Development of High-Z Semiconductor Detectors and Their Applications to X-ray/gamma-ray Astronomy

Taka Tanaka (SLAC/KIPAC)
Outline

- Introduction
- CdTe Diode Detector
- CdTe Pixel Imaging Sensor
  - Readout Analog ASIC
  - Bump Bonding
- Application to Compton Telescope
Collaboration

- ISAS/JAXA (Tadayuki Takahashi)
- SLAC (Hiro Tajima & Taka Tanaka)
- University of Tokyo
- Hiroshima University
- ACRORAD (Manufacturer of CdTe devices)
- IDEAS ASA (Readout ASICs)
- Mitsubishi Heavy Industries (Bump Bonding etc.)
Why High-Z Semiconductor?

Fine imaging is limited in the energy region below \( \sim 10 \text{ keV} \)

e.g.) Supernova Remnants (SN1006)

Accelerator of Cosmic Rays

X-ray (< 10 keV)

Hard X-ray (> 10 keV)

We need hard X-ray optics & Hard X-ray Imager
Cadmium Telluride (CdTe)

High Z semiconductor
($Z_{Cd} = 48$, $Z_{Te} = 52$)

High Density
($\rho = 5.9 \text{ g/cm}^3$)

Efficiency for
60 keV photons

<table>
<thead>
<tr>
<th>semiconductor</th>
<th>density [g/cm$^3$]</th>
<th>$Z$</th>
<th>$E_{\text{gap}}$ [eV]</th>
<th>$\epsilon$ [eV]</th>
<th>$X_0$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>2.33</td>
<td>14</td>
<td>1.12</td>
<td>3.6</td>
<td>9.37</td>
</tr>
<tr>
<td>Ge</td>
<td>5.33</td>
<td>32</td>
<td>0.67</td>
<td>2.9</td>
<td>2.30</td>
</tr>
<tr>
<td><strong>CdTe</strong></td>
<td><strong>5.85</strong></td>
<td><strong>48.52</strong></td>
<td><strong>1.44</strong></td>
<td><strong>4.43</strong></td>
<td><strong>1.52</strong></td>
</tr>
<tr>
<td>CdZnTe</td>
<td>5.81</td>
<td>1.6</td>
<td>4.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HgI$_2$</td>
<td>6.40</td>
<td>80.53</td>
<td>2.13</td>
<td>4.2</td>
<td>1.16</td>
</tr>
<tr>
<td>GaAs</td>
<td>5.32</td>
<td>31, 33</td>
<td>1.42</td>
<td>4.3</td>
<td>2.29</td>
</tr>
</tbody>
</table>

- Mildly Wide Band Gap ($E_g: 1.4 \text{ eV}, 4.4 \text{ eV/e-h pair}$)
  ⇒ Allows room temperature operation or
  the operation under moderate cooling (> $-20 ^\circ \text{C}$)

- High Resistivity $\sim 10^9 \Omega \text{cm}$

Promising for Hard X-ray Imagers for Astrophysics or Medicine
Recent Achievements of Crystal Growth

Traveling Heater Method (THM) by ACRORAD

Large Wafer of Single Crystal

High Uniformity !! (Important Feature for Imagers)
Example of Astrophysical Use

INTEGRAL IBIS
(Launched in 2004)

First large (60×60 cm) CdTe gamma camera
(16384 planar CdTe THM detectors 4×4×2 mm)

Field of view : 19° FWHM
Angular resolution : 12’
Energy range : 15 keV- 250 keV
Energy resolution : 9 % (60 keV)
Time resolution : 100 μsec

ISGRI (15 keV – 250 keV)
the CdTe camera is in front
Development of CdTe Diode Detectors
Poor Charge Collection Efficiency

$^{57}\text{Co}$

122 keV

Tail

$D$

$X$

$PH \propto (\mu \tau)_e E \left\{ 1 - \exp \left( - \frac{D - x}{(\mu \tau)_e E} \right) \right\} + (\mu \tau)_h E \left\{ 1 - \exp \left( - \frac{x}{(\mu \tau)_h E} \right) \right\}$

CdTe: $(\mu \tau)_e = 2 \times 10^{-3} \text{ cm}^2/\text{V}$, $(\mu \tau)_h = 1 \times 10^{-4} \text{ cm}^2/\text{V}$

cf.) Si: $(\mu \tau)_e = 0.42 \text{ cm}^2/\text{V}$, $(\mu \tau)_h = 0.22 \text{ cm}^2/\text{V}$

The exponential terms are not negligible → Tail Structures
To Improve Energy Resolution...

