New developments in wide bandgap CdZnTe (CZT) semiconductor detectors

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1. Introduction

- BNL’s Nonproliferation and National Security Department (NNS)
- Finding solutions and developments related to
  - Nonproliferation of nuclear materials (security of nuclear plants and other facilities)
  - Arms control
  - Movement of spent fuel
  - National security (points of entry, safeguard)
- Detector development efforts: neutron and gamma-ray detectors
- Three research areas:
  - CdZnTe material growth (new)
  - material characterization (samples from vendors)
  - detector development and testing
Advantages of Cadmium Zinc Telluride (CZT) Material

CZT is very attractive material for radiation detectors. Its feasibility has been demonstrated in many applications.

<table>
<thead>
<tr>
<th>Material</th>
<th>CZT</th>
<th>Ge</th>
<th>Si</th>
<th>TlBr</th>
<th>Hg₂I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z (avg)</td>
<td>49.1</td>
<td>32</td>
<td>14</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>5.78</td>
<td>5.32</td>
<td>2.33</td>
<td>7.56</td>
<td>6.4</td>
</tr>
<tr>
<td>Resistivity (Ω·cm)</td>
<td>$10^{10}$</td>
<td>47</td>
<td>2.3x$10^5$</td>
<td>$10^{12}$</td>
<td>$10^{12}$</td>
</tr>
</tbody>
</table>

- Chemically reactive
- Difficult to handle
- Toxic

- Provide high energy resolution close to Ge (0.5% at 662 keV)
- Do not require cooling (best results usually obtained at ~5-10°C)
- Provide sub-millimeter spatial resolution for imaging devices
- Device fabrication utilizes technologies developed in semiconductor industry which make CZT detectors less expensive and more robust
HUGE SOCIETAL NEED: Improved X- and gamma-ray detectors are required for many applications.

National and Homeland Security
- Nonproliferation of nuclear materials
- Secondary inspection for portals
- Safeguards measurements
- Forensics and attribution
- Nuclear waste management

Medical Imaging
- SPECT, PET and CT scanners
- Bone densitometers
- Medical probes

Basic science
- Astrophysics
- Gamma-Ray Spectroscopy
- Synchrotron X-ray research

Industrial imaging
- Bore-hole logging
- X-ray and gamma-ray cameras
- XRF material analyses

Variety of applications requires detectors with spectroscopic and imaging capabilities.

Long-term, widespread and un-met need for advanced detectors.
Progress in CZT detector development

CZT detectors have been proposed more than a decade ago with a goal to replace HPGe in the field applications.

Despite of significant progress in detector technologies and electronics we are still far from achieving this goal.

We believe, that today’s commercial CZT material have excessively high concentrations of the extended defects, which limit the size and performance of CZT detectors.
X-ray and gamma spectrometers required for many security and medical applications

Traditional Nuclear Radiation Spectrometers
- Ge – High energy resolution, cryogenic cooling
- NaI Scintillators – Low energy resolution

Room-Temperature Wide Band-gap Semiconductor Spectrometers
- No cooling requirements
- High energy resolution
- High spatial resolution
Spectra of $^{152}$Eu source measured with different detectors

Detectors with high resolution preserve more information about a source

Comparison of NaI, HPGe and CZT Detectors

Z. He et al., University of Michigan
Many candidate materials considered for detector and photo-voltaic applications

1. Improve our ability to precisely image the distribution of radionuclides in bodies;
2. Enhance our capability to detect the trafficking, storage, and use of radiological materials and devices.

Interest in wide band gap semiconductor detector materials has been sustained for over three decades.
Cadmium Zinc Telluride (CZT) detectors capable of energy resolution close to High-Purity Germanium

Enriched Uranium (95%) Spectrum Taken with Cadmium Zinc Telluride Detector

Energy (keV) vs Counts

- U235 Gamma Photons
- X-rays

X-rays

Cs-137 Spectrum
FWHM ~ 0.67%

Energy (keV)

FWHM – 4.4 keV

X-rays

Backscatter

Pb X-rays

Escape

Energy (keV)

