Recent Advances
on CdTe/CdZnTe detectors

For High Energy PHOTON

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Outline

- Demand and CdTe/CdZnTe
- Recent Progress on technology
  - Crystal and ASIC
- X-ray Imager
  - Pixel & Strips
- Gamma-ray Detector
  - Coded Mask /PET
  - Compton Camera
- Summary/Future Prospects
Demands

Need Detector Material which can be used as
an alternative to Si (in terms of Efficiency)
an alternative to Ge (in terms of Operating Temperature)

Good Energy Resolution similar to Ge (0.2%@662keV)
High Efficiency, above 10 keV upto 1 MeV
Position resolution a few hundred micron
A detector can be operated at room temperature

In the field of
Medical Application
Homeland Security
Astronomical Observation

Seems to be very difficult and would need another 10 to 20 years for the final answer
All next generation telescopes need a Hard-X camera above 10 keV, where Si becomes transparent.

NuSTAR Small Explorer
Two hard X-ray (6 - 79 keV) focusing telescopes
Launch August 2011

NeXT Mission
(J APAN)
Launch 2013

Simbol-X
(ASI/CNES)
Launch 2014

To take a photo of SuperNova explosion in hard X-ray

T.Takahashi
With Newly developed
Hard X-ray Mirror

Pt/C depth-graded multilayer supermirror

Bragg Reflection

TEM cross-section of Pt/C ML-SM (Ohnishi et al. 2004) 50nm

Key principle: Pt/C ML-SM

Reflectivity vs. energy (keV)

Effective area (cm²)

Mirror

Detector

10-20 m

Newton

Suzaku

NeXT/HXT

NeXT/SXT

Chandra

energy (keV)

T. Takahashi

Nagoya U.
CdTe/CdZnTe seem to be the only candidate at least, at this moment

- High Z semiconductor ($Z_{Cd} = 48$, $Z_{Te} = 52$), $\rho = 5.9$ g/cm$^3$

- Room Temperature Operation or Cool Environment

<table>
<thead>
<tr>
<th>Material</th>
<th>Ge (77K)</th>
<th>HgI$_2$</th>
<th>CdTe</th>
<th>CdZnTe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>32</td>
<td>80, 53</td>
<td>48, 52</td>
<td>48, 30, 52</td>
</tr>
<tr>
<td>Band gap (eV)</td>
<td>0.74</td>
<td>2.13</td>
<td>1.50</td>
<td>1.57</td>
</tr>
<tr>
<td>Energy per e-h pair (eV)</td>
<td>2.97</td>
<td>4.2</td>
<td>4.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Fano factor</td>
<td>0.08</td>
<td>0.19</td>
<td>0.11</td>
<td>0.09</td>
</tr>
<tr>
<td>$\mu_e$ (cm$^2$/Vs)</td>
<td>40,000</td>
<td>100</td>
<td>1100</td>
<td>1000</td>
</tr>
<tr>
<td>$\mu_h$ (cm$^2$/Vs)</td>
<td>40,000</td>
<td>4</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>$\tau_e$ (s)</td>
<td>$10^{-3}$</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
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</tr>
</tbody>
</table>


Takahashi and Watanabe (2000)
Slow mobility/ short lifetime of carriers are a bit problem for CdTe/CdZnTe

Signal is Depth Dependent

Pulse height depends on the interaction depth

We now know how to handle this Charge Collection Issue (Coplanar Grid/Cross Strip etc.)

For the case of thin detector, and with high bias voltage (400 V/0.5mm), can collect full charge.

Thick vs Thin approaches, I’ll explain later

Takahashi and Watanabe (2000)

T.Takahashi
CdTe/CdZnTe seem to be the only candidate at least, at this moment

Because, they've already shown good performance

Thin CdTe diode at -20 deg

137Cs
662keV
FWHM
2.1 keV
0.3%

260 eV at 6.4 keV
CdTe/CdZnTe Commercial Products

Amptek

AXION CdTe dental panoramic digital imaging system

aguila (US)

X-ray Spectrometer

Radiation-Threat-Detector

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Commercial Products

Hard X-ray Imager

Integrated type

100 micron pitch

AJ AT, Finland

1 dim Imager (30cm)
Technologies

Crystal & ASIC

T.Takahashi
Who makes CdTe/CdZnTe Crystal?

