X-Ray Detector Activities in Japan

Aug. 1st, 2012

BES Neutron and Photon Detector W.S. @Gaithersburg

Yasuo Arai (yasuo.arai@kek.jp)

High Energy Accelerator Research Organization, KEK

Institute of Particle and Nuclear Studies
Neutron & Photon Facilities in Japan

RIKEN, JASRI
SPRING-8 (8 GeV SR)
SACLA (8 GeV XFEL)
SPRING-8II

KEK & JAEA,
J-PARC
(30GeV Proton → Neutron)

Super KEKB(e⁺ - e⁻)
PF(2.5 GeV SR)
PF-AR(6.5GeV SR)
ERL
Although there are many activities on X-ray detector developments in Japan, I do not cover all the work.

**Today's Topics**

- CdTe detector (JASRI SPring-8)
- MPCCD detector (Riken SACLA)
- SOI detector (KEK, Riken SACLA)
- STJ detector (AIST)
Cd Te detector

<table>
<thead>
<tr>
<th></th>
<th>CdTe</th>
<th>CZT</th>
<th>Ge</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>density (g/cm³)</td>
<td>5.85</td>
<td>5.8</td>
<td>5.33</td>
<td>2.33</td>
</tr>
<tr>
<td>atomic number</td>
<td>48, 52</td>
<td>48, 30, 52</td>
<td>32</td>
<td>14</td>
</tr>
<tr>
<td>band gap energy (eV)</td>
<td>1.44</td>
<td>1.65</td>
<td>0.67</td>
<td>1.12</td>
</tr>
<tr>
<td>Ionization energy (eV)</td>
<td>4.43</td>
<td>5.0</td>
<td>2.96</td>
<td>3.62</td>
</tr>
<tr>
<td>resistivity (Ωcm)</td>
<td>10⁹</td>
<td>10⁹~10¹¹</td>
<td>3900</td>
<td>1400</td>
</tr>
<tr>
<td>μₑ (cm²/V·s)</td>
<td>1100</td>
<td>1000</td>
<td>3900</td>
<td>1400</td>
</tr>
<tr>
<td>μₕ (cm²/V·s)</td>
<td>100</td>
<td>50~80</td>
<td>1900</td>
<td>480</td>
</tr>
<tr>
<td>τₑ (s)</td>
<td>3×10⁻⁶</td>
<td>3×10⁻⁶</td>
<td>&gt;10⁻³</td>
<td>&gt;10⁻³</td>
</tr>
<tr>
<td>τₕ (s)</td>
<td>2×10⁻⁶</td>
<td>10⁻⁶</td>
<td>1×10⁻³</td>
<td>2×10⁻³</td>
</tr>
</tbody>
</table>

- CdTe is a promising semiconductor for high-energy X-ray region due to its high atomic number and density.
- Low leak current due to its wide band gap energy even at room temperature.

Most of the CdTe crystals used in the world are produced in Japanese company (Acrorad Co. Ltd.). (However, it entered Siemens group last year)
CdTe pixel detector

Ohmic and Schottky configurations

X-ray - Bias voltage

+ Bias voltage

- Bias voltage

Pt/CdTe/Pt-pixel

In/CdTe/Pt-pixel

Pt/CdTe/Al-pixel

In/Au stud bonding

(developed with JAXA)

Three metal configurations were investigated by using high resistivity p-type CdTe wafers 500μm in thickness.

CdTe + SP8-02 ASIC (TSMC 0.25um)

Combined image with 4 x 6 positions

200um, 20 x 50 pix

(toyokawa@spring8.or.jp)
CdTe strip detector (Collab. with PSI)

Plan to install BL19B2 diffractometer
1st stage: standard Si sensor MYTHEN
Final: CdTe sensor with MYTHEN chip

Sample: CeO₂
X-ray energy: 30 keV
Exposure time: 60 sec

CdTe detector shows 20 times higher efficiency and comparable energy resolution with Si detector.

