Development of a TES-Based Hard X-Ray Spectrometer

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Abstract

Conventional semiconductor-based energy-dispersive spectrometers offer high detection efficiency but relatively limited energy resolution, whereas crystal-based wavelength-dispersive spectrometers can achieve excellent energy resolution at the cost of collection efficiency and simultaneous spectral coverage. Transition-edge sensor (TES) microcalorimeters can combine high energy resolution, high detection efficiency, and broadband spectroscopic capability.

This work describes the development of a TES-based hard X-ray spectrometer, including aluminum–manganese (AlMn) TES design, absorber optimization, electrothermal characterization, and system-level design and simulation. The spectrometer targets an energy resolving power of E/ΔE ~ 2000 over the 10–100 keV energy range. TES devices exploit the steep resistance–temperature dependence within the superconducting transition to resolve the small temperature rise produced by an absorbed photon. The transition temperature (Tc) of AlMn films can be adjusted by annealing, which facilitates control of Tc and its uniformity across detector arrays. A gold–bismuth bilayer absorber is used to combine the high thermal conductivity of gold with the relatively low heat capacity and high X-ray stopping power of bismuth. The absorber geometry and TES–absorber coupling are optimized for efficient thermalization while reducing position-dependent response and maintaining a balance between energy resolution and absorption efficiency. Electrothermal measurements are used to characterize device performance and guide further detector optimization and cryogenic system integration.

The development can be used for applications in hard X-ray Compton spectroscopy and X-ray emission spectroscopy at synchrotron radiation facilities. The TES detector can also be used for 511-keV positron-annihilation spectroscopy of the Galactic center.

Keywords: Transition-edge sensor (TES); Hard X-ray spectroscopy

1. AlMn TES Design & Absorber Optimization

10–100 keV	E/ΔE ≈ 2000	Tc ≈ 100 mK	2 μm Au / 5+ μm Bi
Target energy range	Resolving power	AlMn target Tc	Bilayer absorber

1.1 Operating Principle & Negative Electrothermal Feedback

- Photon absorption gives a temperature rise, ΔT = Eγ/C, across the steep R–T transition.
- Voltage bias stabilizes the operating point and speeds up pulse recovery.
- High transition sensitivity, low heat capacity and ≈100 mK operation support high energy resolution.

α = (T₀/R₀)(dR/dT) β = (I₀/R₀)(dR/dI)

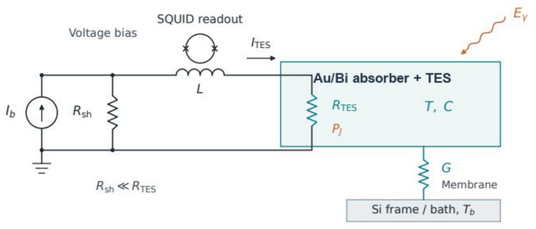


Fig. 1. Voltage-biased TES electrothermal feedback circuit.

$$\Delta E_{\mathrm{FWHM}} = 2\sqrt{2\ln 2}\,\sqrt{\frac{4k_B T_0^2 C}{\alpha}}\sqrt{\frac{n(1+2\beta)}{2}}$$

1.2 AlMn Tc Tuning by Annealing

- AlMn: 200 nm film with 2000 ppm Mn and low magnetic sensitivity.
- Baking at 210 °C gives Tc ≈107 mK.

1.3 Interdigitated Nb Electrodes

Interdigitated electrodes reduce Rn from 50 to 10 mΩ/□.



1.4 Au/Bi Bilayer Absorber & Thermalization

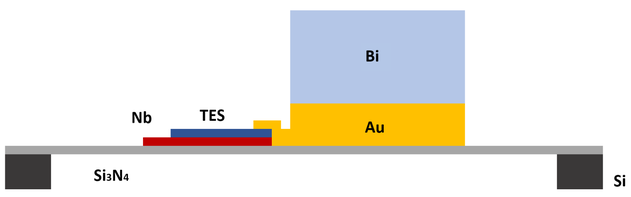


Fig. 2. Original Au/Bi absorber and TES schematic.

- Au (2 μm): Spreads heat and couples the absorber to the TES.
- **Electroplated Bi (5+ μm)**: High stopping power and low heat capacity. Large grains reduce energy trapping.
- Suspended SiN: Sets the weak thermal link to the bath.

