A Systematic 3D Simulation Study Comparing BNL's 3D-Trench Electrode Detectors with Conventional 3D Detectors

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Table of Contents

Introduction

Past Silicon Pixel Detectors

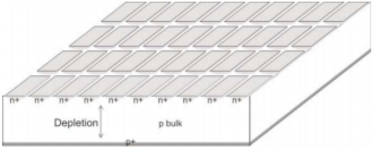


Fig 1a. ***Typical planar pixel detector.***

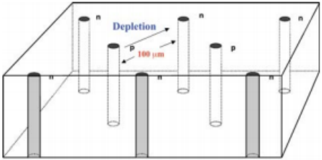


Fig 1b. ***Standard 3-D detector.***

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

3D

Advantages of 3D

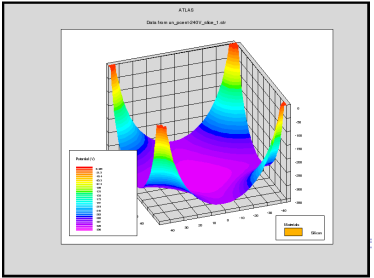
- Decouples depletion from thickness
- Reduces depletion voltage by decreasing the electrode spacing

Conventional 3D Limitations

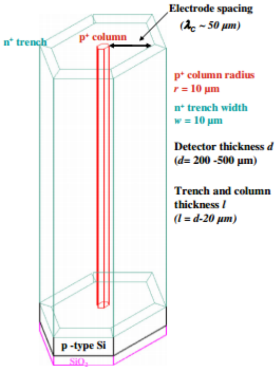
- High electric field along junction at the column
- Columns create inhomogeneities in $\vec{E}$

We want to:

- Fix the saddle point in the potential.
- Remove θ dependence
- Make each cell independent of its neighbors



Our High Energy 3D-Trench Electrode Detector



- Electrode spacing: 50 μm
- Shape: Hexagon

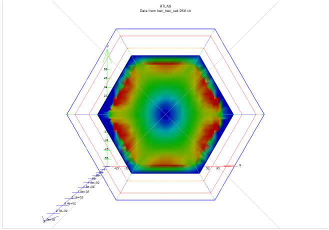
- Depth: 500 μm - Simulated: 300 μm
- Width of doping: 10 μm
- Depth of doping: Simulated - 270/300 μm
- When simulated with radiation, treated after $\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2
- Doping:
  - p+ column
  - n+ trench
  - p type bulk (simulates after SCSI)

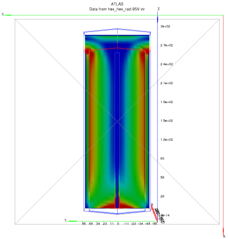
Simulation Specifics

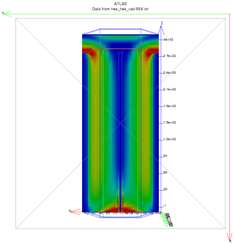
- Used commercial software from Silvaco (TCAD's programs - Devedit 3d, Device 3d, Atlas, etc) to simulate the detectors' electrical properties.
- Radiation defects are not built into the program
- Simulate the detector after high radiation by changing the effective doping concentration of the bulk.
- This gives us first order effects.

Full Depletion - 95V

Full Depletion Voltage was simulated to be 95 V. Electrode spacing is 50μm Treated with $\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2