From a review talk by P.J. Sellin (2005)
Recent Advances on Technologies

ACRORAD (JAPAN)
Large Single Crystal

Travel Heater Method (THM)
Careful treatment of post heating
Very uniform wafer

1st Large Scale CdTe Camera in Space (INTEGRAL)

Quartz ampoule
CdTe poly crystal
Te-rich Cl-doped Cd-Te solvent
Heater unit

CdTe single crystal seed
Cl-doped CdTe grown single crystal

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Recent Advances on Technologies

eV Products (High Pressure Bridgman and improved method)

Large Crystal

CZT Size and Price History

SWIFT γ-ray satellite (2004-)

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Recent Advances on Technologies

REDLEN succeeded to make CZT by THM
Large Single Crystal

Chen et al. J AP, 2008

662 keV 1.18% (7.8 keV, FWHM) without additional signal correction)

2 x 2 x 1.05 cm³ monolithic pixel
pixel size 2.46 mm

T. Takahashi
We need ASIC:
If you need CdTe/CdZnTe imaging detectors

Spectrum

Need 50 e- at 0pF for both cases

Photon Counting
Hard X-ray Camera

For photons
above 10 keV
below 100 keV
CdTe Photon-counting imager using XPAD chip

0.7 mm thick CdTe
20 kpixels (130μm x 130μm) 2 ms/frame 10^6 photons/pixel

Basalo et al., NIMA 2008
CdZnTe Imager with Spectroscopic Capability

for NuStar Satellite

Prototype (for HEFT)

0.5mm pitch, 2mm thick
Two hybrids: 24 x 48

32 x 32 array, 0.6 mm pitch
2 mm thick CdZnTe

Flat Image

non-uniformity of the image comes
from CZT, not from ASIC

1 pixel

CSA

16 capacitors

T.Takahashi
CdZnTe Imager with Spectroscopic Capability

for NuStar Satellite

Prototype (for HEFT)

0.5mm pitch, 2mm thick
Two hybrids: 24 x 48

32 x 32 array, 0.6 mm pitch
2 mm thick CdZnTe

Counts map for Module A Side B detector

non-uniformity of the image comes from CZT, not from ASIC

5 mm CdZnTe, 800 V, 1C
Single pixel $^{155}$Eu
900 eV FWHM @ 86 keV

F. Harrison, 2008

T. Takahashi
HED: mosaic of 64 independent CdTe (Al/CdTe/Pt) cameras
Caliste 64: first prototype of detection unit

See A. Meuris’ talk in this session

$^{241}\text{Am}$ spectrum at -10°C, 500V with the single events of the 64 pixels

- 0.66 keV fwhm @ 13.94 keV
- 0.84 keV fwhm @ 59.54 keV
Large Area Hard X-ray Imager

Large Area 1024 pixel CdTe Array
(pixel size 1.4 x 1.4 mm²)

0.5 mm thick
A plant (tobacco) in water with $^{99m}$Tc and $^{201}$Tl

Allow us to study where in the leaf absorb which kind of metal (multi-tracer imaging)

$^{140}$ keV

$^{69-80}$ keV

$^{99m}$Tc

$^{201}$Tl
Previously
1) Difficult to make strips on the barrier electrode (In) for CdTe diode.
2) Wire-bond does not work on CdTe.

