Microcalorimeter array development for the ATHENA X-ray Integral Field Unit

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On behalf of the X-IFU array development team

Key contributors:
Currently assumed X-IFU baseline
- Uniform Large Pixel Array - LPA.
- 3840 identical transition-edge sensor (TES) pixels, 0.25mm pitch.
- $\Delta E_{\text{FWHM}} = 2.5$ eV @ 7 keV.
- Baseline changed in Nov 2016 to make use of defocusing optic (for high rate point source observations).
- Reduces count-rate requirement to ~ few cps, enables reduced speed pixels (~x2-3) and more optimal use of available readout resources (greater engineering margin).
  › LPA-1 -> LPA-2
Transition-edge sensor arrays, 2016 state of the art

- Previously proposed “LPA-1” GSFC TES pixel.
  - Mo/Au Bilayer TES, target $T_C \sim 90$ mK, suspended on SiN ($\sim 1$ μm).
  - Low impedance TES, $R_n = 10$ mΩ.
  - Composite Au/Bi electroplated absorbers (low heat-capacity and fast thermalization).
  - Thermal conductance $G_b = 200$ pW/K, Fast $\sim 400$ μs decay times (originally for LPA-1, 10’s cps / pixel).
Transition-edge sensor arrays, 2016 state of the art

• GSFC devices were historically optimized for *Time Division Multiplexing (TDM)* approach under study as back-up.
  - See J. Ullom et al. 10699-60 @ 4:30pm

• However baseline readout approach uses *Frequency Division Multiplexing (FDM).*
  - See H. Akamatsu et al. 10699-58 @ 4:00pm

• In TDM TESs are DC biased (multiplexing via switching SQUIDs).
  - TES transition is independent of the muxing.

• In FDM the mux encoding via AC TES bias with different frequencies.
  - In Mo/Au TESs lead to frequency dependent variations in TES transition shape and degraded resolution performance.
Pixel optimization activities

- Technology development focused on 3 main areas:
  
  (1) Pivot towards lower count-rate ‘LPA-2’.
  - x2-4 slower pixels, control of thermal conductance to the heat-sink via TES size / membrane thickness.
  
  (2) Uniformity optimizations.
  - Exploring better transition uniformity, less sensitive to environment (role of stripes, size effects).
  
  (3) Reduce the impact of frequency dependent effects in the AC-TES.

Mixed arrays for transition and \( G_b \) studies

- Pixel size. \( G_b \) scales with TES phonon emitting perimeter.
  
  140 -> 50 \( \mu \)m => 3x reduction in \( G_b \).

- Impact of geometry (pixel size/metal features) on transition shape.
DC transition studies – studying role of stripes

- LPA optimization activities has led to growing understanding of geometry effects in TESs.
  - Exploring the role of stripes, historically used on larger TESs for noise and transition shape control (empirically).
  - Measurements in large arrays show undesirable variations in transition shape.
    - Presence of ‘kinks’ hard to predict and can impact array uniformity.
    - Improving understanding of how they come about / evolve – See Wakeham et al., LTD-17, 2017.
    - Maybe due to alignment difference between the different metal layers (stripes/stems).

Different transition shapes in different quadrants of 32x32 array

Q1 and Q3 have majority ‘kinked’ transition
Q2 and Q4 had majority ‘smooth’ transition

α_{IV} = \frac{T}{R} \frac{dR}{dT}

Resistance (mΩ) vs Temperature (K)

‘kink’
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Quadrant 1

Quadrant 2

Quadrant 3

Quadrant 4

2 stripes + T-stem

No stripes, dot-stem
First uniform kilo-pixel arrays of no-stripe pixels

- First uniform 32x32 arrays, no stripes, 50/75/100/120 μm, 250 μm pitch.
- Example for 50 μm devices, show good DC transition shape and uniformity.
- Large transition phase space with no kinks, less sensitive to environment (B-field)

![Graphs showing R vs T and α vs R/Rn curves]
DC transition studies – example 50 μm TES, no stripes

- Good pulse shape and noise uniformity.
- DC performance is excellent, $\Delta E_{\text{FWHM}}$ consistently at 2.0 eV level.
- Smaller TES sizes. $G_b = 75$ pW/K at $T_C = 90$ mK.
  => slower speed $\tau = 2.2$ ms.

Very promising LPA2 DC pixel understudy for use with backup TDM readout.

Average pulse shapes for 10 pixels at 15% $R_n$

$\Delta E = 1.58 \pm 0.12$ eV
6220 counts
Mn-Kα (6 keV)
AC Pixel optimization activities

- Large collaborative effort NASA/SRON/NIST to understand frequency effects in AC TES.
- Identified two main contributors:
  1. **AC, dissipative, losses** (magnetic coupling to nearby metals) broadens transition (lower $\alpha$). Limits access to most sensitive part of the transition used to achieve < 2.5 eV. [Sakai et al. 2017].
  2. **AC Josephson reactance**, periodic steps through the transition due to variation in Josephson inductance. Undesirable non-linearity and noise properties, hard to find good bias points. [Gottardi et al. 2017].

