Phonon-Mediated Distributed Transition-Edge-Sensor X-ray Detectors

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Overview

• Goals, applications and detector basics

• Energy systems, charge traps and neutralization

• 2-d Si

• 2-d Ge

• 2-d Si with deep trenches

• Energy Resolution
Performance Goals

- 2 dimension resolving.
- 1-10 keV band.
- Position resolution $x/\delta x$ and $y/\delta y \approx 100$.
- Energy resolution $E/\delta E \approx 1000$.
- Eventually multiplexed into 30 x 30 arrays.
- Equivalent to a 10 megapixel device.
Applications

• Large area, time resolution, energy resolution and position resolution, dead time...

• Astrophysical studies such as...

• Magnetic recombination in the solar corona.
• Warm–hot intergalactic medium
• Surveys of clusters and groups of galaxies.

• These have been suggested by Blas Cabrera, Steven Kahn, Bob Stern, Steve Deiker and others.
2x2 Detector

- Position cuts in 2 directions.
- Third dimension not resolvable.
- The four TESs cover a region 500µm x 500µm.
- The crystal is 350µm thick.
- The trenches are ~220 µm deep.
Detector with Source

1cm

2cm
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Energy Systems

- Si Electron - Hole System
- Si Phonon System
- W Phonon System
- W Electron System
Charge Traps

Counts

Modes:
- Mode 1
  - Sn L\(_{\alpha}\)
  - Cu K\(_{\alpha}\)
- Mode 2
  - Sn K\(_{\alpha}\)
  - \(^{237}\text{Np}\) to \(^{237}\text{Np}\)

Energy Absorbed
Neutralization Completion

Mode 1 → Mode 2

Hours of $^{241}$Am Exposure

X-ray peak energy

59.54 keV
59.54 keV
25.27 keV
8.05 keV

44%
31%
21%
Crystal Neutralization

L.E.D.

Tungsten TESs

Aluminum electrical leads and bonding pads

Phonon containment trenches

Incoming x-ray

Silicon substrate
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Energy Partitioning

Black points used for position correction

Total Energy [eV]

Y position [arb unit]

X position [arb unit]
Energy Partitioning

- Total Energy [eV]
- Y position [arb unit]
- X position [arb unit]

Black points used for energy histogram
Spectra

- Center = 5900 [eV]
- FWHM = 80 [eV]
- # Events = 12479

- Center = 6471 [eV]
- FWHM = 92 [eV]
- # Events = 2118

Calibrated energy absorbed in TESs [eV]
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Energy Losses

• Energy resolution is degraded due to energy going into nondetectable channels.
  – Electron—hole pairs lost in charge traps.
  – Electron—hole pairs diffuse through bridge and lost to the environment.
  – Phonons escape through bridge and lost to the environment.
Germanium Absorbers

- Want pure Ge absorbers (less charge traps).
- First use cheaper doped Ge absorbers.
- Problems...
  - Xtal thicker.
  - Bridges thicker (Very conservative trenching since Ge is more fragile).
  - Debye frequency ~1/2 of Si’s (coupling to W ~frequency).
Germanium Detector

• These problems led to a reduction in the amount of energy absorbed in the TESs (~500eV).
  – Actually, only 3 TESs were working and the 500eV amount is what would be expected in four working TESs.
  – This is consistent with simulation indicating that the simulation’s parameters are not far off.

• An actual line width was not determined.
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2-d Si Detector with ``split’’ TESs and deep trenches

- Deeper trenches to reduce phonon and charge losses through the connecting bridge.
- The trenches are 320μm deep, 90% of crystal thickness.
- ~70% of the initial x-ray energy was read out by the TESs.
- Considering the 220μm deep trenches and 320μm deep trenches absorption of 49 & 70% respectively, a total of 76% absorbed in completely trenched detector.
Split TESs

- Split TESs suppress / reduce phase separation in the current flowing direction.

\[ l_{\text{max}}^2 = \pi^2 L_{\text{Lor}} / \alpha \Sigma T_c^3 \rho_n \]
Band Mixing

100 4-channel-summed events.
After Cuts

Center = 5900[eV]
FWHM = 73[eV]
# Events = 10298

Center = 6458[eV]
FWHM = 89[eV]
# Events = 1215

Calibrated energy absorbed in TESs [eV]
scaled so $E_{K\alpha} = 5.9$keV
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Noise FWHM Effect

![Graph showing the Energy TES₂ vs Energy TES₁ with a FWHM contribution of 36.5861 eV.](image-url)
Fano Factor

\[ \sigma = \sqrt{F \times E / \varepsilon_0} \]
\[ \sigma = \sqrt{0.08 \times 5900[\text{eV}] / 3.8[\text{eV}]} \]

- X-rays absorbed \( \rightarrow \) electron—hole pairs produced.
- Average 3.8eV of energy for their production.
- Their fluctuation however is no Poisson, but modified by the Fano factor.
Phonons

$$\sigma = 1.2[\text{eV}] \times \sqrt{0.08 \times 5900[\text{eV}]/3.8[\text{eV}]}$$

- These electron–hole pairs shed energy until they reach the velocity of sound.
- Their gap energy then dominates ~1.2eV.
Full-Width at Half-Maximum

\[ \Delta E_{FWHM} = 2.355 \times 2 \times 1.2\,[\text{eV}] \times \sqrt{0.08 \times 5900\,[\text{eV}]} \div 3.8\,[\text{eV}] \]

\[ = 63\,[\text{eV}] \]

\[ \sqrt{63^2 + 37^2} = 73 \approx 80 \]

- \~2\ calibration factor.
- 2.355 to convert to FWHM.
- 68\% of energy initially goes into phonons. 76\% could be absorbed in completely trenched TESs.
- Could this suggest the electron—hole pairs are not releasing their energy in the detector?
Trap Concentrations

- Penn / Dougherty
  - 8,000 Ω cm
  - $10^{13}$ traps / cm$^3$

- Us
  - 10 Ω cm
  - $10^{16}$ traps / cm$^3$
PHiMates