Silicon Detectors for the Super LHC

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University of New Mexico
for the RD50 Collaboration

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17 February 2010
249 scientists and engineers from 47 member institutes:

Barcelona, Bari, BNL, Bucharest
NIMP, Uni. Bucharest, CERN,
Dortmund, Erfurt, Fermilab, Florence,
Freiburg, Glasgow, Hamburg, Helsinki
HIP, Ioffe Inst., ITE, ITME, Karlsruhe,
KINR, Lancaster, Lappeenranta,
Liverpool,

Ljubljana, Louvain, Minsk,
Montreal, Moscow ITEP, Munich,
New Mexico, Nikhef, Uni. Oslo,
Padova, Perugia, Pisa, Prague Academy, Prague Charles,
Prague CTU, PSI, Purdue,
Rochester, UC Santa Cruz,
SINTEF, Syracuse, Tel Aviv,
Trento, Valencia, Vilnius
Super LHC (sLHC) is a proposed upgrade of the LHC to luminosity $10^{35}$ cm$^{-2}$ s$^{-1}$.

Expected hadron fluence at $r \sim 4$ cm: $1.6 \times 10^{16}$ cm$^{-2}$ n$_{eq}$.

The primary limitation is trapping: decrease in charge collection efficiency.

Timescale for start of sLHC under discussion, $\geq 2018$. 


- **Phase I upgrades:**
  - CMS: New 4 layer pixel detector
  - ATLAS: Additional inner pixel layer (IBL)

- **Phase II upgrades:**
  - CMS: Tracker replacement
  - ATLAS: New ‘all silicon’ tracker

- **Graph:**
  - Integrated luminosity [fb$^{-1}$]
  - Integrated luminosity (Phase II)
  - sLHC integrated luminosity
  - 1 MeV neutron equivalent fluence [10$^{15}$ cm$^{-2}$]
  - at radius of 3.7 cm (ATLAS - layer 0)

Year:
- 2008
- 2010
- 2012
- 2014
- 2016
- 2018
- 2020
- 2022
- 2024
- 2026
Predicted fluences ($n_{eq}$), including safety factor 2:

B layer ($r = 3.7 \text{ cm}$): $2.5 \times 10^{16}$ (1140 MRad)
Inner pixel layer ($r = 5 \text{ cm}$): $1.4 \times 10^{16}$ (712 MRad)
Second pixel layer ($r = 7 \text{ cm}$): $7.8 \times 10^{16}$ (420 MRad)
Outer pixel layer ($r = 11 \text{ cm}$): $3.6 \times 10^{15}$ (207 Mrad)
Short strips ($r = 38 \text{ cm}$): $6.8 \times 10^{14}$ (30 Mrad)
Long strips ($r = 85 \text{ cm}$): $3.2 \times 10^{14}$ (8.4 Mrad)

Radial distribution of sensors determined by occupancy < 2%, still emerging.
Reported here:

- Connections between microscopic defect properties and macroscopic sensor properties
- Epitaxial silicon
- Magnetic Czochralski (MCz) silicon sensors
- p-type silicon sensors
- 3D silicon sensors
- New structures

What follows is just a sample of recent results. For the full story, please see rd50.web.cern.ch/rd50/.
Use of High Resolution Photo-induced Transient Spectroscopy to compare radiation defects in standard and oxygenated epitaxial Si

<table>
<thead>
<tr>
<th>Material</th>
<th>[O] [10^{16} cm^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPI-ST 150</td>
<td>4.5</td>
</tr>
<tr>
<td>EPI-DO 150</td>
<td>14.0</td>
</tr>
</tbody>
</table>

24 GeV p

- After annealing to 240°C, mid-gap traps develop independent of [O].
- # traps is maximized in standard and oxygenated epi layers after annealing at 80 and 160 °C.
Use of High Resolution Photo-induced Transient Spectroscopy to compare radiation defects in standard and oxygenated epitaxial Si, continued

Example result, for $\Phi = 1.7 \times 10^{16}$ p cm$^{-2}$:

Conclusions:

- Dominant trap in low-fluence standard n-epi is at 410 meV, likely $I_2O$, conc. $5.2 \times 10^{16}$ cm$^{-3}$. As fluence rises, 315 meV trap dominates, likely $V_xO_y$, conc. $5.8 \times 10^{16}$ cm$^{-3}$.
- In oxygenated n-epi, 420 meV trap dominates at all fluences, likely $V_2^{-/0}$.
- After 1 hr 240°C anneal, dominant defect at 575 meV.
More results in defect characterization

• DLTS studies of p-Si irradiated with 6 MeV e- and α find that self-interstitial Si can persist after irradiation at 273K when \((\text{e-hole gen rate})/(\text{Frenkel pair gen rate})\) is small. Mobility small at 273K. Current injection at liq Ni temperature destroys them.