With new electrode material on CdTe (Al as anode/Pt as cathode) we have succeeded to make fine pitch Double Sided Cross Strip detector

strip pitch 100-400 micron

wire-bonding

ASIC

wire-bonding

In/Au stud bump

ceramic board with through holes

CdTe

strip electrode
Results (imaging)

Shadow Image

various RIs\(^{241}\text{Am}, {^{133}\text{Ba}, ^{57}\text{Co}}\)

\(-20^\circ\text{C}, 500\text{V bias}\)

nut(M2)

washer(M3)

solder (0.6mm)

spectra

\(241\text{Am}\)

\(133\text{Ba}\)

\(57\text{Co}\)

\(\Delta x \sim 400\mu\text{m} \quad \text{Imaging Spectroscopy !!}\)
Gamma-ray
above 100 keV
CdTe & CdZnTe detectors for gamma-ray

Thick Approach

8.5 keV FWHM Pulser
11.5 keV FWHM @ 662 keV 1.7%

Energy at room temperature

P. Luke (LBNL)

T. Takahashi
Cross Strip CdZnTe

For a Large NIH Program 1 mm spatial resolution, ~2% energy resolution at 511 keV

Depth Correction by using Cathode/Anode Info.

511keV
3.1% FWHM

Edge on geometry
Eff. of 86% for 511 keV by 4cm CZT

by C. Levin of Stanford, and J. Matteson et al.
2008

California Breast Cancer Research Program, CBCRP Grant Number 12IB-0092
Mini Coded Mask (cross strip CZT)

DGAS specs:
- Image a 5 mCi source at >5 m in less than 10 sec, and localize it to <10 degrees
- Energy band of 40 - 250 keV
- Better than 10% energy resolution at 122 keV
CdTe & CdZnTe detectors for gamma-ray

**Thin Approach**

- Concept
- Full Charge Collection (No Tail)
- Stack thin CdTe layers to get high efficiency.

40 layer = 20 mm thick CdTe

**Amptek**

XR-100T-CdTe-STACK

- Area 5 x 5 mm
- Thickness 2.25 mm (three layers)

Watanabe, TT et al. 2002

T. Takahashi
Gamma-ray Detector

CdTe PET (1st Result)

Achieved Spatial Resolution < 1mm
Array of 1mmX1mmX5mm
5120 CdTe BAR

Press Release by K. Ishii,
Tohoku Univ., Japan

NDIP08

Tohoku Univ.

Edge on geometry

Brain

Rat

Mouse

Fine Structure Imaging PET scanner

T. Takahashi
Gamma-ray Compton Camera for High Sensitivity Imaging
CdZnTe Compton Camera (Thick)


- Cathode/Anode Ratio (Depth Info)
- Timing Measurement (Drift Time) (Multiple Interaction/Depth Info)

2×2×1.5 cm³
= 6 cm³ CZT (eV Products)

ASIC front-end
(Gamma-Medica-Ideas AS)
Room-temperature handheld CdZnTe γ-ray imaging spectrometers with energy resolution ~ 1% FWHM at 662 keV
Demonstration of $\gamma$-Ray Imaging using a Single 1.5×1.5×1 cm$^3$ CZT Detector (FOV=4π)

Accidentally Detected a 10 $\mu$C $^{137}$Cs source next door

angular resolution $\sim$10 degrees at 667 keV

T. Takahashi
Si/CdTe Compton Camera (Thin)

Japanese ASTRO-H “formerly called as NeXT (New exploration X-ray Telescope)” Satellite will use it for the sensitive measurement from 100 keV to 600 keV.

Si is ideal device as “Scatterer”, since it is low Z material and momentum of electron around the nuclei is small -> Less affected by Doppler Broadening

1 unit

32 layers of 0.5 mm thick Si Pixel
8 layers of 0.75 mm thick CdTe Pixel
Prototype

Angular resolution ~3 degrees at 511 keV

511 keV point source (2.5 degrees)
>80 deg FOV

Source direction

(Takeda et al. IEEE NS 2008)
Si/CdTe Compton Camera

Good performance for both multiple and diffuse sources. Large FOV and good energy resolution

ISAS, 2008

(Takeda et al. IEEE NS 2008)
1. **CdTe and CdZnTe are now in the phase of real application.**
2. Large and Thin CdTe wafers are widely used for the commercial products of hard X-ray camera.
3. Photo Counting Detector (10^9-10^10 photons/pixel /s) would be the next step.
4. For gamma-ray detection, Thick approach and Thin approach both work.
5. Homeland Security and Medical Imaging boost the development.
6. Space missions are always one step ahead in terms of technological requirements, which is good.