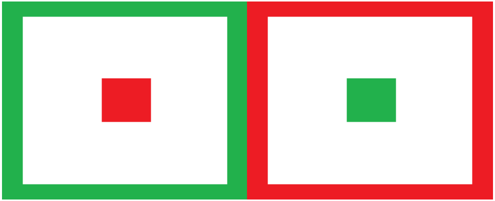


The different types of detectors possible

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

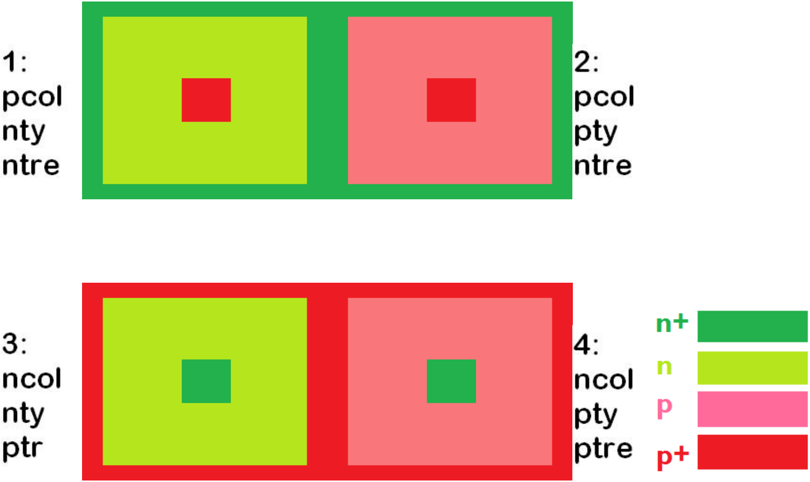
- For our detectors, the difference will cause different $\vec{E}$
- We choose:
  - Doping of the center column
  - Doping of the cylindrical-shaped trench in each cell
  - Doping of bulk n (green) and p (red)

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 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 $\vec{E}$


1:
pcol
nty
ntre
2:
pcol
pty
ntre
3:
ncol
nty
ptr
4:
ncol
pty
ptre
n+
n
p
p+

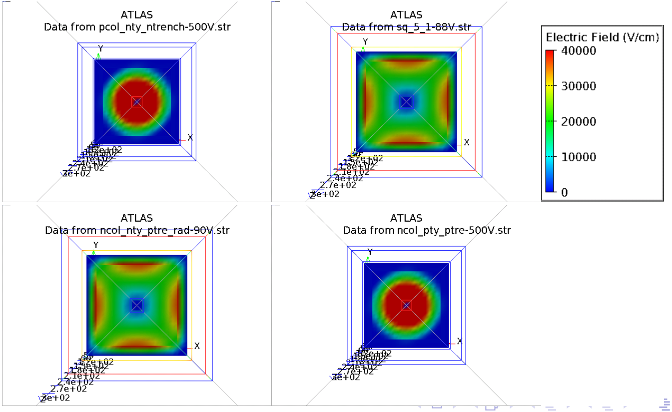
Electric Fields, Fully Radiated

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

N Type   P Type

P column

N column

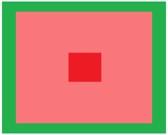


Type Comparison Results

Table: Comparison of Different Doping schemes

column, bulk, trench	V_{dep}	Junction	Dep Direction
n+, n, p+	90 V	trench	inward
n+, p, p+	$>$ 500 V	column	outward
p+, n, n+	$>$ 500 V	column	outward
p+, p, n+	88 V	trench	inward