Defect introduction rate versus temp: Irradiated MCz diodes, after 30 min. annealing. Dose rate: \(1\times10^{11} \text{ cm}^{-2} \text{ s}^{-1}\).

Growth of the concentration of C-related defects, caused by \(\text{Si}_i\) disappearance, during annealing for diodes irradiated at 78 K.
Defect characterization:

Shallow donor E(30K) generated by electron irradiation of n-type FZ diodes. E(30K), a cluster defect associated with non-type inversion of epi diodes after high p fluence, overcompensates deep acceptors. E(30K) generation is suppressed for high electron energies---suggesting point-like character?
Defect characterization:

TSC study of $p$- and $n$-type MCz Si irradiated with reactor $n$ up to $10^{16}$ cm$^{-2}$. Features correspond qualitatively to band diagrams. Interpretation: presence of residual electric field (polarization of the irradiated Si bulk) due to frozen charged traps in bulk and barriers close to electrodes. Residual field is opposed to external $V_{\text{bias}}$. 

M. Scaringella, M. Bruzzi, D. Menichelli, R. Mori
Epitaxial silicon

Benefits: oxygenation and controlled thin layer growth
TCT studies and simulation of charge collection in 150µm-thick epi devices after $\phi=(1 - 4) \times 10^{15} \text{ cm}^{-2}$ reveal field-dependent contribution to lifetimes.

$$\tau = \tau_0 + \tau_1 E$$

$$-dN = \frac{1}{\tau (E(x(t)))} \frac{N}{dt}$$

T. Pöhlsen, J. Becker, E. Fretwurst, R. Klanner, J. Lange
Epitaxial Si, continued

Charge collection, trapping well described by including:

- distortions to the space charge distribution leading to parabolic electric fields (double peak)
- field-dependence of trapping time $\tau$ (to fit CCE curves)
- electronic circuit effects (to simulate TCT signals)
- Trapping probability decreases with increasing E-field: high $E$-fields desirable to reduce trapping probability

![Graph 1: Trapping probability against electric field](image1)

![Graph 2: Trapping probability against fluence](image2)
Studies of charge multiplication in highly irradiated sensors

Please see talk by Lange, Junkes, et al.

n-type epitaxial, $[O] = 9 \times 10^{16}\text{cm}^{-3}$, $<111>$, $N_{\text{eff,0}} = 2.6 \times 10^{13}\text{cm}^{-3}$

Beneficial Charge Multiplication in highly irradiated ($10^{16}\text{cm}^{-2}$ 24-GeV p) devices due to impact ionization provides proportional response, long-term stability, homogeneous production, only slight noise increase.
A theoretical model for charge multiplication

- Assume avalanche multiplication in p-n junctions and E field controlled by current injection in deep-level doped semiconductors.
- Model has only 2 free parameters, uses E field in detector base region and potential sharing between base and depleted region adjacent to segmented side.

• Predicts: charge multiplication can only occur in detectors with segmented n+ side.
Czochralski silicon

*Please see also the talk by L. Spiegel*

Benefit: enhanced oxygenation intrinsic to the process
Comparison of $V_{\text{dep}}$ and $I_{\text{leak}}$ in n-Fz and n-MCz after (24 GeV) proton and (300 MeV) pion irradiation

- MCz: 1 kΩ-cm ($V_{\text{dep}}$ 300V); FZ: 15 kΩ-cm ($V_{\text{dep}}$ 20V)
- Collected charge on MCz > on FZ
- Collected charge less after pion than after proton irradiation
- Conclusions: trapping probability lower after pion irradiation; hole trapping different for FZ and MCz.
Device modeling of neutron damage effects in n-MCz Si