Example R vs T 50 μm TES

\[ \alpha_{IV} = \frac{T}{R} \frac{dR}{dT} \]

Sakai et al. 2017
AC loss and Josephson-effect mitigation strategies

- Comparison of many different geometries and improved theoretical understanding has led to optimization routes.
- Strategy is to explore higher resistance regime in GSFC Mo/Au TES.
  - AC loss independent of TES Z => higher Z bias point reduces impact of fixed AC loss.
  - High Z devices have small Josephson oscillations.
    - Seen for example in SRON Ti/Au very high-Z devices 200 mΩ [P. Khosropanah, 10699-57]
  - Challenge is to increase Z enough, without affecting other noise or uniformity properties.

1) 15 -> 50 mΩ/□ bilayer sheet resistance. Thinner TES films. Now implemented and in testing.
2) Change aspect ratio (1:1 -> 1:0.25). Longer and thinner. Now implemented and in testing.
First high-Z devices with good DC performance

DC measurement of 120 μm TES

$R_n = 32.7 \text{ mΩ}$ (increased from 9 mΩ)

- No additional thermal noise.
- Same achieved $\Delta E$ as low-Z films
- Larger TES $\Rightarrow$ steeper transition
- $C = 1.5 \text{ pJ/K}$, Au 2.30 μm / Bi 3.39 μm
  - increased x2 to maintain linearity

$\Delta E_{\text{FWHM}} = 1.87 \pm 0.13$ eV

Counts: 5,213

Increasing $\alpha$ with size
First results on high-Z TES under AC bias at SRON

- First spectral measurements on mixed arrays at SRON yielded AC-TES x-ray resolution comparable to DC.
- Best performance seen in 100/120 µm sizes. Smaller, slower 50 µm sizes not as good performance.
- Less structure + more access to lower bias points. => consistent access to < 2.5 eV 1-5 MHz range.
- Later presentation by H. Akamatsu will show more results and FDM testing from 1-5 MHz

Predicted resolution vs \( R/R_N \)

Low-Z
High-Z

100 µm, \( R_n = 38 \, \text{mΩ} \), \( f = 2.5 \) MHz
Mn-K\( \alpha \), Counts: 5327
\( \Delta E_{\text{FWHM}} = 2.06 \, +/- \, 0.12 \) eV

Figures courtesy Luciano Gottardi
First uniform high-Z arrays suitable for large scale FDM demonstrations

- Two 32x32 arrays screened at GSFC and sent to SRON for 40-pixel FDM testing.
- Good DC transition properties and uniformity, R vs T, pulse shape, $\Delta E$.
- $<\Delta E_{\text{FWHM}}>$ = 1.95 eV for 6 pixels tested.
- Larger TES size => Pixels are fast => for X-IFU may still need to slow these down.

100 $\mu$m TES, no stripes
$T_C$ uniformity 1.5 mK

13 R-T curves, $R_n = 30$ mΩ

450 $\mu$s decay time

± 2%
First DC results from high aspect ratio 120 µm TESs

- First 120 µm high aspect ratio devices in DC testing.
- Preliminary measurements suggest no strong ΔE dependence on aspect ratio.
- Added design flexibility: higher Z and lower Gb.
- First AC tests planned soon.

ΔE = 2.08 +/- 0.09 eV  
Counts = 9,723

ΔE = 2.13 +/- 0.11 eV  
Counts = 6,180

ΔE = 2.18 +/- 0.11 eV  
Counts = 6,206
First large X-IFU array scale test parts yielded

- 90 mm diameter hexagonal chip and prototype detector array.
- 3540 sensors on 250 μm pitch.
- 960 pixels connected to bond pads.
- First DC tests planned for later this year.
- Later iteration will include coil-coupling for AC biased testing.
Summary

• Improved DC and AC pixel designs:
  - Evolved original 3-stripe 140 μm TES design to smaller TESs without stripes.
    ‣ Larger transition phase-space without ‘kinks’ -> Improves array uniformity.
  - Developed first high-Z Mo/Au TESs for reduced AC Loss and + Josephson effect in AC TES.
    ‣ Improved access good transition regions.
    ‣ Break through energy resolution < 2.5 eV results for AC TESs at both low and high frequency.
  - First high-Z uniform 32x32 arrays now delivered to SRON for 40-pixel FDM testing.

• Ongoing development activities:
  - First high aspect ratio devices in DC testing.
    ‣ Designs offer addition parameter space for higher Z and low Gb.
    ‣ AC testing planed for this fall.
  - First large scale X-IFU testing planned for 1000-pixel testing later this year.