(toyokawa@spring8.or.jp)
CdTe Applications

Hitachi Gamma Camera

16x16 CdTe laminated Pin Hole Camera (Fukushima NPP)

Dental Panoramic Image

40x40 CdTe Photon Counting


http://www.telesystems.co.jp/dental/
Multiport CCD (MPCCD) detector for X-ray Free-Electron Laser Facility, SACLA

- High-Speed, 8-ports, Front Illumination CCD.
- First Detector for SACLA.
- Proven state-of-art technologies in collaboration with industry sensor: e2v, readout: Meisei Co).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Size</td>
<td>50 x 50 um²</td>
</tr>
<tr>
<td>Peak Signal</td>
<td>&gt; 4.4 Me- (2700 ph.@6 keV)</td>
</tr>
<tr>
<td>Noise</td>
<td>&lt; 300 e- 0.18 ph. @ 6keV</td>
</tr>
<tr>
<td>Pixel Number</td>
<td>1k x 512 pix/sensor</td>
</tr>
<tr>
<td>Rad. Hardness</td>
<td>&gt; 1.6 x 10^{14} ph./mm² @ 12 keV</td>
</tr>
<tr>
<td></td>
<td>&gt; 1 year annual dose</td>
</tr>
<tr>
<td>Sensitive Layer</td>
<td>50 um (300 um in Phase III)</td>
</tr>
<tr>
<td>Dead Area at Edge</td>
<td>300 um</td>
</tr>
</tbody>
</table>

More than half present proposals are using this detector.

8 port readout

(hatsui@spring8.or.jp)
MPCCD

Octal Module
(110mm x 110mm, 2048 x 2048 pix)

Working successfully!

(hatsui@spring8.or.jp)
Although the MPCCD is working successfully as a first detector for SACLA, this does not yet reach for final target spec.

→ SOI Pixel R&D is also going.
SOI Pixel Detector (SOIPIX)

Monolithic Detector having fine resolution of silicon and data processing power of CMOS LSI by using Silicon-On-Insulator (SOI) Technology.
Feature of SOI Pixel Detector

- No mechanical bonding. Fabricated with semiconductor process only, so high reliability, low cost are expected.
- Fully depleted thick sensing region with Low sense node capacitance.
- On Pixel processing with CMOS transistors.
- Can be operated in wide temperature (4K-570K) range, and has low single event cross section.
- Based on Industry Standard Technology.
SOIPIX Collaboration:
Regular Multi-Project Wafer (MPW) run. (~twice/year)

0.2 μm Fully-Depleted SOI Pixel Process of Lapis Semiconductor Co. Inc.

JAXA
RIKEN
AIST
Osaka U.
Tohoku U.
KEK
Kyoto U.
Tsukuba U.

U. of Hawaii
Fermi Nat'l Accl. Lab.
Lawrence Berkeley Nat'l Lab.
MPI
INP Krakow
U. Heidelberg
IHEP China
Louvain-la-Neuve Univ.

SOIPIX MPW Mask
Integration Type Pixel (INTPIX5)

Pixel Size: 12x12 μm²
896x1408 (~1.3 M) pixels, 11 Analog out port, Column CDS.

12.2 mm

18.4 mm
Measurement with SOIPiX

Dried Sardien (3 images are combined)

Compton Electrons Tracks

X-ray Energu Spectrum@-50°C

Al-Ka (1.49 keV)

188 eV (FWHM)
noise 18e- rms

5mm
High Resistive FZ(p and n) SOI Wafer

Not only CZ-SOI wafer, we succeeded to process 8-inch FZ-SOI wafer.

<table>
<thead>
<tr>
<th>Before Oxidation</th>
<th>Conventional SOI Process</th>
<th>Improved SOI Process</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>

We optimized the process parameters, and succeeded to perform the process without creating many slips.
Wafer type and Leakage Current

- **CZ(n)**: 0.7 kΩcm, 260 μm
- **FZ(n)**: 7 kΩcm, 500 μm
- **FZ(p)**: 40 kΩcm, 500 μm

Graph showing leakage current versus depletion width for different wafer types.

- **INTPIX3e**
- **VDET**
- **237V**
- **377V**
- **320V**
- **112V**
- **55V**
- **Over Deplete**
- **Mechanical Grind**
- **Chemical Etch**
Issues in SOI Pixel

Sensor and Electronics are located very near. This cause ..

We need additional back-plane to suppress these effects.
Buried p-Well (BPW)

- Cut Top Si and BOX
- High Dose

- Keep Top Si not affected
- Low Dose

- Suppress the Back Gate Effect.
- Shrink pixel size without losing sensitive area.
- Increase break down voltage with low dose region.
- Less electric field in the BOX which improves radiation hardness.
- Shield transistors from bottom electric field
- Compensate electric field generated by the trapped hole in the BOX.
- Reduce crosstalk between sensors and circuits.

First Chips will be delivered this week.
Silicon-On-Insulator PHoton Imaging Array Sensor (SOPHIAS)

Multi-via concept

Utilize lateral diffusion of electron-hole cloud.