Parameters of the ‘four trap level model’ for n-type MCz Si

<table>
<thead>
<tr>
<th>trap type</th>
<th>energy level [eV]</th>
<th>$c_{\text{np}}$ [cm$^2$] from exp.</th>
<th>$c_n$ [cm$^2$]</th>
<th>$c_p$ [cm$^2$]</th>
<th>$\eta$ [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_2$+0.46</td>
<td>$E_C-0.46$</td>
<td>$1.0 \times 10^{-14}, 1.0 \times 10^{-13}$ (estimated)</td>
<td>$3.0 \times 10^{-15}$</td>
<td>$4.1 \times 10^{-13}$</td>
<td>12.4</td>
</tr>
<tr>
<td>$H_{152K}$</td>
<td>$E_{\gamma}+0.42$</td>
<td>unknown, $2.3 \times 10^{-14}$</td>
<td>$3.05 \times 10^{-13}$</td>
<td>$1.0 \times 10^{-13}$</td>
<td>0.06</td>
</tr>
<tr>
<td>$C_{1}O_{4}$+0</td>
<td>$E_{\gamma}+0.36$</td>
<td>$2.05 \times 10^{-18}, 1.64 \times 10^{-14}$</td>
<td>$1.64 \times 10^{-14}$</td>
<td>$2.24 \times 10^{-14}$</td>
<td>1.1</td>
</tr>
<tr>
<td>$E_{30K}$+0</td>
<td>$E_C-0.1$</td>
<td>$2.3 \times 10^{-14}, 2.7 \times 10^{-15}$</td>
<td>$2.77 \times 10^{-15}$</td>
<td>$2.0 \times 10^{-15}$</td>
<td>0.017</td>
</tr>
</tbody>
</table>

- Good agreement in $V_{\text{full dep}}$ and $I_{\text{leak}}$ between simulation (Synopsys TCAD) and data.
- Theoretical calculations based on Shockley Read Hall recombination theory reproduce the $V_{\text{full dep}}$ data but underestimate the measured $I_{\text{leak}}$ at 293K.
- Plan: mixed irradiation model (n-MCz Si) for charge carrier trapping, electric field distribution.
Low resistivity n-Czochralski:

• Motivated by challenges to strip isolation in p-type.

• Competitive with p-FZ up to few $10^{15}$ n.

• Good CCE up to 10000 min @ 60°C.

• The challenge: high current.
Mixed irradiation of sensors in Czochralski silicon

Irradiated with neutron-proton mix with charged/neutral as expected at sLHC

Expected ratio of charged hadrons to neutral hadrons

R. Eber, Th. Müller, W. de Boer, A. Dierlamm, M. Frey, P. Steck, T. Barvich
Mixed irradiation of sensors in Czochralski silicon, continued