662 keV
Mobility-Lifetime Products

\[ \mu \tau_e = 6.5 \times 10^{-3} \text{ cm}^2/\text{V} \]

\[ \mu \tau_h = 4 \times 10^{-4} \text{ cm}^2/\text{V} \]
Progress in CdZnTe growth

Commercial producers: Endicott
Redlen

Strong Demand
- Lower cost
- Increase throughput
- Increase device size

Future

Up to 300-mm diameter
Ingot length: 2 m

Brookhaven Science Associates
Low- and high pressure Bridgman growth from melt

- Load charge and oriented seeds into growth ampoule
- Load growth ampoule into PMZF furnace *(Programmable Multi-Zone Furnace)*
  - 24 zone furnace built as NASA flight furnace
  - +/- 0.1°C temperature control
  - Gradient = 1°C/mm
  - Translation rate = 0.42 mm/hour (10 mm/day)

LPB is a bulk crystal growth method that directionally solidifies a molten charge
CZT 11-1 seed loading procedure

Seeds are carefully ground and etched to size, to prevent the melt from leaking past the seeds.

Seeds being loaded into growth ampoule
PMZF furnace before tilting to vertical growth orientation

Close-up of PMZF furnace, loaded for growth (crystal growth in vertical orientation)
CZT synthesis in rocking furnace

- Load elements and dopants into reaction ampoule
- React and melt charge in rocking furnace (>1100°C, very exothermic)
- **Mechanically rock** ampoule to homogenize charge
- Quench charge (exothermic reaction)
- Melting points (°C):

Rocking furnace ensures homogeneous charge
CZT 10-1 ingot

949 grams
38 mm OD
156 mm long → 18 wafers

CZT 10-1 CdZnTe ingot
CZT 10-1 results – grain structure of selected wafers

Wire saw-cut CZT wafers have large grains

Wafer locations in ingot
Recent advances of Redlen THM CZT
Crystal and detector volume expansion

Redlen’s 50 mm dia. CZT ingot

75 mm dia.

100 mm dia.

20x20x5 mm³ tiles

20x20x15 mm³
2010

20x20x10 mm³
2008

20x20x5 mm³
2006
Redlen’s more recent 100 mm diameter boule
Conclusions 1

- Two growth methods: Bridgman, THM, and floating zone
- THM is the most promising
- Grown crystals are far from perfect:
  - Te-reach secondary phases (inclusions and precipitates)
  - Twinning
  - Subgrain boundaries
- Difficult to grow in comparison to Ge and Si (Czochralski)
2. Operation principle of ionization detectors

- Low mobility of holes (single-charge carrier device)
- This makes CZT detectors different from HPGe

\[ Q_{out} = Q_{col} - Q_{ind} \]

Collected charge (mostly electrons)

Charge induced by trapped carriers (mostly holes). It is function of coordinates

\[ Q_{ind} = \frac{E_{ph}}{D} \cdot z \]

A detector’s design should provide efficient way for illuminating the effect of holes!
Elimination of the influence of the uncollected holes

Electrostatic shielding

Virtual Frisch-grid detectors

Coplanar-grid detectors

Theoretically, all these designs should provide energy resolution close to its statistical limit determined by the Fano-factor (~0.5% at 662 keV)

$$A \sim Q_{col}^{el} + Q_{ind}^{hol}$$
3. Defects in commercial CZT material

- Yield of CZT crystals which provide energy resolution close to statistical limit is very low
- Several types of the extended defects that can be found in an average commercial CZT crystal:
  - twins,
  - sub-grain boundaries,
  - Te inclusions,
  - and dislocations which usually arranged in dislocation walls or mosaic strictures

- Most of these defects are not readily seen with visible or IR microscopes => they are often overlooked by vendors

- The extended defects are less important in thin detectors, but their critical roles increase with device thicknesses
Experimental techniques available in BNL

- Experimental techniques are used to identify the extended defect and to measure their effect:
  - IR microscopy
  - White X-ray beam diffraction topography
  - Micro-resolution X-ray beam mapping
  - Surface etching
IR microscopy

Motorized X-Y-Z translational stage, with custom slab holder. (not shown)

Light source

Objective lens (high field of view)