Therefore, we use p+ column with p-type bulk and n+ trench

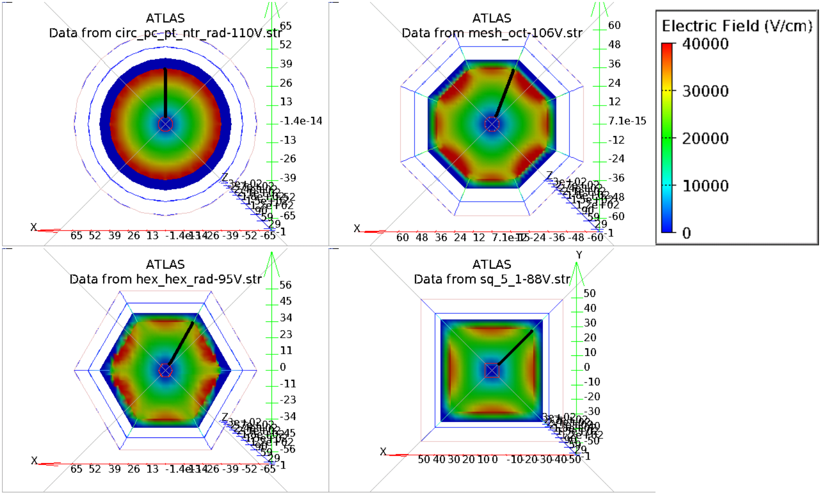


Variable Shapes

- There are multiple shapes we can simulate the cylindrical trench as:
  - Circle
  - Octagon
  - Hexagon
  - Square
- Only the hexagon and square lend themselves to multi-celled arrays because they can be tiled
- The circle configuration can be useful in scientific studies.
- We studied the corner effects by comparing these depletion voltages and electric field distributions

Variable Sides

$\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2, electrode spacing (black line): $50\mu m$



Variable Sides Results

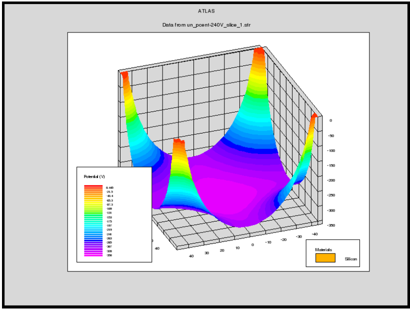
- The θ dependence decreases as we increase the number of sides
- The depletion voltage increases with the number of sides because of the increase in volume of each cell

