Design and optimization of multi-pixel transition-edge sensors for X-ray astronomy applications


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ABSTRACT:

Multi-pixel transition-edge sensors (TESs), recently revived as an "array" type of position-sensitive microcalorimeter that realizes very small angular resolutions, have been considered as a next generation experiment for detecting X-ray photons. The excitations are in the number of readout channels and associated wiring. In the hybrid design, a single TES is replaced by discrete absorbers on a thermal link. The excitations to the link thermal signals differ to provide a different characteristic pulse shape for a ray photon absorbed in each of the hydra (sub)pixels. We report on the experimental results from hydra consisting of up to 40 pixels per TES. We discuss the design trade-offs between shape for x-ray photons absorbed in each of the hydra subpixels. In this work, the designs utilize a hierarchical structure using trunks and branches that support absorbers.

1) Multiple absorbers with different thermal coupling to 1 readout sensor.
2) Position discrimination is here focused on TES readout.
3) Position dependent pulse-shape from thermal diffusion.
4) Designed to increase array coverage with fewest TESs.
5) Reduces focal-plane array complexity, lower heat loads, less wiring, fewer readout channels.

Example hybrid array concept under study for Lynx, which could combine single pixels and hydra in one array.

(See Bandler et al. PE-46 for further details on Lynx).

3) 4 and 9-pixel hydra

- Arrays presented here are small-pixel designs < 75 μm pitch for high angular resolution.
- 8 × 8 arrays of 4 and 9 pixel hydrams have been developed.
- 35 × 35 μm² Mo/Au bilayer TES.
- 65 × 65 μm² electroplated Au x-ray absorbers, 5 μm thick. Provides 98% absorption at 6 keV.
- Absorbers are centered above substates and TES for high fill factor.
- Fabricated on thick Si wafers with embedded Cu heat sink layer.
- ~ 500 nm Au thick, few μm wide links couple the TES to the absorbers.

4) 4 and 9 pixel energy resolution

- AE scales approximately with (number of pixels).
- Mf, upper ≈ 0.9 μV at 1.5 keV.
- 9 pixel Hydra Mf, upper ≈ 2.3-3.4 μV at 9 pixels for E = 1.5 keV.
- 4 pixel Hydra Mf, upper ≈ 1.4-2.2 μV at 4 pixels for E = 1.5 keV.
- Excellent resolution consistent across all pixels and consistent with expectations.

5) Position sensitivity

- Position determined from rise-time.
- Thermal links designed using a finite element model to calculate the pulse shapes and noise.
- Position sensitivity decreases as energy decreases (ΔE = 1/E).
- Position discrimination demonstrated down to ~ 1 keV for both 4 and 9 pixel designs.
- Simulations suggest sensitivity should be down to a few 100 eV.
- Pulse shapes match well with numerically simulated.
- Hits in exposed links between absorbers have been identified.
- LOW: ΔE in excellent ΔE but relatively slow decay times (ms). Thus, this particular detector is excellent for lower-count rate X-ray astronomy applications.

6) 20-pixel hydra design

- Extending designs to develop the first prototype 20-pixel hydra.
- These designs utilize a hierarchical structure using trunks and branches that make it easier to design and lay out, but require more complex position discrimination algorithm.
- 3° design iteration consisting of 5 clusters of 4 absorbers, where each cluster is individually coupled to the TES (schematic below).
- TES is 25 × 250 μm².
- Tc = 80 mK.

7) 20 pixel hydra results

- Measured average pulse shapes (right) qualitatively agree with simulations.
- The 5 clusters each with 4 pixels have different characteristic pulse shapes.
- Additional pole in rise time requires 2nd metric for parameterizing pre-equilibrium signal.

Example shown here uses 2 rise time metrics: τe, determined from 50% and τp from 50-95% of the peak. Two X-ray data runs at different energies:

- Mn K (6.4 keV) and Cr K (277 eV).
- Good position discrimination measured on most pixels down to < 1.5 keV.
- However due to very fast rise time and low sampling rate (only 4 data points on rise of fastest pixels), position discrimination between fastest pixels (cluster 2).
- A better evaluation of Cr K using crystal monochromator.
- AE (ΔE) = 3.39 ± 0.18 eV including all 20 pixels, already surpassing 5 eV goal for Lynx.
- Future plans include:
  - Test large area arrays with multiplexed microcalorimeter readout.
  - Design hydrams with 25 μm pitch pixel to better match Lynx 0.5 arc-second goal.

Average measured pulse shapes for all 20 pixels.