CCD camera

Connected to PC

Nikon microscope

- A stack of images is taken each position of a camera
- Background subtraction
- Locating individual inclusions
Te inclusions found to various degrees in all detector-grade CZT

- Te precipitates
  - Single crystals, dislocation fields (sub-grain boundaries), twin boundaries, grain boundaries
An example of a stack of 100 images projected on the one plane after background subtraction

Volume 1.1x1.5x10 mm³

Te inclusions “starry sky”
IR image analysis

- Size distribution of Te inclusions
- Resolution is limited by the wavelength
- Min size is $\sim 1 \, \mu m$

Grain boundaries decorations by Te inclusions

Twins decorations by Te inclusions

1.1x1.5x6 mm$^3$ volume
Twin boundaries decorated by Te inclusions

Volume: 1.1x1.5x6 mm$^3$
Four views rotated by 90°

We note that inclusion-free regions were observed around decorated twin and subgrain boundaries.
Syntrotron Radiation at NSLS

What is a synchrotron? It is a source of tiny beams of very bright x-rays, UV, visible and IR light

NSLS is a user facility

To investigate the role of precipitates and other non-uniformities in single-crystal CZT, we performed X-ray scans of CZT samples by using a highly-collimated X-ray beam.

Minimum beam size = 10 μm

Quasi-monochromatic beam 85 keV (bulk effects)
Monochromatic beam 30 keV (surface effects & bulk).

For each location of X-ray beam, we collected a pulse-height spectrum and evaluated a peak position, which represents the device response from a small area illuminated by X-rays.

The results of scans were plotted as 2-D maps of device response versus beam position.
Correlations between x-ray response map & infrared transmission image

X-ray map shows the degraded regions precisely correspond to Te inclusions on the right.

IR image shows Te inclusions, which could be identified by composition and shape.

Very high correlation found for all CZT samples.
Spatial resolution and flux of Synchrotron Light Source required to understand the role of extended defects

In the past, small-scale non-uniformities caused by Te inclusions were overlooked because of the wide beams used.

X-ray maps of a planar detector containing a grain boundary and Te inclusions measured with different beam sizes:

- 400 x 400 µm²
- 200 x 200 µm²
- 100 x 100 µm²
- 50 x 50 µm²
- 20 x 20 µm²
- 10 x 10 µm²
Modeling fluctuations caused by Te-inclusion

- Micro-scale resolution X-ray mapping clearly indicates that Te inclusions are opaque to electrons => charge losses are proportional to the geometrical areas of inclusions
- These effects can be easily simulated

Inclusions < 3 μm can be neglected!

Inclusions >10 μm are the most harmful!

Confirmed experimentally!

These results help vendors to improve CZT crystals!
Comparison between two detectors

Detector A
4x4x11 mm$^3$
Energy resolution 0.8% at 662 keV

Detector B
6x6x12 mm$^3$
Energy resolution 3.8% at 662 keV

Not 100% conclusive
Electron trapping by Te inclusions in the case of thin detectors

X-ray scan of 10x10x1.2 mm³
Cathode 200 V, 20 µm step

This X-ray map represents the intrinsic response of the detector without electronic noise contribution.

3-D representation of the response map

How important these peaks for the device spectral response?

Histogram of the response map. Effect is negligible in thin detectors. 0.5% can be attributed to the peak fitting errors.

Efficiency loss
Response map in the case of a 10-mm thick detector

X-ray scan of 10x10x10 mm$^3$

Plotted region

Histogram of the response map

After correction for large-scale variations, which is equivalent to the response from a pixel detector made of this crystal, 1x1 mm$^2$. Fluctuations is ~1.2%, compared to 0.5%.

The fluctuations are primary attributed to Te inclusions.

Detector response degrades with device thickness.
1x1x1 cm³ detector with high concentration of inclusion

X-ray scan of 10x10x10 mm³, 28 keV, 1000 V, 50 μm step

Selected area

Histogram of a whole area

After dividing area in small pixels and normalizing responses generated from each pixel.
The origin of such defects is unclear. Two mechanisms are discussed in the literature: 1) caused by high pressure built inside inclusions (R. D. S. Yadava et al., J. Electron. Mater 21, p. 1001, 1992); 2) moving dislocations interact with inclusions or precipitates (P.B. Hirsh, J. Inst. Metals 86, p. 7, 1957).