	Square	Hex	Oct	Circle
V_{dep}	88 V	95 V	107 V	110 V

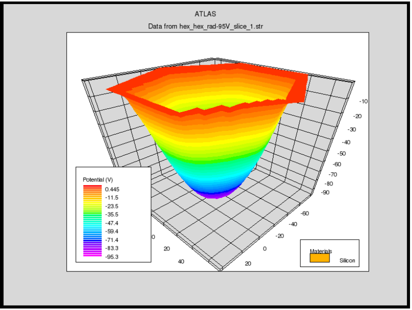
Conventional Vs. BNL's

Potential

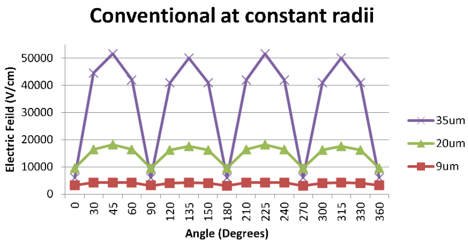
Conventional

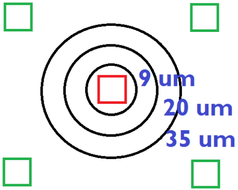


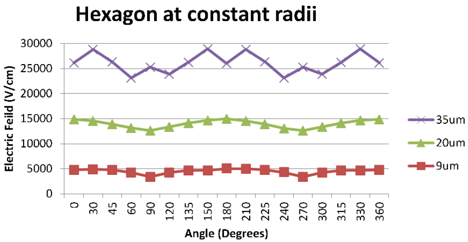
BNL's

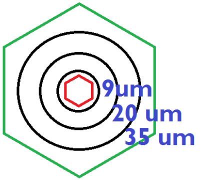


Electric Field's θ Dependence



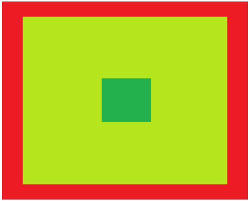






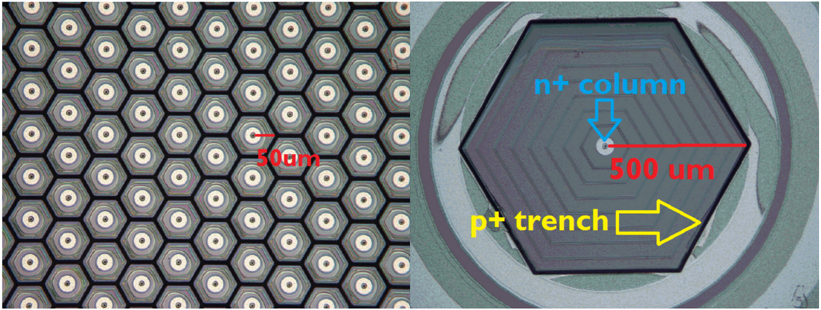
Photon Sciences

- 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 (x10 larger)
- Chose n+ column with n-type bulk and p+ trench



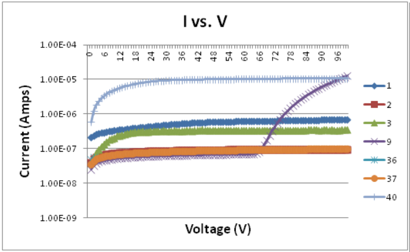
Prototypes

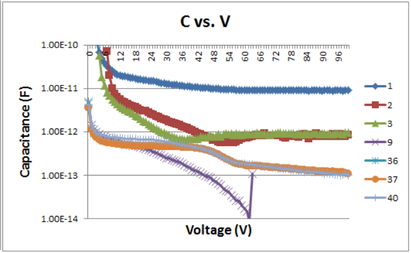
Being manufactured by CNM (National Centre for Micro-electronics)



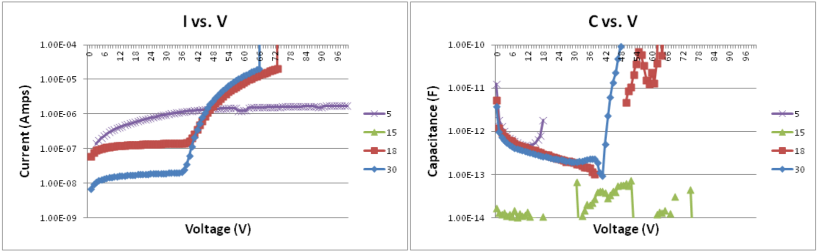
Array of High Energy pixels on left, and a single Photon Science pixel on right.

Measurements of Good Prototypes

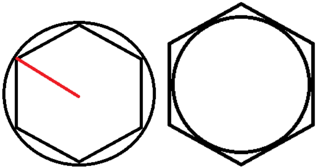




Measurements of Less than Ideal Prototypes



Conclusions



For V_{dep}, the shapes are all inscribed inside of a circle with electrode spacing of $50\mu m$. For $\langle V_{dep} \rangle$, these shapes are averaged with the shapes which have the same sized circle inscribed inside of it.

Var	Conv	Square	Hex	Oct	Circle
V_{dep}	250 V	88 V	95 V	107 V	110 V
$\langle V_{dep} \rangle$	n/a	120 V	118 V	124 V	110 V
Potential Irregularities	Yes	No	No	No	No

Summary

- Completed a systematic study comparing BNL's 3D-Trench Electrode Detectors with Conventional 3D detectors
- Simulated BNL's to have a depletion voltage of 95V, about $\frac{2}{5}$ of the conventional detectors.
- One can also see that the electric field is more uniformly distributed in the hexagonal 3D-Trench Electrode Detectors than in the conventional 3D.
- Some preliminary measurements from the first prototypes are done.
- The next step is to measure the charge collection efficiencies
- CNM has started the next round of prototypes.

Thank you for your attention!

References

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Atlas Insertable B-Layer Technical Design Report
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Silicon detectors with 3-D electrode arrays: Fabrication and initial test results
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Nuclear Instruments and Menthods in Physics Research A, 2011.