Trapping times extracted for fluences $< 10^{15} \text{ cm}^{-2} \text{ n}_{eq}$

<table>
<thead>
<tr>
<th>Diode</th>
<th>$F_{eq}(n)$ $n_{eq}$ $\text{cm}^{-2}$</th>
<th>$F_{eq}(p)$ $n_{eq}$ $\text{cm}^{-2}$</th>
<th>$\tau_e \text{[ns]}$</th>
<th>$\tau_h \text{[ns]}$</th>
<th>$\beta_e \text{ cm}^{2} \text{[ns]}^{-1}$</th>
<th>$\beta_h \text{ cm}^{2} \text{[ns]}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCz-n_3N-A</td>
<td>3.2 $\cdot 10^{14}$</td>
<td>-</td>
<td>5.96 ± 0.7</td>
<td>2.87 ± 0.8</td>
<td>5.2 $\cdot 10^{-16}$</td>
<td>10.8 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-n_3N-B</td>
<td>3.5 $\cdot 10^{14}$</td>
<td>-</td>
<td>5.40 ± 0.6</td>
<td>1.21 ± 1.0</td>
<td>5.3 $\cdot 10^{-16}$</td>
<td>23.6 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-n_4-A</td>
<td>3.3 $\cdot 10^{14}$</td>
<td>6.8 $\cdot 10^{13}$</td>
<td>4.92 ± 0.5</td>
<td>2.2 ± 0.5</td>
<td>5.2 $\cdot 10^{-16}$</td>
<td>11.6 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-n_4-B</td>
<td>3.0 $\cdot 10^{14}$</td>
<td>6.8 $\cdot 10^{13}$</td>
<td>4.44 ± 0.5</td>
<td>1.51 ± 0.6</td>
<td>6.1 $\cdot 10^{-16}$</td>
<td>17.9 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-n_6-A</td>
<td>3.6 $\cdot 10^{14}$</td>
<td>2.9 $\cdot 10^{14}$</td>
<td>3.00 ± 1.5</td>
<td>1.74 ± 2.0</td>
<td>5.1 $\cdot 10^{-16}$</td>
<td>8.84 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-n_17-A</td>
<td>4.4 $\cdot 10^{14}$</td>
<td>1.3 $\cdot 10^{15}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCz-n_108-A</td>
<td>8.1 $\cdot 10^{14}$</td>
<td>1.0 $\cdot 10^{16}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diode</th>
<th>$F_{eq}(n)$ $n_{eq}$ $\text{cm}^{-2}$</th>
<th>$F_{eq}(p)$ $n_{eq}$ $\text{cm}^{-2}$</th>
<th>$\tau_e \text{[ns]}$</th>
<th>$\tau_h \text{[ns]}$</th>
<th>$\beta_e \text{ cm}^{2} \text{[ns]}^{-1}$</th>
<th>$\beta_h \text{ cm}^{2} \text{[ns]}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCz-p_3N_spray</td>
<td>3.2 $\cdot 10^{14}$</td>
<td>-</td>
<td>6.7 ± 2.6</td>
<td>1.8 ± 1.9</td>
<td>4.7 $\cdot 10^{-16}$</td>
<td>17.4 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-p_4_spray</td>
<td>3.1 $\cdot 10^{14}$</td>
<td>6.8 $\cdot 10^{13}$</td>
<td>5.3 ± 4.9</td>
<td>5.7 ± 4.0</td>
<td>5.1 $\cdot 10^{-16}$</td>
<td>4.7 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-p_6_spray</td>
<td>3.7 $\cdot 10^{14}$</td>
<td>2.9 $\cdot 10^{14}$</td>
<td>2.3 ± 1.2</td>
<td>2.2 ± 2.2</td>
<td>6.6 $\cdot 10^{-16}$</td>
<td>6.9 $\cdot 10^{-16}$</td>
</tr>
<tr>
<td>MCz-p_17_stop</td>
<td>4.5 $\cdot 10^{14}$</td>
<td>1.3 $\cdot 10^{15}$</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCz-p_108_stop</td>
<td>7.4 $\cdot 10^{14}$</td>
<td>1.0 $\cdot 10^{16}$</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R. Eber, Th. Müller, W. de Boer, A. Dierlamm, M. Frey, P. Steck, T. Barvich

Defect sources....gold?
Sensors in p-type bulk

Benefits:
• collect electrons
• no radiation-induced type inversion
• single-sided processing reduces cost

p-on-n geometry (after type inversion)

n-on-p geometry
n-on-n geometry (after type inversion)
Edge-TCT study of long term annealing on highly irradiated Si detectors

- The same locations in the detector were illuminated for all annealing steps.
- Sample temperature stabilized to less than 1°C.
- Annealing at 60°C.
- After each annealing step, voltage scans from -800V to 500V.

- p-FZ Si received $5 \times 10^{15}$ n
- Sample annealed in the setup with the Peltier.
- Charge measurement precision: a few percent.
- Laboratory temperature: 21 °C.

Q(y) [arb.] vs. distance, $t_{\text{ann}} = 80 \div 10240 \text{min.}$
Charge collection efficiencies of \( n\text{-in-p} \) planar sensors after \( n, p, \) and \( \pi \) irradiation

Corrected for annealing for pions and 24 GeV p

Charge collected by \( n\text{-in-p} \) FZ Si may be sufficient at innermost layer.
Guard ring design for n-on-p

Synopsis: Sentaurus used to predict electric field profile / breakdown voltage for various implant/oxide/metal/passivation configurations. Result sustains $V_{\text{bias}} = 900 \text{ V}$ for $\phi = 10^{15} \text{ cm}^{-2}$ $n_{\text{eq}}$ and $Q_{\text{ox}} < 10^{12} \text{ cm}^{-2}$.
p- versus n-type, Float Zone versus Magnetic Czochralski