Not remnants of inclusions or precipitates are seen inside the “stars”.

Photograph of the etched surface of a 5x5x12 mm³
Prismatic punching defects

2x2 mm$^2$
Photograph of the etched surface

2x1.5 mm²
White beam X-ray diffraction topography

Beam-size: 200 μm x 22 mm
White beam up to 200 keV
Scan in z and 2θ
Two types of contrast: geometrical and dynamic

Example of geometrical contrasts

- Image can be explained based on geometrical optics
- Twins, grains and subgrains

Example of dynamic contrast

- Features can be explained based on the dynamic diffraction theory which takes into account interaction of the beam with a crystal
- Difficult to reconstruct images
- Crystal strains and dislocations patterns
Examples of diffraction topography images

IR Transmission Map

White beam diffraction topography
Subgrain boundaries exist in all commercial CZT regardless of growth techniques or vendors.

There are large varieties of subgrain boundaries in commercial CZT material. It is important to find the extent to which they can be neglected.
Correlations of subgrain boundaries and X-ray response maps for a 2-mm thin detector

Impurities and secondary phases accumulated within subgrain boundaries are primary cases for carries trapping (known from other semiconductors).

Diffraction topograph
~10x15 mm² area, 2-mm thick

Well-defined subgrain boundary with a high density of dislocations

A dark (low response) band due to trapping by impurities, while the dark spots correspond to Te inclusions

High-resolution X-ray response map, 10 μm
X-ray response mapping of the network of subgrain boundaries in a 2-mm thick sample

Charge losses are small (~1%) \(\rightarrow\) less important in thin detectors

But they could cause significant fluctuations of the collected charge that would affect energy resolution in thick detectors?
Effects of the subgrain boundaries with high dislocation density (previously reposted)

Contact pattern “chessboard”

X-ray response map of a 2-mm thick pixel detector illustrating variations of pixel sizes

X-ray diffraction topography image of the subgrain boundaries with high dislocation density

Such subgrain boundaries with high dislocation density are very detrimental and cannot be tolerated in CZT detectors
X-ray maps of CPG

Illuminating from the grid-electrode side

Illuminating from the planar-electrode side

Raster scan area: 15.5mm x 15.5mm
Step size: 100 µm; 600 V; 18keV

Raster scan area: 15.5mm x 15.5mm
Step size: 50 µm; 600 V; 18keV
Defects is the main problem:
  • Point defects (impurities) -> electron lifetime, can be electronically corrected
  • Extended defects (secondary phases, subgrain boundaries, dislocations) -> non-uniformities in spatial distribution of trapping centers, cannot be corrected

Solutions:
  • Purification of starting materials (Cd, Te, Zn)
  • Improving crystal growth techniques
  • Electronic corrections and rejecting incomplete charge collection events
Rejection of the incomplete charge collection events (ICC)

- Charge signals readout from the cathode and anode in generalized spectroscopic detector (e.g., Frisch-grid ionization chamber)

![Diagram showing charge signals readout from anode and cathode](image)
Example of the virtual Frisch-grid detector

15-mm long virtual Frisch-grid detector
Rejection of ICC

(a) Before rejection

(b) After rejection

137Cs

1.5% FWHM
Rejection of ICC events

(a) Before rejection

(b) After rejection

Counts

Channels

137Cs

FWHM 1.0%

Brookhaven Science Associates
$^{133}$Ba source
Corrections and rejections of ICC events

Raw data spectrum

After rejecting the events interacting close to the anode

After charge-loss correction

After rejecting the ICC events

A 6x6x15 mm³ virtual Frisch-grid detector readout with two hybrid preamplifiers
Applications
Arrays of virtual Frisch-grid detectors

- Selected 4 representative detectors (out 30 tested detectors)
- Mounted detectors on the substrate with connectors matching a plug-in board for the 3D readout system
- Collected the data stream from $^{137}$Cs at 2000 V bias (amplitudes and drift times for each event)
- Use cooling (dry ice) to stabilize the temperature just below 17 C (without cooling the temperature quickly rises > 40 C)

2x2 array of 6x6x15 mm$^3$ virtual Frisch-grid detectors with the common cathode

Test box containing readout electronics and CZT array plugged into detector board
Testing the array: raw data

Use the raw data to plot the following distributions:

- **Amplitude vs. Drift time** were used to correct for charge trapping and reject events taking place in the collection region.