<table>
<thead>
<tr>
<th>Gain</th>
<th>Csens [fF]</th>
<th>Via #</th>
<th>Gain [uV/e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>16</td>
<td>24</td>
<td>7.2</td>
</tr>
<tr>
<td>Low</td>
<td>240</td>
<td>4</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Large Dynamic Range

High Gain Via : 24
Low Gain Via : 4

30 um pixel

x48
## Specification of SOPHIAS and MPCCD

<table>
<thead>
<tr>
<th></th>
<th>SOPHIAS</th>
<th>MPCCCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Signal/Pixel</td>
<td>7 Me^-</td>
<td>4.5 Me^-</td>
</tr>
<tr>
<td>Peak Signal/100 um☐</td>
<td>78 Me^-</td>
<td>18 Me^-</td>
</tr>
<tr>
<td>Noise</td>
<td>100 e^-</td>
<td>300 e^-</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>30 um☐</td>
<td>50 um☐</td>
</tr>
<tr>
<td>Pixel Number</td>
<td>1.92 M</td>
<td>0.5 M</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>100 %@6 keV</td>
<td>95 %@6 keV</td>
</tr>
<tr>
<td>Gain</td>
<td>7 uV/e^-</td>
<td>0.4 uV/e^-</td>
</tr>
<tr>
<td>Frame rate</td>
<td>60 fps</td>
<td>60 fps</td>
</tr>
</tbody>
</table>
SOPHIAS Detector

- XFEL Application has driven and is driving critical technologies
  - Back-side process
  - MIM cap onto 3M layer
  - Introduction of optimized Pcells
  - Stitching lithography
  - Depletion of 500 um by SOI-FZ wafer
  - Radiation hard transistor

- achieved

- Under progress

Raw Data

25 msec Exposure
Ag 20 kV 0.2 mA
Superconducting Tunnel Junction (STJ)

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Nb</th>
<th>Al</th>
<th>Hf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c [K]$</td>
<td></td>
<td>9.23</td>
<td>1.20</td>
<td>0.165</td>
</tr>
<tr>
<td>$2\Delta [\text{meV}]$</td>
<td>1100</td>
<td>1.550</td>
<td>0.172</td>
<td>0.020</td>
</tr>
<tr>
<td>$H_c [\text{G}]$</td>
<td>1980</td>
<td>105</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

$T_c$ : Phase Transition Temp  
$2\Delta$ : Band Gap Energy  
$H_c$ : critical magnetic field

Band Gap Energy $< 1/1000$ Si, so extremely good energy resolution!

R&Ds are going at several institutions (KEK, AIST, RIKEN, NAOJ, Tsukuba U., Okayama U. ...)

Tc : Phase Transition Temp  
2Δ : Band Gap Energy  
Hc : critical magnetic field
Soft X-ray spectrometer using 100-pixel STJ array

- Motivation
  - measurement of local structure in light element dopants
  - fluorescent yield X-ray absorption spectroscopy (XAS) in soft X-ray region
  - high sensitivity (1mm²), high resolution (10-20 eV @ < 1keV), fast response (1M cps)
- 100-pixel STJ array is developed.

Microphotograph of STJ detector fabricated in AIST.

XRF spectrum of BN at 600eV taken by an STJ detector.

Ukibe et. al,

(s-shiki@aist.go.jp)
Soft X-ray XAS instrument using STJ array

- **STJ-XAS**
  - SR source, BL-11A (bending), BL-16A (undulator) in KEK-PF
  - Vacuum sample chamber, quick sample preparation using load lock
  - Automated $^3$He cryostat, base temperature of 300mK
  - 100-pixel STJ array, 91 channels available
  - Robust readout, room temp. preamplifiers, FADC-FPGA MCAs

![Soft X-ray XAS instrument using STJ array](image)
- **SiC measurement**
  - power electronics device
  - nitrogen dope → n-type semiconductor
  - problem: overlap of C-Kα during N-K edge measurement

XRF spectrum of SiC:N (300ppm)

CNO lines are clearly separated.

STJ-XAS is useful to study nitrogen dopant in SiC.
Summary

• X-ray Imaging is one of very active field.

• Although number of researchers working on detector developments is not so large in Japan, collaboration with industry enables us to do state-of-art detector developments.

• There are several development activities of CdTe detectors in academic and industry sectors in Japan. We are in a bit good position since the crystals are produced in Japan.

• First detector (MPCCD) for SACLA is developed successfully in collaboration of RIKEN and e2v. However, R&D for larger dynamic range detector (SOPHIAS) using SOI technology is also going.

• Developments of SOI pixel detector was initially started at KEK in 2005. Now many collaborators are participating the SOIPIX process at MPW run.

• STJ and other superconducting devices (MKID) are actively developed in several Japanese institutions.