A Systematic 3D Simulation Study of BNL’s 3D-Trench Electrode Detectors

A. Montalbano\(^1\) D. Bassignana\(^2\) W. Chen\(^3\) Z. Li\(^3\) S. Liu\(^3,4\)
D. Lynn\(^3\) G. Pellegrini\(^2\) D. Tsybychev\(^1\)

\(^1\)Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA

\(^2\)National Microelectronics Centre, Barcelona, Spain

\(^3\)Physics Department, Brookhaven National Laboratory, Upton, NY, USA

\(^4\)School of Nuclear Science and Technology, Xi’an Jiaotong University, China

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Introduction - Past Silicon Pixel Detectors

C. Kenny, S. Parker, et al. IEEE, NS46 (4), 1999

- Planar pixels (left) have limited depletion zone close to the electrodes at moderately high voltages after high radiation exposure.
- The Column 3D detector (right) solved this problem, but introduced a saddle point in the potential and nonhomogeneity in $\vec{E}$, meaning it introduced a $\theta$ dependence.
Advantages of 3D

- Decouples depletion from thickness
- Reduces depletion voltage by decreasing the electrode spacing

Column 3D Limitations

- High electric field along junction at the column
- Columns create inhomogeneities in $\vec{E}$

We want to:

- Remove the saddle point in the potential.
- Remove $\theta$ dependence
- Make each cell independent of its neighbors
Our High Energy 3D-Trench Electrode Detector

- Depth: 500 $\mu m$ - Simulated: 300 $\mu m$
- Width of trench: 10 $\mu m$
- Diameter of column: 10 $\mu m$
- Depth of doping: Simulated - 270/300 $\mu m$
- When simulated with radiation, treated after $\Phi_{eq} = 10^{16}$ 1 MeV $n_{eq}/cm^2$
- Doping:
  - p+ column
  - n+ trench
  - p type bulk (simulates after SCSI)

Z. Li, NIMA Vol 658, Issue 1 (2011)
- Electrode spacing: 50 $\mu m$
- Shape: Hexagon
Simulation Specifics

- Used commercial software from Silvaco (TCAD’s programs - Devedit 3d, Device 3d, Atlas, etc) to simulate the detectors’ electrical properties.
- Simulate the detector after high radiation by changing the effective doping concentration of the bulk.
- In the future, will use explicit radiation defects in Silicon
- This gives us first order effects.
Full Depletion Voltage was simulated to be 95 V. Electrode spacing is 50\(\mu\text{m}\) Treated with \(\Phi_{eq} = 10^{16} \text{ 1 MeV n}_{eq}/\text{cm}^2\)
The different types of detectors possible

The different doping does not matter in the column detectors, since differences would just correspond to a translation.

- For our detectors, different doping will cause significant changes in the potential’s shape
- We choose:
  - Doping of the center column
  - Doping of the cylindrical-shaped trench in each cell
  - Doping of bulk n (green) and p (red)

1. Outer trench is n+ and center column is p+
2. Outer trench is p+ and center column is n+
4 Combinations

Now for both of the previous two, there are two more versions with the type of doping of the bulk Si

1. n-type
2. p-type

Under high radiation, the bulk material may undergo space charge sign inversion (SCSI). This “type inversion” turns n-type doping into “p-type equivalent”

This determines where the junction is, at the trench or at the column

Junction at the column makes high electric field, while having the junction at the trench allows for more uniformity and a lower absolute maximum $\overrightarrow{E}$
Electric Fields, Fully Radiated

The electrode spacing is 50 $\mu m$, and is simulated with $\Phi_{eq} = 10^{16}$ $1$ MeV $n_{eq}/\text{cm}^2$. Top is fully depleted, bottom is not.

P Type

P column

N column
Type Comparison Results

The electrode spacing is 50 $\mu m$, and is simulated with $\Phi_{eq} = 10^{16}$ 1 MeV $n_{eq}/cm^2$

<table>
<thead>
<tr>
<th>column, bulk, trench</th>
<th>$V_{dep}$</th>
<th>Junction</th>
<th>Dep Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>n+, n, p+</td>
<td>90 V</td>
<td>trench</td>
<td>inward</td>
</tr>
<tr>
<td>n+, p, p+</td>
<td>&gt; 500 V</td>
<td>column</td>
<td>outward</td>
</tr>
<tr>
<td>p+, n, n+</td>
<td>&gt; 500 V</td>
<td>column</td>
<td>outward</td>
</tr>
<tr>
<td>p+, p, n+</td>
<td>88 V</td>
<td>trench</td>
<td>inward</td>
</tr>
</tbody>
</table>

After $\Phi_{eq} = 10^{14}$ 1 MeV $n_{eq}/cm^2$ the n-type will type invert, so we might as well start off with p-type. Therefore, we use p+ column with p-type bulk and n+ trench.
Column 3D Detector

- Electrode spacing: 50 $\mu m$
- Depth: 300 $\mu m$
- Shape: Column
- Diameter of doping columns: 10 $\mu m$
- When simulated with radiation, treated after $10^{16} n/cm^2$
- Doping:
  - $p^+$ center column
  - $n^+$ corner columns
  - $p$ type bulk (simulates after SCSI)
Column Vs. BNL’s

Potential at Full Depletion

Column (250 V)  BNL’s (95 V)
Electric Field’s $\theta$ Dependence

**Column at constant radii**

![Graph showing electric field dependence on angle with constant radii](image)