- **Cathode-to-Anode ratio vs. Drift time** was used to reject the ICC events.

Detector 1 shows poor performance!

- **R vs. T** is too broad due to systematic error in drift time detection → ASIC needs to be optimized for the array!
Pulse-height spectra measured from 4 detectors

Spectra after the charge-loss correction and rejecting the events interacting inside the collection region near the anode

Good energy resolution
Large peak-to-Compton ratio
BNL develops camera for prostate cancer detection

- High spatial resolution images (10x better than current gamma cameras)
- High specificity for cancerous tumors (based on pharmaceutical tracers)
- Compact design (capable of trans-rectal measurements)
- Low cost (less than 1/3 of conventional imaging devices)
Medical

Redlen NM module for Spectrum Dynamic

Molecular Imaging... Redefined

Though nuclear cardiology has grown significantly in the past 25 years, supporting detector technology has not improved.

Redlen iodide and xenon tubes continue to be the dominant technology in the nuclear medicine marketplace. The lack of industry investment in new technologies has placed severe constraints on clinical workflow and the development of new applications. With exciting new molecular imaging technologies and the horizon and tremendous gains being made routinely in computing technology and applications, the limiting factor necessary to unlock the true potential of molecular imaging will be data collection.

Spectrum Dynamics redefines SPECT imaging with the innovative Di-SPECT™ Cardiac Imaging System.

**10x**
The Sensitivity

For New Clinical Applications

Larger Radiation Collection Angles
Unmatched Scan Patterns

**2x**
The Resolution

For Sharper, Enhanced Images
Novel Design of Scanning Solid State Detectors
Unique Reconstruction Algorithms

**10x**
The Speed

For Unprecedented Throughput

Simplified SPECT can be Complated in as Little as 2 Minutes

Breaking the Paradigm

Spectrum Dynamics provides technology that allows medical professionals to experience a true advancement in Nuclear Imaging. Now no longer have to choose between speed and image quality.

Dramatic improvements in both clinical workflow and image quality are now possible with the Di-SPECT™ Cardiac Imaging System, powered by Spectrum Dynamics' unique FastView™ Technology. This new technology represents a breakthrough (almost every component of molecular cardiology imaging, diagnosis and workflow, including up to a 50% improvement in energy resolution, which will provide the capability to image multiple organs simultaneously).

Three dramatic gains in detective performance combined, with proprietary high resolution reconstruction algorithms, allow medical professionals to enhance clinical results while simultaneously reducing acquisition time, thereby improving overall clinical workflow. With these improvements, the Di-SPECT™ Cardiac Imaging System establishes a new molecular imaging process.
Medical - Future

- $B/Yr market – Biggest driver
- Full body scanning in nuclear medicine
- CZT for X-ray Computed Tomography (high flux X-ray CT)
- CZT for Positron Emission Tomography (PET)
  (See Gu et al. Phys. Med Biol. 56 (2011) 1563 for instance)

Figure 1. CZT high-resolution small animal PET system under development.
High-Resolution Digital Radiography Enabled

- Single-Photon Emission Computed Tomography (SPECT) + (CT) Imaging
- Position Emission Tomography (PET) also demonstrated

$^{99}$Tc uptake in tumors
We are developing a MRI-compatible SPECT system with four heads installed on a rotational gantry.

- Two key objectives: (a) demonstrate the capability of achieving an sub-500 μm SPECT resolution inside MRI scanner (b) provide a flexible platform for testing different detector and system designs.

Left: A 3-D whole-body image of a rat acquired with the 3 T Allegra scanner. Right: T2* relaxation of the tissues. The images were obtained with a multiecho fast low angle shot (FLASH) sequence written by Professor Brad Sutton of UIUC. It resulted in 0.5 mm isotropic resolution from an 8 minutes whole body scan.

NCI, R21/R33CA004940, R21CA135736-01A1.