A study of $V_{\text{full dep}}$ after p irradiation and annealing

<table>
<thead>
<tr>
<th></th>
<th>n-on-p Fz</th>
<th>p-on-n Fz</th>
<th>n-on-p MCz</th>
<th>p-on-n MCz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>HPK</td>
<td>Micron</td>
<td>Micron</td>
<td>Micron</td>
</tr>
<tr>
<td>Resistivity</td>
<td>13 kΩ-cm</td>
<td>3.3 kΩ-cm</td>
<td>1.9 kΩ-cm</td>
<td>1.4 kΩ-cm</td>
</tr>
<tr>
<td>Active Area</td>
<td>3mmx3mm</td>
<td>3mmx3mm</td>
<td>3mmx3mm</td>
<td>3mmx3mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>300 µm</td>
<td>300 µm</td>
<td>300 µm</td>
<td>300 µm</td>
</tr>
<tr>
<td>Initial $V_{fd}$ [V]</td>
<td>75</td>
<td>95</td>
<td>520</td>
<td>220</td>
</tr>
</tbody>
</table>

800 MeV p @Los Alamos
60° C anneal

- Beneficial annealing observed for the first 80 minutes anneal time, then $V_{fd}$ begins to increase for samples shown to have neg space charge after proton irradiation:
  - n-on-p Fz
  - p-on-n Fz
  - n-on-p MCz
  - p-on-n MCz shows annealing behavior typical of n-type devices that have +sc after proton irradiation.
p- versus n-type, Float Zone versus Magnetic Czochralski, continued

- FZ show greatest increase of $V_{fd}$ with increasing fluence
- n-on-p MCz shows little change
CCE versus annealing of p-in-n sensors

- Motivations: An examination of results for long annealing times, to reduce dependence upon model-based extrapolations; to acquire signal data after high dose and long annealing times, in the regime where CV-based models predict under-depletion.

- FZ, $2 \times 10^{14}$ cm$^{-2}$ $n_{eq}$ @ Ljubljana

Models:
- ATLAS TDR 5 CERN/LHCC/97-17.

Even when the CV-based models predict significant under-depletion, the signal is still sizeable and diminishes only slowly.
Lorentz angle in silicon strip sensors

- Red laser: best signal
- IR laser: MIP-like

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Material</th>
<th>Thickness [μm]</th>
<th>$U_{dep}$ [V]</th>
<th>Fluence $[\text{n}_{\text{eq}} \text{cm}^{-2}]$</th>
<th>Pitch [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>ST Microelectronics</td>
<td>FZ n-type</td>
<td>500</td>
<td>154</td>
<td>0</td>
</tr>
<tr>
<td>Micron / RD50</td>
<td>FZ p-type</td>
<td>300</td>
<td>12</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>1000</td>
<td>Micron / RD50</td>
<td>FZ p-type</td>
<td>$\approx$ 1000</td>
<td>$1 \cdot 10^{15}$</td>
<td>300</td>
</tr>
<tr>
<td>1000</td>
<td>Micron / RD50</td>
<td>FZ p-type</td>
<td>$&gt; 1000$</td>
<td>$9.8 \cdot 10^{15}$</td>
<td>80</td>
</tr>
<tr>
<td>n-169</td>
<td>HIP</td>
<td>MCz n-type</td>
<td>300</td>
<td>169</td>
<td>7.1 $\cdot 10^{14}$</td>
</tr>
<tr>
<td>n-272</td>
<td>HIP</td>
<td>MCz n-type</td>
<td>300</td>
<td>272</td>
<td>7.1 $\cdot 10^{14}$</td>
</tr>
<tr>
<td>n-1000</td>
<td>HIP</td>
<td>MCz n-type</td>
<td>300</td>
<td>$&gt; 1000$</td>
<td>7.2 $\cdot 10^{14}$</td>
</tr>
<tr>
<td>47</td>
<td>HIP</td>
<td>MCz n-type</td>
<td>300</td>
<td>347</td>
<td>0</td>
</tr>
</tbody>
</table>