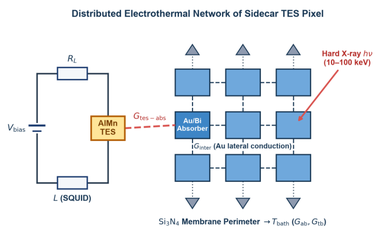


Fig. 3. Distributed FEM thermal network.

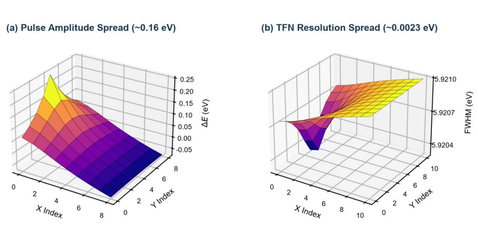
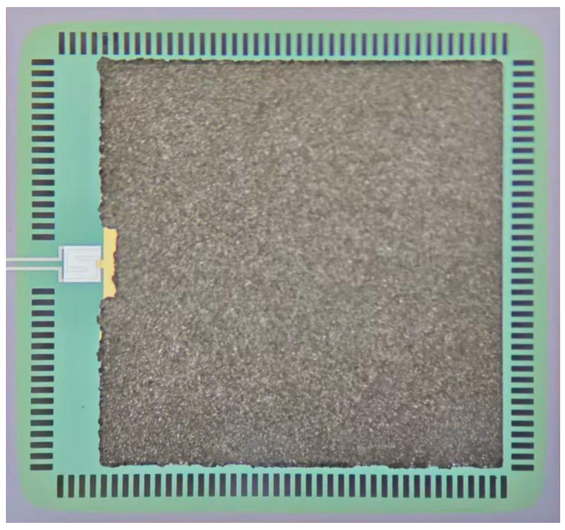
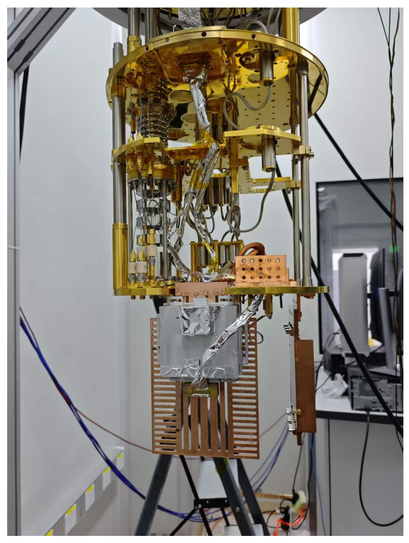


Fig. 4. Modeled position broadening (<0.2 eV).

1.5 TES Device & Cryogenic Setup



TES device



DR cryogenic setup

2. Electrothermal Characterization & X-Ray Calibration

Tests use DR and SQUID readout. I–V, bias-step, complex impedance, noise and X-ray response guide detector optimization.

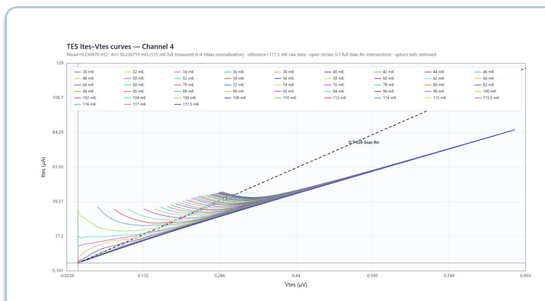


Fig. 5. I–V curves across bath temperature.

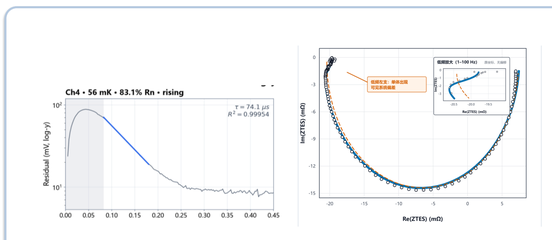


Fig. 6. Bias-step decay and complex Z(f).

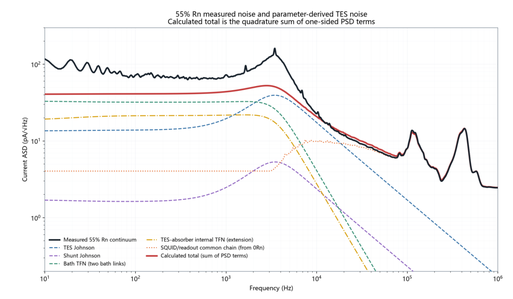


Fig. 7. Current noise ASD.