Basic design target: generic, high performance and flexible.

- Hybrid photon detector concept with highly pixelated (pixel size: 350 μm) CdTe or CZT bump-bonded to 2-D readout ASIC – compact, high resolution.
- ADC on each channel – all digital output, amplitude, time stamp, pixel address for each hit.
- Flexible sparse logic – allowing signals from adjacent pixels to be summed together.

The proposed ERPC detector. (1) CZT crystals of 4.4cm × 4.5 cm × 2-4 mm in size, (2) ERPC ASICs, (3) Readout PCBs, (4) indium bump-bonding between CZT detector to the ASIC, (5) wire-bonds between the ASIC and the PCBs and (6) Cathode signal out.


Meng et al, 2011 IEEE NSS/MIC/RTSD, Valencia
A Sub-500 μm Resolution PET Insert

(A) Geometry of a potential 4-panel VP-PET insert device inside an animal PET scanner.
(B) A potential implementation of the detector technology proposed in this work.
(C) A prototype PET detector developed for the PET application.

DOE, Office of Biological and Environmental Research (DE-FG2-08ER6481).

Meng et al, 2011 IEEE NSS/MIC/RTSD, Valencia
A pixelated CdTe detector of 11mm × 22mm × 1 or 2 mm in size and having 32×64 350 μm × 350 μm pixels.

ERPC detectors with 2 mm thick CdTe detectors will be used in the prototype system.

Other pixel sizes – 515 um, 700 um read out with the same ASIC?
We are exploring the use of CZT detectors of 2 mm and 5 mm thicknesses with the ERPC ASIC (fabricated by Creative Electron Ltd.).

Two different CZT-ASIC bonding techniques (SnBi bump-bonding and Ag/Cu conductive epoxy bonding) are under evaluation.

Meng et al, 2011 IEEE NSS/MIC/RTSD, Valencia
Dedicated MRI-Compatible Ultrahigh Resolution CZT/CdTe Detectors

**A New Digital Readout System for the SPECT/MRI Project**
devolved by Dr. H. Krawczynski’s group at Washington Univ.

**Left**: The proposed MRI-compatible ERPC CdTe detector. **Right**: Using the cathode-to-anode ratio to derive the depth-of-interaction information.

- **Significantly improved readout speed,**
- **Relatively compact**, width of the readout PCB is equal to the width of the CZT/CdTe detectors (4.5 cm), allowing a compact ring geometry.
- **Cathode readout system** is under development.

Meng et al, 2011 IEEE NSS/MIC/RTSD, Valencia
Applications: tomography

Tomographic acquisition setup
Radius of rotation=22.5 mm
(Courtesy of Biospacelab)
Instruments for space applications use CZT detectors
Scientific Research

- Astrophysics - NASA driven
  - **Current:** Single focal plan array detectors in conjunction with a focusing optic.
  - **Future:** Space-flight gamma burst instrument; high-energy x-ray astronomy.

- High Energy Physics (Future)
Applications of CZT detectors in basic science

- Burst Alert Telescope (BAT) for detecting gamma-ray bursts and other transient cosmic events, e.g., supernovas (launched in 2004)
  - Detection plane 30,000 5x5x2 mm$^3$ CZT crystals
  - Total area of 2 m$^2$
  - A coded aperture mask
  - Locate bright sources within 4 arcmin
  - Wide field-of-view.

Swift relays a burst's location to other telescopes around the world.
CZT-based Gamma Camera

CdZnTe gamma camera
32,000 4x4x2mm³ detectors
250 modules
NuStar X-ray Satellite Mission, Caltech/JPL

NuSTAR Focal Plane Detector
(focusing multilayer, deep studies of single objects)

X-ray focusing optics

Focal plane detector
Motivation for ProtoEXIST

Implementation of a wide-field Hard X-Ray Telescope using CZT with:

• Sensitivity between 5 keV and 600 keV
• Wide FOV for all sky transient monitoring.
• Good (~5 arcmin) angular resolution.
• Low power consumption for implementation of large high sensitivity missions (4.5–5.0 m² total active area)

The MIRAX–HXI was proposed US contribution to the Brazilian Cesar Lattes Program:

• Would carry out monitoring of the southern sky approx. every 90 min.
• 70° × 70° FWHM FOV
• 5 arcmin angular resolution in a compact package.
• Provide contemporaneous observations with Advanced LIGO, next generation TeV observatories, and next generation radio optical transient monitors.