- 23 MeV p (Karlsruhe)
- Magnet up to 8 T

W. de Boer, A. Dierlamm, A. Sabellek, M. Schmanau, M. Schneider
Lorentz angle, continued

Large difference between Lorentz angle for h and e at high fluences---in situ measurement needed for sLHC.
Simulation of the electron and hole contributions to total charge collection in irradiated Si detectors

- Contribution of holes to total collected charge increases with fluence in an n⁺ segmented Si detector.
- At $1 \times 10^{16}$ $n_{eq}$/cm², contribution of holes to total collected charge is comparable to that of electrons.
- At sLHC fluences, total collected charge is approximately $Q = 80e/\mu m \cdot (d_{CCE}^e + d_{CCE}^h)$
- To improve radiation hardness, carrier trapping distance has to be increased --- e.g. by pre-filling of the traps or decreasing carrier drift distance (3D).

For $P \geq 60 \mu m$, hole contribution is ~43% due to $P \gg d_{CCE}$ or $d_t$

For $P < 60 \mu m$, hole contribution decreases as $P$ approaches $d_{CCE}$ or $d_t$. 
Sensors with 3D geometry

Motivation: decouple thickness from charge collection distance
Sensors with 3D geometry

RD50 is examining designs by:
FBK (Trento) and CNM (Barcelona):

- Columns unfilled
- Ohmic columns connected by uniform n+-doping layer and metallization
- AC and DC coupled readout pads

- Columns partially filled with polysilicon
- Ohmic columns connected by polysilicon and metallization
- DC coupled readout pads
FBK-irst Sensors with 3D geometry

For details please see talk by Per Hansson.

3D-Double side Double Type Column: “ATLAS 3D-DDTC”

First results show good performance in lab and beam test.

M. Boscardin, G.-F. Dalla Betta, G. Darbo, C. Gemme, A. La Rosa, H. Pernegger, C. Piemonte, M. Povoli, S. Ronchin, A. Zoboli, N. Zorzi
Glasgow/CNM Sensors with 3D geometry

*For details please see talk by Giulio Pellegrini.*

First results show good performance in lab and beam test.
Simulation, Laboratory, and Test Beam Studies of CMS 3D (SINTEF) sensors

Columns become dead regions at $\Phi > 10^{14} n_{eq} \text{cm}^{-2}$
CCE highest between electrodes ($\sim 9 \text{ke}^{-} \text{at } \Phi = 10^{16} n_{eq} \text{cm}^{-2}$), lowest near cell edges ($\sim 5.5 \text{ke}^{-} \text{at } \Phi = 10^{16} n_{eq} / \text{cm}^{2}$)

- 2 columns per cell:
  - lower capacitance between readout electrodes ($\sim 0.7 \text{fF at } \Phi=0, Q_{ox}=4 \times 10^{11} \text{cm}^{-2}$)
  - less dead volume ($\sim 4\%$ of total volume)

- 4 columns per cell:
  - faster charge collection
  - less trapping at high fluences
  - lower depletion voltage
  - higher breakdown voltage
  - larger capacitance between readout electrodes ($\sim 3.2 \text{fF at } \Phi=0, Q_{ox}=4 \times 10^{11} \text{cm}^{-2}$)
  - larger dead volume ($\sim 8\%$ of total volume)

O. Koybasi, D. Bortoletto, G. Bolla
New electrode geometry

- Novel, asymmetric electrode configurations produce homogeneous, well-defined E.
- Total collected charge 39%
- Dead space can be reduced to <14% for sLHC

- Concept of the new Independent Coaxial Detector Array (ICDA) ------ US patent pending (3D-Trench Electrode Detectors), any projects related to this subject must sign official agreements with BNL Office of Technology Commercialization and Partnership (Kimberley Elcess, Principal Licensing Specialist, elcess@bnl.gov, 001-631-344-4151)

At least one electrode is a trench, each cell can be an independent detector

Homogeneous electric field, no saddle point

Zheng Li

Concentric type
Electric field with nearly no θ dependence

Parallel plate type
Near-linear electric field
Summary

- Major advances have been made in correlation of microscopic defect properties with observed material properties.

- New information is provided on epitaxial, Czochralski, and p-bulk silicon substrates.

- Work is ongoing to understand and optimize Lorentz angle, guard rings, and other design features.

- New geometries including 3D and Independent Coaxial Detector Array continue to evolve.