$57\text{Co}$

$122 \text{ keV}$

Tail

$$P H \propto (\mu \tau)_e E \left\{ 1 - \exp \left( -\frac{D - x}{(\mu \tau)_e E} \right) \right\} + (\mu \tau)_h E \left\{ 1 - \exp \left( -\frac{x}{(\mu \tau)_h E} \right) \right\}$$

Sufficiently High $E$ (Bias Voltage) up to $\mu \tau E \gg D$
To Improve Energy Resolution...

\[ PH \propto (\mu \tau)_e E \left\{ 1 - \exp \left( -\frac{D - x}{(\mu \tau)_e E} \right) \right\} + (\mu \tau)_h E \left\{ 1 - \exp \left( -\frac{x}{(\mu \tau)_h E} \right) \right\} \]

Sufficiently High E (Bias Voltage) up to \( \mu \tau E >> D \)

However, Low Leakage Current is Essential for Good \( \Delta E \)
CdTe Schottky Diode

Use Indium (small work function) as the anode

→ Schottky barrier

Low Leakage Current
CdTe Schottky Diode

Use Indium (small work function) as the anode
→ Schottky barrier
Low Leakage Current
CdTe Schottky Diode

CdTe (p-material)

Anode

Cathode

Pt

In

Leakage Current [A]

Bias Voltage [V]

2×2×0.5 mm³ 20°C

CdTe

CdTe diode without Guard-Ring
CdTe Schottky Diode

Most of the Leakage Current Flows through the Edges of the Device
Guard-Ring Structure

Extremely Low Leakage Current

→ Bias Voltage of 800 V for a 0.5 mm Thick Device at Room Temperature
Spectral Performance of CdTe Diodes

Non-Diode

![Graph showing spectral performance of CdTe diodes](image-url)
Spectral Performance of CdTe Diodes

Non-Diode

Diode

High Bias Voltage

→ Full Charge Collection (No Tail)!!
High Uniformity

Important Property for Imagers

High Uniformity was verified with our large-area device

21.5 mm

0.2%

0.2%
Development of CdTe Pixel Detectors
Pixel Detectors

Key Technologies

- CdTe Devices with Good Energy Resolution and High Uniformity
- Analog ASICs
- Bump Bonding
Readout Analog ASIC

VA64TA: Development with IDEAS ASA, Norway

- Self Trigger Capability
- Good Noise Performance (50e− (RMS) @ 0pF)
- Low Power Dissipation (0.2 mW/channel)

Test Result with SSD:

- 6.4 keV Fe K\textsubscript{x} line
- 122 keV FWHM 1.2 keV

VA

Charge Integrator (preamp.)

Semigaussian “slow” shaper

Multiplexer

TA

Level-sensitive Discriminator

Semigaussian “fast” shaper

Monostable (fixed width)

Peaking Time = 3–5 μs

Peaking Time = 600 ns

Vdd

Trigger Out

Vss

7 mm
Bump Bonding

CdTe: Fragile against High Compression and High Temperature
Co-planarity is 2 µm at Most

Using Soft Metals:
Double Gold Studs with an Indium Topping
CdTe Pixel Detectors

8x8 Pixel Modules

- Area: 18 x 18 mm²
- Thickness: 0.5 mm
- Pixel size: 2 x 2 mm²
- 64 ch, cathode side
- Guard ring: 1 mm width

- Area: 11.2 x 11.2 mm², 0.75 mm thickness
- Pixel size: 1.35 x 1.35 mm², 64 ch, cathode side
Spectral Performance

Good Energy Resolution & High Uniformity

Energy [keV]

122 keV
FWHM 1.5 keV

14.4 keV
FWHM 1.1 keV

$^{57}$Co
Large Area Imager

$4 \times 4 = 16$ CdTe Pixel Modules

5.4 cm $\times$ 5.4 cm Large Area Imager

Shadow Image 30–150 keV

M5 Nut

5.4 cm
Fine Pixel Detector

Developments of Fine Pixel (200–500 μm) are on-going

Example

Collaboration with Bonn University (MPEC chip)
Photon Counting Chip
High-Resolution (200 μm) Image !!
Example of Applications
Application to Compton Telescope

10–80 keV: CdTe Pixel Detectors + Hard X-ray Optics

80 keV–MeV: Compton Telescope

Compton Kinematics

\[ \cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1 + E_2} \right) \]

\[ E_{in} = E_1 + E_2 \]

Compton Telescope with Semiconductors

Good $\Delta \theta$ & $\Delta E$
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Compton Telescope with Semiconductors

Good $\Delta \theta$ & $\Delta E$
Si/CdTe Compton Telescope

Si: Scatterers
CdTe: Absorbers

Semiconductor (Scatterer & Absorber)
good energy & position resolution
→ Good Angular Resolution
   Good Energy Resolution
   Compact Design

Good from several 10 keV to MeV

Si: High Compton Efficiency
   Low Photo Abs. Efficiency
CdTe: High Abs. Efficiency

Goal: Angular Resolution ~ 1° @ 1 MeV
Detection Efficiency ~ 1–10 %
Double-sided Silicon Strip Detector (DSSD)

Another Key to our Compton Telescope
Development with HAMAMATSU

area: 26×26 – 38×38 mm²
thickness: 300–500 µm
pitch: 100–400 µm
64–128 strips on each side
Compact Modules for Compton Telescope

4-layer DSSD module

4-layer CdTe module

Prototype Compton Telescope
Configuration of Prototype

CdTe

Stacked DSSD module

CdTe
Succeeded in Compton Reconstruction from 60 keV to 700 keV
Good Angular Resolution
↑ Good ΔE of Our Detectors
Reconstructed Spectrum

Background Rejection by Compton Kinematics

Energy Resolution: 8.0 keV (FWHM) @ 511 keV
Summary

• CdTe is an attractive material for hard X-ray or soft gamma-ray detection
• We developed CdTe Schottky diode detector which features good energy resolution
• Our CdTe pixel detectors show good energy resolution & high uniformity
• We demonstrated imaging with fine-pixel sensors
• Application to Compton telescope is successful