**Hexagon at constant radii**

![Graph showing electric field dependence on angle with constant radii](image)
Photon Sciences

- Also useful for X-ray detection at the National Synchrotron Light Source II at Brookhaven National Laboratory.
- The natural separation of cells is good for spectrometry.
- Radiation is no longer an issue, simulated at a much lower bulk doping concentration.
- The cell size is $\approx 500 \mu m$ which means it is much larger than the High Energy cells ($\times 10$ larger).
- In our first prototype the Trench and center column have a width of 10 $\mu m$ and a depth of 200 $\mu m$.
- Chose n+ column with n-type bulk and p+ trench.
Prototypes

Being manufactured by CNM (National Centre for Micro-electronics)

Array of High Energy pixels on left, and a single Photon Science pixel on right.
Electric Properties of Good Prototypes

I vs. V

C vs. V

Stony Brook University
Charge Collection Efficiency Measurements

- Am241 Source placed on detector inside Faraday cage
  - Signal is readout by a commercial cremat preamplifier
  - Trigger on equivalent voltage of 59.5 keV $\gamma$ particle signal (16,500 $e^-$)
- The output is sent into the oscilloscope in two channels:
  1. Inline CR filter for noise reduction
  2. No inline filter (can apply software filters in labview)
- Collected 1000 events
- Schematic view of experiment below on left, picture of detector on right

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[Diagram and image]
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Experimental Setup

- Inline CR filter
- Read Out Electronics
- Power Supplies
- Detector
Glast Detector

- Glast mini-square detector
- Well-known characteristics (T. Ohsugi et. al, NIMA Vol 541, Issues 1-2, 2005) so it provides a baseline
- Less than full charge collection at perimeter of active region
- Provided to us by Hartmut Sadrozinski (Thank you!)
Same mean shows collection is identical. Different vertical scales on left.
3D-TED isolation from charge sharing

- Same charge collection
- Less charge sharing (important for photon sciences)
- More isolation details to be studied with laser injection
The two detectors had similar peaks (peak value $\propto$ Energy deposited)

The peak mean values are consistent, meaning they are collecting roughly the same amount of charge

Consistent over different voltages (plots in back-up slides)

Approximate signal to noise ratios are decent and similar to each other ($\text{glast} \approx 15$, 3D-Trench-Electrode $\approx 13.5$)

We see that the 3D-Trench-Electrode detector is more noisy. Expected because of its higher leakage current

We expect CCE to depend on location. Will be studied more closely with laser injection.
Summary

- Simulated 3D-Trench-Electrode Detector has a depletion voltage of 95V, about $\frac{2}{5}$ of the column detectors.
- One can also see that the electric field is more uniformly distributed in the 3D-Trench Electrode Detectors than in the column 3D.
- Preliminary electrical and charge collection efficiency measurements from the first prototypes are done.
- We see full charge collection and much reduced charge sharing with the 3D-Trench-Electrode Detector.
- Will do simulations with simulated radiation defects.
- Will do higher resolution CCE measurements with laser injection.
- CNM has started the next round of prototypes.
Thank you for your attention!
1. The ATLAS Collaboration,  
*Atlas Insertable B-Layer Technical Design Report*  
ATLAS TDR 19, 2010  
2. C. Kenny, S. Parker, J. Segal, C. Storment,  
*Silicon detectors with 3-D electrode arrays: Fabrication and initial test results*  
3. T. Ohsugi, S. Yoshida, Y. Fukazawa, K. Yamamura, K. Sato, K. Yamamoto, Hartmut F.-W. Sadrozinski, the GLAST-LAT collaboration,  
*Design and properties of the GLAST flight silicon micro-strip sensors*  
4. Silvaco International, 
5. Z. Li,
*New BNL 3D-Trench electrode Si detectors for radiation hard detectors for sLHC and for X-ray applications.*
6. Z. Li,
*Radiation damage effects in Si materials and detectors and rad-hard Si detectors for SLHC.*
Journal of Instrumentation, 4 P03011 2009.
Electrons Versus Holes

- There is a difference between collecting and reading out electrons versus holes because of their mobility.
- But because of the high $\vec{E}$, we don’t see the mobility difference over such a small distance.
- This is because we are near the saturation.
- There is only a 20% difference in this case, so it is not significant.
Glast Detector Results

Waveform

Peak Histogram

Peak vs Offset

Standard Deviation [VRMS]

Points/Time [s]

Voltage [V]

Ch2 Filter

Save Data

Filter Type

Low F Cutoff

Workbook Name

High F Cutoff

Sheet Name

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Glast Detector Results

Waveform

Peak Histogram

Peak vs Offset

Standard Deviation [VRMS]

Points/Time [s]

Voltage [V]

Ch2 Filter

Save Data

Filter Type

Low F Cutoff

Workbook Name

High F Cutoff

Sheet Name
Peaks at different voltages
Rough Fits

3D-Trench-Electrode Detector

GLAST Detector
Full Depletion Voltage was simulated to at 250 V. 
\[ \Phi_{eq} = 10^{16} \text{ 1 MeV } n_{eq}/\text{cm}^2, \text{electrode spacing: } 50\mu m \]

On the left, the maximum (red) is 40,000 V/cm while on the right the maximum is almost 1,300,000.