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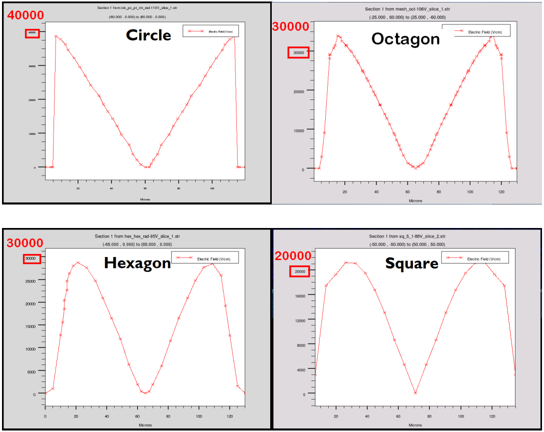
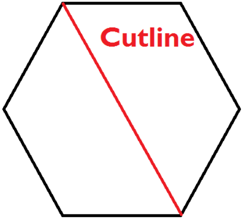
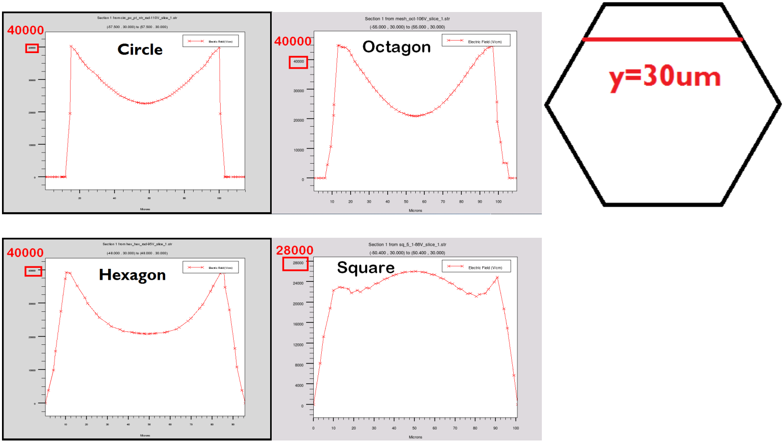
Journal of Instrumentation, 4 P03011 2009.

