Possibilities for Thick, Simple-Structure Silicon X-Ray Detectors Operated by Peltier Cooling

Hideharu Matsuura\(^1\), Derek Hullinger\(^2\), Ryota Okada\(^1\), Seigo Kitanoya\(^1\), Seiji Nishikawa\(^1\), and Keith Decker\(^2\)

\(^1\)Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan
\(^2\)MOXTEK, Inc., 689 W. 1285 N., Orem, UT 84057, USA

IC-MASD2011, May 17th, 2011, Kos Island, Greece
Requirement

Detection of a trace of hazardous atoms in materials

For examples;
A. Cd contamination in foods
   1. less than 0.4 ppm in rice
   2. less than 0.2 ppm in wheat
B. Hazardous elements in soil
   1. less than 150 ppm of cadmium
   2. less than 250 ppm of hexahydric chromium
   3. less than 150 ppm of arsenic
   4. less than 15 ppm of mercury

To detect fluorescent X-rays of atoms in materials is useful.
Energies of X-ray fluorescence of hazardous elements

Excitation X-ray

Material

X-ray fluorescence

Cd: $K_{\alpha} (23.11 \text{ keV})$

Br: $K_{\alpha} (11.91 \text{ keV})$

Pb: $L_{\alpha} (10.54 \text{ keV})$

Hg: $L_{\alpha} (9.98 \text{ keV})$

Cr: $K_{\alpha} (5.41 \text{ keV})$
Transportable X-ray detectors require

1. large active area for high sensitivity
2. small capacitance of detector for high energy resolution
3. operation by Peltier Cooling
Silicon Drift Detector (SDD)

1. Large active area
2. Small capacitance of detector
3. Operation by Peltier cooling

The p-rings are electrically coupled using MOSFET to form an adequate electric field in SDD.

Fabrication processes are complicated.

SDD is very expensive.
### Requirement of Si thickness

<table>
<thead>
<tr>
<th>Element</th>
<th>$^{48}\text{Cd}$</th>
<th>$^{50}\text{Sn}$</th>
<th>$^{51}\text{Sb}$</th>
<th>$^{53}\text{I}$</th>
<th>$^{55}\text{Cs}$</th>
<th>$^{56}\text{Ba}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_{\alpha}$</td>
<td>$K_{\alpha}$</td>
<td>$K_{\alpha}$</td>
<td>$K_{\alpha}$</td>
<td>$K_{\alpha}$</td>
<td>$K_{\alpha}$</td>
</tr>
<tr>
<td>Energy [keV]</td>
<td>23.1</td>
<td>25.2</td>
<td>26.3</td>
<td>28.5</td>
<td>30.8</td>
<td>32.0</td>
</tr>
<tr>
<td>Si Thickness [mm]</td>
<td>Absorption [%]</td>
<td>0.3</td>
<td>0.6</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>0.3</td>
<td>19</td>
<td>14</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>0.6</td>
<td>35</td>
<td>27</td>
<td>23</td>
<td>18</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>1.0</td>
<td>51</td>
<td>41</td>
<td>35</td>
<td>29</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>1.5</td>
<td>65</td>
<td>54</td>
<td>48</td>
<td>40</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>2.0</td>
<td>76</td>
<td>64</td>
<td>58</td>
<td>49</td>
<td>41</td>
<td>38</td>
</tr>
</tbody>
</table>

K-line X-ray fluorescence: $^{11}\text{Na}(1.0\text{ keV}) \sim^{50}\text{Sn}(25.2\text{ keV})$

L-line X-ray fluorescence: $^{51}\text{Sb}(3.6\text{ keV}) \sim^{92}\text{U}(13.6\text{ keV})$

**Si thickness is required to be thicker than 1.5 mm**
Aim of our study

X-ray detectors that meet the following requirements are materialized.

1. Large active area for high sensitivity
2. Small capacitance of detector for high energy resolution
3. Operation by Peltier Cooling for transportable unit
4. Simple structure for inexpensive detector
5. Thick Si wafer for high sensitivity of high energy X-rays
6. Only one high voltage bias for inexpensive unit
Proposal of New X-ray detector

1. Large active area for high sensitivity
2. Small capacitance of detector for high energy resolution
3. Operation by Peltier Cooling for transportable unit
4. Simple structure for inexpensive detector

Prior art SDD

Simple-structure SDD (SSDD) Without MOSFET
Produced electron-hole pair in depletion region

- Incident X-ray
- Negative bias
- Depletion layer
- Bulk
- C
- n
Produced electron-hole pair in depletion region

- Negative bias
- Depletion layer
- Bulk
- Signal
- C
Produced electron-hole pair in bulk

- Incident X-ray
- Negative bias
- Bulk
- C
- n
- p
Produced electron-hole pair in bulk
To deplete the whole i layer is required

In Si, 3.6 eV of X-ray produces one hole-electron pairs.