Sensitivity of the Mirax–HXI compare with the Swift–BAT
ProtoEXIST Program

ProtoEXIST:
- Dedicated to the production of a modular and highly scalable CZT detector plane architecture.
- ProtoEXIST1 successfully integrated and completed a successful 7 hour balloon flight
- ProtoEXIST2 development ongoing.

ProtoEXIST1:
- Composed of 64 individual CZT detectors readout using a RadNET ASIC via an interposer board.
- 2.5 mm pixel pitch.
- Detectors are grouped into modular 4×2 sub-arrays called detector crystal array (DCAs)
- Full detector plane composed of a 2×4 array of DCAs mounted to a flight control board.

ProtoEXIST2:
- Individual detectors now utilize the NuASIC originally developed for NuSTAR (to launch in early 2012).
- 604.8 μm pixel pitch.
- Detectors now grouped in 4×4 sub-arrays, Quad Detector Modules (QDMs).

<table>
<thead>
<tr>
<th>Detector (ASIC)</th>
<th>Pix. Pitch [mm]</th>
<th>N_ch</th>
<th>Power [mW/ch.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTEGRAL-ISGRI</td>
<td>4</td>
<td>128</td>
<td>2.8</td>
</tr>
<tr>
<td>Swift-BAT (XA)</td>
<td>4</td>
<td>64</td>
<td>3.3</td>
</tr>
<tr>
<td>ProtoEXIST1 (RadNET)</td>
<td>2.5</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>ProtoEXIST2 (NuASIC)</td>
<td>0.6048</td>
<td>1024</td>
<td>0.05</td>
</tr>
<tr>
<td>ProtoEXIST3 (ExASIC)</td>
<td>0.6048</td>
<td>1024</td>
<td>0.01</td>
</tr>
</tbody>
</table>

![Diagram of detector planes and components](image_url)
ProtoEXIST2 Detectors Crystal Units (DCU)

The RadNET ASIC attached to the ProtoEXIST1 IPB. ASIC anode inputs were mapped to a $8 \times 8$ array of inputs on the upper surface of the IPB for bonding to CZT.

Development of the ProtoEXIST 2 detectors continues in collaboration with Creative Electron Inc. (hybridization), Caltech and GSFC. 20 mm $\times$ 20 mm, 5 mm thick Redlen CZT are utilized at the detector medium.

Current Status:
- Front-end electronics for ASIC control validated and successfully demonstrated in a test board implementation.
- 2 bonding methods utilizing a conductive epoxy bond + anode pad gold studs, and conductive epoxy bond + metallized anode pads.
- 5 hybridized detectors completed to date: 3 $\times$ bonded to test boards (upper right), 2 $\times$ complete prototype DCUs (lower right)
- Full production of 80 detectors to commence shortly in preparation for flight of a test detector in September 2012.
Detectors for homeland security applications currently under development

J. Matteson et al., University of California in San Diego

Consists of 25x25x5 mm\(^3\) orthogonal strip detector detectors

Z. He et al., University of Michigan

Consists of 18 20x20x15 mm\(^3\) pixel detectors

Brookhaven Science Associates
• Nuclear spectroscopy application of CZT moving from traditional small detector based nuclear instrumentation (past) to very compact prototype imaging system (current) and eventually mobil type imaging system (Future)

High Efficiency Multimode Imager (HEMI)
Myriagami: system architecture

- Power board with HV supply
- System manager/Interface board
- 4x4 CZT crystal plane
- Preamplifier & digital processing boards
CZT Coplanar Grid (CPG) detectors

- Source material: Redlen 19 x 19 x 5 mm³ with 8 x 8 pixel
- Removal of pixel and backside contacts
- Deposition of CPG contacts and new backside contact
- Stack of two detectors used to increase volume ~4 cm³

C. Disch: “Coincidence Measurements and long-term Stability Analysis with Stacked (Cd,Zn)Te Coplanar Grid Detectors”, RTSD.S Postersession I/II
Underground COBRA Gran Sasso Underground Laboratory
Pixel detectors

In collaboration with group of Z. He (Univ. Michigan)

The power of pixels!