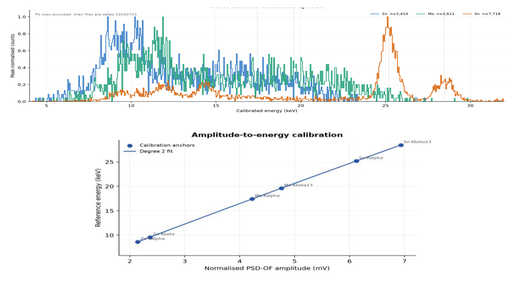


Fig. 8. X-ray spectrum and energy calibration.

Conclusions

A. Calibration linearity deviation is <1%.
B. Electrothermal analysis suggests that an AlMn oxide layer weakens thermal contact, causing photon energy loss from the absorber and poor resolution. The next run will remove this layer during absorber fabrication.

3. Hard X-Ray Compton & Emission Spectrometer

Synchrotron XCS and XES combine high energy resolution with large collection solid angle. The Compton scattering angle is 135°.

$$\Delta p_z = \sqrt{\left(\frac{\partial p_z}{\partial E_1}\Delta E_1\right)^2 + \left(\frac{\partial p_z}{\partial E_2}\Delta E_2\right)^2 + \left(\frac{\partial p_z}{\partial \phi}\Delta\phi\right)^2} \approx 0.17 \text{ a. u.}$$

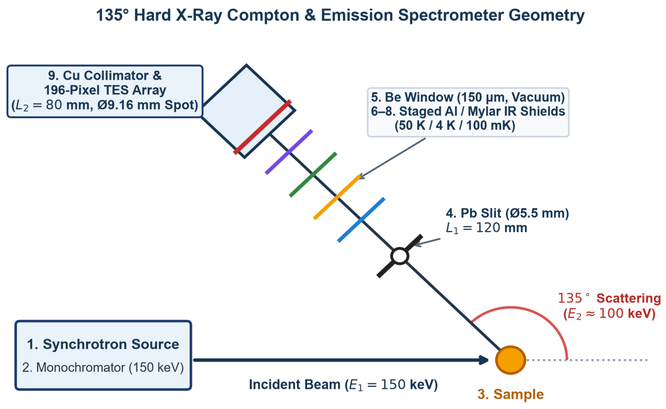


Fig. 9. 135° Compton geometry and IR shields.

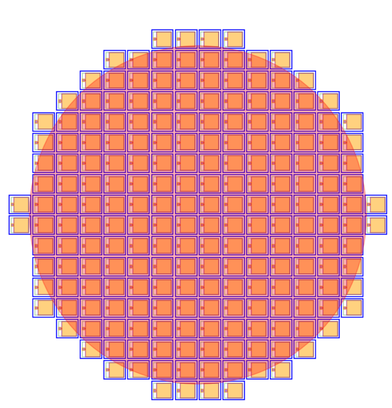


Fig. 10. 196-pixel TES array.

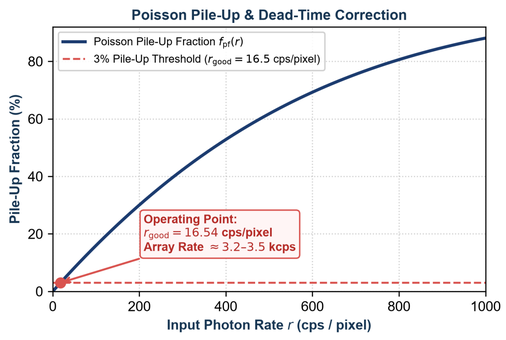


Fig. 11. Pile-up and throughput model.

Key Design Parameters

- E/ΔE ≈2000 at 10–100 keV.
- ΔE ≈50 eV at 100 keV.
- Momentum resolution ≈0.17 a.u.
- 196 pixels; 400 × 400 μm² absorbers.
- 2 μm Au + 5+ μm Bi.
- >3000 counts/s at 3% pile-up (model).

[1] L. Gottardi & K. Nagayoshi. Applied Sciences 11, 3793 (2021).
[2] E. M. Vavagiakis et al. J. Low Temp. Phys. 199, 408–415 (2020).
[3] D. Yan et al. IEEE Trans. Appl. Supercond. 29(5), 1–4 (2019).
[4] F. Shirazi et al. J. Astron. Telesc. Instrum. Syst. 9, 024006 (2023).