$\vec{E}$ For Different Geometries

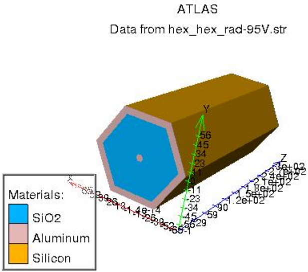


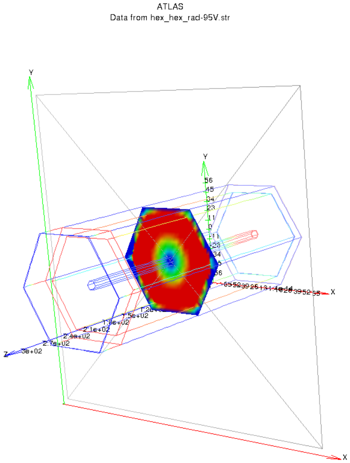


$\vec{E}$ For Different Geometries



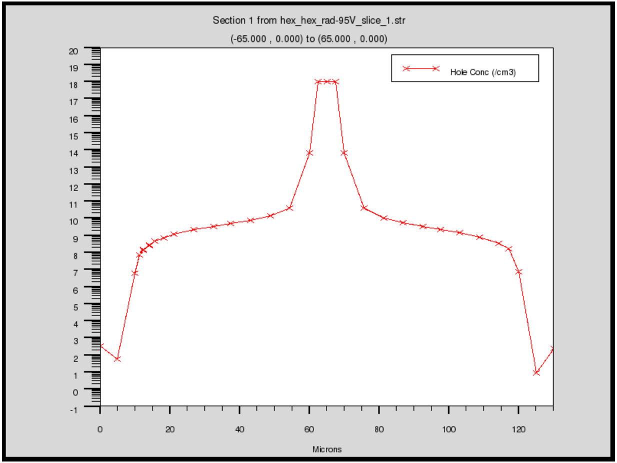
Hexagon Simulation



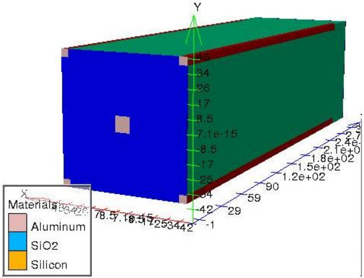


Hole Concentration in Hexagon

$\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2, $V_{dep} = 95V$

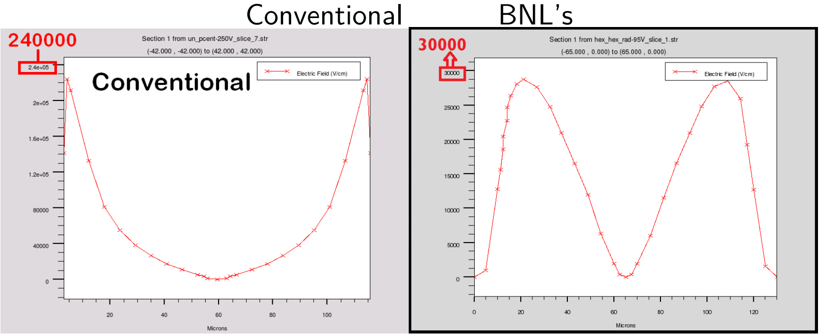


Conventional 3D



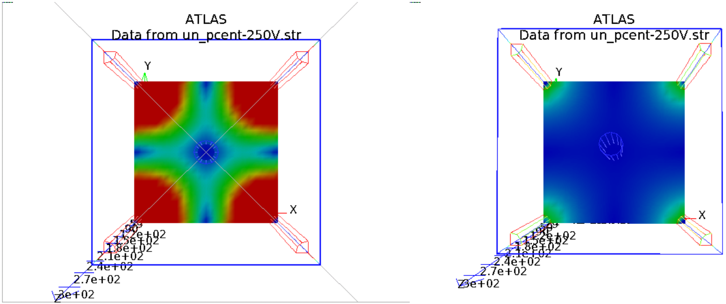
- Electrode spacing: 50 μm
- Depth: 300 μm
- Shape: Conventional
- Diameter of doping columns: 10 μm
- When simulated with radiation, treated after $10^{16} n/cm^2$
- Doping:
  - p+ center column
  - n+ corner columns
  - p type bulk (simulates after SCSI)

$\vec{E}$ Conventional vs. BNL's



Conventional

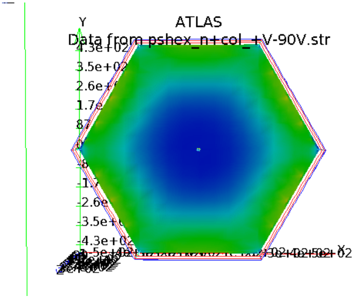
Full Depletion Voltage was simulated to at 250 V.
$\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2,electrode spacing: $50\mu m$

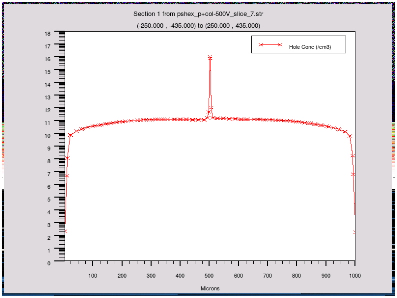


On the left, the maximum (red) is 40,000 V/cm while on the right the maximum is almost 1,300,000.

Type Comparison for Photon Science

At this size, we can only get full depletion before breakdown with n+ column and p+ trench. Left is n+ column fully depleted at 90 V, and right is p+ column at 500 V, not close to full depletion.





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
- The trapping is very minimal