Running at Gran Sasso Sep. 2009 - January 2010

20x20x15 cm³ CZT detector (as used in Polaris system)
11x11 pixels

NB: Also running a pixel system developed at Washington University at St. Louis at Gran Sasso
Learn about background using 1cm³ CPG CZT detectors
**Motivation**

Dose rate monitoring network in Germany

- ~1800 probes
- Geiger-Müller counters
- Connected to server via phone line
- No energy information → no particle identification
- ~200 spectroscopic systems planned
Digital MCA with preamplifier and high voltage supply

Peltier cooling

Detectors with preamplifiers

Air duct
- Silicon and CZT in one copper box
  - 6.5 cm distance between
- Readouts coupled by 4 signals
  - Counter Clear
  - Counter Oscillator
    - 3.125 MHz
  - Busy In
  - Busy Out
- Selected events that:
  - Matched counters
  - Coincidence between both sides of Silicon
    - Energy match of 10 keV
- Cs-137 source 24 cm away from Si
  - ~77 Bq

- Event Ordering
  - Assumed smallest interaction energy is first
    - True for ~75% of events at 662 keV
      - 0-76° scatter angles
    - Silicon scatter events
      - Lower Doppler broadening
  - Reconstruct cone of probable locations based on energy and locations of interactions
    - Angular resolution of 8.5° FWHM
3 generations to reach optimal performance

Caliste development

<table>
<thead>
<tr>
<th>Features</th>
<th>Caliste 64</th>
<th>Caliste 256</th>
<th>Caliste HD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel detector</td>
<td>8 × 8</td>
<td>16 × 16</td>
<td>16 × 16</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>1 mm</td>
<td>580 µm</td>
<td>625 µm</td>
</tr>
<tr>
<td>Guard ring</td>
<td>900 µm</td>
<td>200 µm</td>
<td>20 µm</td>
</tr>
<tr>
<td>Front-end</td>
<td>IDef-X 1.1</td>
<td>IDef-X v2</td>
<td>IDef-X HD</td>
</tr>
<tr>
<td>Power consumption</td>
<td>200 mW</td>
<td>800 mW</td>
<td>200 mW</td>
</tr>
<tr>
<td>Pin grid array</td>
<td>7 × 7</td>
<td>7 × 7</td>
<td>4 × 4</td>
</tr>
<tr>
<td>Energy range</td>
<td>2-250 keV</td>
<td>2-250 keV</td>
<td>2 keV-1 MeV</td>
</tr>
</tbody>
</table>

**Sum spectra**
- 0.7 keV@14 keV
- 0.9 keV@60 keV
Medipix-2 Detector Chip

- Photon Counting detectors
- 65,536 pixels (256 × 256)
- 55 × 55 μm² pixels
- 1.4 × 1.4 cm² area

Fig (a) shows Medipix-2 detector chip
Fig (b) magnified view of (a)
Flood Frames

Dual CdTe Medipix2

Si Medipix2
Image Correction Demonstration of Si

- **Detector parameters:**
  - 100 V bias
  - Low energy threshold $\approx 13$ keV
  - 200 frames
  - Tube Current = 200$\mu$A
  - Shutter time = 40ms
  - SDD = 190mm
Image Correction Demonstration of CdTe

- **Detector parameters:**
  - -438 V bias
  - Low energy threshold ≈ 13 keV
  - 200 frames
  - Tube Current = 23 µA
  - Shutter time = 30ms
  - SDD = 190mm
CT Images With Medipix2-CdTe

Mouse Sample

Brookhaven Science Associates

2-D Projection Images

3-D CT images (selected region from projection image)

≈ 50 mm

≈ 35 mm

15 keV and above

35 keV and above

55 keV and above

SP-5

SP-4

SP-3

SP-2

SP-1
Conclusions

- Quality and high cost of crystals is the main factor limiting wide spread of CZT detectors.
- Due to developments in readout electronics and charge loss correction techniques CZT detectors continue finding places in many areas of applications.
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