for stopping power
  - Solid substrate TES devices (no membrane isolation): make absorber attachment stems w/ small area to minimize athermal phonon loss to substrate
Example of Surface Effects (energy loss)

- Small exponential tail related to photons absorbed near surface of HgTe absorbers (Astro-H SXS detectors)

\[ \sim 2\% \text{ at } 270 \text{ eV} \quad <0.1\% \text{ at } 5410 \text{ eV} \]

- Tail measured from 0.3 keV – 8 keV. Fraction of counts in tail drops with energy in manner consistent with decreasing fraction of photons absorbed near surface.

- Possible trapping states due to altered band structure near surface (first tens of Å)?
Technical Challenges (2)

Heatsinking
1) Effective $T_b$ change caused by TES bias power

2) Pixel-to-pixel crosstalk – need good heatsinking to accommodate high x-ray fluxes

- Thick Au layer connect to heat sink with Au bonds
Improve heatsinking: Coat sidewalls of wells with thick Cu

- steep angle deposition from back
- rotating jig to deposit on all four sidewalls
- remove DRIE passivant before deposition to ensure good Si/Cu conductance

40% coating of sidewalls on this wafer (80% currently possible)
3.5 micron thick
Reduced Heat Capacity Devices (1)
X-ray TES Microcalorimeters
Typical low-C response in soft X-ray band:

Heat capacity $C \sim 0.1 \text{ pJ/K}$ (x10 smaller than standard design)

$\Delta E \propto T C^{0.5}$
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New operating regime for X-ray TESs – soft saturation:

- miniaturized pixel: 35 µm TES, 57 µm x 57 µm x 4.5 µm absorber
New operating regime for X-ray TESs – soft saturation:

- small pixels

- highly current dependent transition

- enabled good energy resolution over extended energy range, and $\Delta E_{FWHM} = 0.72$ eV at 1.5 keV
Reduced Heat Capacity Devices (2)
Optical TES Microcalorimeters
Optical TES Microcalorimeters
Stanford (Cabrera et al.), NIST/Boulder (Nam, Lita et al.)

Example of NIST/Boulder optical devices:
• W-TES with Al leads (also explored Hf-TES)
• device Tc tuned to ~150mK
• 25 x 25 µm²
• Detecting photons of 0.6 eV (2 µm) – 3 eV (400 nm)
• push to get high QE, low timing jitter, faster decay times

B. Calkins, A. Lita, A. Fox, and S. W. Nam. APL (2011).
Optical TES Microcalorimeters – with advanced pulse processing

retaining energy resolving power beyond linear range

Lower energy optimization thoughts:

**smaller C:**
how: smaller device volume, different materials
cautions: often means smaller collecting area; in case of smaller TESs, proximity from leads can raise $T_c$ and change transition shape

**lower operating T:**
how: can tune sensor operating temperature – bilayer thicknesses (Mo/Au, Mo/Cu) or crystal structure (W)
cautions: only gain like $\sqrt{T}$, requires lower heatsink temperature

**increase $\alpha$:**
how: not straightforward, change normal metal features on TESs, ...
cautions: we observe excess noise ($M^2$ term) with high $\alpha$

**advanced pulse processing techniques:** retain device performance into saturated regime
cautions: calibration needs increase significantly