X-ray with 5.9 keV produces approximately 1600 electrons.

Signal is proportional to the number of electrons.
Reverse bias required to deplete a whole i layer of **pin diode**

<table>
<thead>
<tr>
<th>Resistivity [kΩcm]</th>
<th>2</th>
<th>10</th>
<th>20</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_D [cm⁻³]</td>
<td>2x10¹²</td>
<td>4x10¹¹</td>
<td>2x10¹¹</td>
<td>1x10¹¹</td>
</tr>
<tr>
<td>Si Thickness [mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>137</td>
<td>27</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>0.6</td>
<td>547</td>
<td>109</td>
<td>55</td>
<td>27</td>
</tr>
<tr>
<td>1.0</td>
<td>1519</td>
<td>304</td>
<td>152</td>
<td>76</td>
</tr>
<tr>
<td>1.5</td>
<td>3417</td>
<td>683</td>
<td>342</td>
<td>171</td>
</tr>
<tr>
<td>2.0</td>
<td>6074</td>
<td>1215</td>
<td>607</td>
<td>304</td>
</tr>
</tbody>
</table>

**Higher-resistivity Si substrate is required to operate at adequate high reverse bias.**
Conditions of the prior art SDD

SDD currently in use
Si
thickness: 0.3 – 0.5 mm
resistivity: 2 k Ωcm

Applied voltages
0.3-mm-thick case
Cathode: -50 V
outermost p-ring: -100 V
innermost p-ring: -10 V
Fabrication of SSDD

To investigate a possibility of use of higher-resistivity Si substrate.

Two type of SSDD
Si
resistivity: 2 k $\Omega$ cm
6.5 k $\Omega$ cm
thickness: 0.3 mm

Applied voltages
- cathode: -80 V
- outermost p-ring: -80 V
- inner p-ring: -42.5 V
- innermost p-ring: -5 V
Unfortunately, the current for 6.5 kΩcm Si increased with bias, and exceeded the current for 2 kΩcm Si.
The current between cathode and p-ring became of the order of mA.

This occurred due to the difference in voltage between cathode and p-ring.
To operate SSDD using high-resistivity Si, the same voltage should be applied to the cathode and p-rings, that is,

1. Outermost p-ring is applied to a negative bias that is the same as the cathode.
2. Inner p-rings are floating.
Proposal of second new structure

SSDD

1. Outermost p-ring is applied to a negative bias that is the same as the cathode.
2. Inner p-rings are floating.

Gated SDD (GSDD)

P-ring and all the gates are applied to a negative bias that is the same as the cathode.

SSDD and GSDD require only one high voltage bias
Simulation and Fabrication of GSDD

Si resistivity: 10 kΩ·cm
Si thickness: 0.625 mm
Distance between center and p-ring: 2.455 mm
The potential at the SiO$_2$/Si interface is strongly dependent on the fixed oxide charge and the gap between the gates.
Potential distribution in the detector

Active area: 18 mm²
Experimental result: $^{55}\text{Fe}$ spectrum

Energy resolution:
145 eV at 5.9 keV
at -35 °C
at a peaking time of 5 μs
Experiment:

1. X-rays were incident through 100-μm-diameter pin hole.

Active area: 18 mm²
Experiment:
1. X-rays were incident through 100-μm-diameter pin hole.
2. Detector was moved in 100-μm increments.

Active area: 18 mm²
Simulation of GSDD with 1.5-mm-thick Si

Si
- thickness: 1.5 mm
- resistivity: 10 kΩ cm

SiO$_2$
- thickness: 3 μm

SiO$_2$/Si interface
- fixed charge: $1 \times 10^{10}$ cm$^{-2}$

Cathode
- radius of area: 1.23 mm

P-ring and all gates are applied at -400 V
Potential Distribution in Si

Cathode

Anode

p ring

Beneath gate
Potential Distribution in Si

Cathode

Anode

p ring
Electrons produced by X-rays can flow smoothly to the anode.
Summary

From experimental results and simulations, we showed the possibilities for Si X-ray detectors satisfied with the followings.

1. Large active area for high sensitivity
2. Small capacitance of detector for high energy resolution
3. Operation by Peltier Cooling for transportable unit
4. Simple structure for inexpensive detector
5. Thick Si wafer for high sensitivity of high energy X-rays
6. Only one high voltage bias for inexpensive unit