A prototype SOI pixel sensor for CEPC vertex

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• Introduction for CEPC vertex
  – Physics driven requirements
  – Technical challenges
  – Advantages of SOI technology for tracking

• Concept of CPV2 chip

• Basic characterization
  – Sensor test
  – calibration
  – noise test

• Single point resolution measurement
  – Infrared laser test setup
  – Laser beam response
  – Measurement results

• Conclusion and outlook
Introduction

• High Energy Circular Electron Positron Collider (CEPC)
  – $e^+ e^-$ Higgs and Z factory
  – $E_{cm} \approx 240\text{GeV}$, luminosity $\approx 2 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$ @Higgs
  – Higgs precision 1% or better
Physics driven requirements

### Table 6.1  Required performance of the CEPC sub-detectors for critical benchmark Higgs processes.

<table>
<thead>
<tr>
<th>Physics Process</th>
<th>Measured Quantity</th>
<th>Critical Detector</th>
<th>Required Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH \rightarrow \ell^+\ell^- X$</td>
<td>Higgs mass, cross section</td>
<td>Tracker</td>
<td>$\Delta(1/p_T) \sim 2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>BR($H \rightarrow \mu^+\mu^-$)</td>
<td></td>
<td>$\oplus 1 \times 10^{-3}/(p_T \sin \theta)$</td>
</tr>
<tr>
<td>$H \rightarrow bb, cc, gg$</td>
<td>BR($H \rightarrow bb, cc, gg$)</td>
<td>Vertex</td>
<td>$\sigma_{r\phi} \sim 5 \oplus 10/(p \sin^{3/2} \theta) \mu$m</td>
</tr>
<tr>
<td>$H \rightarrow qq, VV$</td>
<td>BR($H \rightarrow qq, VV$)</td>
<td>ECAL, HCAL</td>
<td>$\sigma_{E_j}/E \sim 3 - 4%$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>BR($H \rightarrow \gamma\gamma$)</td>
<td>ECAL</td>
<td>$\sigma_E \sim 16%/\sqrt{E} \oplus 1%$ (GeV)</td>
</tr>
</tbody>
</table>

- excellent tagging capability of b-/c-quark jets and $\tau$-lepton
  - Impact parameter resolution, $\sigma(r_{\phi}) = a \oplus \frac{b}{p(GeV) \sin^{3/2} \theta} \mu$m, $a=5$, $b=10$

- Design requirements on vertex:
  - Single point resolution near the IP: $\leq 3$ $\mu$m
  - Material budget: $\leq 0.15\% X_0$/layer
  - Very close to IP ($<16$mm)

Continuous operation with $\sim$500ns bunch spacing for Higgs
Technical challenges

- vertex design requirement leads to technical challenges
  - Technical target is a compromise of all design details
SOI for tracking

- Features of SOI technology for tracking
  - Full CMOS circuit at 0.2um process node
  - High resistive (up to >10kΩcm) substrate, full depletion/over depletion (large signal and fast charge collection)
  - Pixel pitch below 10um possible
  - Sensor can be thinned to ~50um
  - Double SOI wafer and process available
outline

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CPV2 chip concept

- Double-SOI wafer
  - Second SOI layer as shielding between Front-end and sensing diodes
  - Compensation voltage can be applied to mitigate TID effect
  - High resistive substrate: FZ(p) \( \sim 1\,\text{k}\Omega\text{cm} \)
  - Thinning the sensor down to 75um (usually 300um)
CPV2 chip concept

- Fine pitch matrix with in-pixel discriminator
  - 16µm pitch and digital readout to achieve single point resolution < 3µm
  - In-pixel discriminator to enable a low power operation in a continuously colliding mode
  - Sensing diode, amplifier, CDS stage, discriminator
  - Half of matrix are analog readout for calibration CPV2 digital blocks
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Sensor test

• I-V curve
  – Total Leakage current reaches the plateau when bias voltage is -15V
  – No breakdown at high voltage
  – Thinning chip has larger leakage current
  – Diode current is very small both (~nA/total pixel array), below the accuracy of current meter

![I-V curve graph]

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Sensor test

• $^{55}$Fe signal Efficiency versus bias voltage
  – x-ray illuminates the sensor from backside
  – plateau reached @ $V_{bias} = -30V$
  – An evidence of fully-depleted sensor

\[ \eta = \int_{h-d}^{h} ue^{-us} ds = e^{-uh} (e^{\sqrt{V}} - 1) \]

\[ \eta = \int_{0}^{h} ue^{-us} ds = 1 - e^{-uh} \]
Calibration

• Charge voltage factor (CVF)
  – $^{55}$Fe 5.9KeV X-ray@1640e$^-$
  – SF gain measured 0.87
  – Most probable signal amplitude around 180ADC in single pixel mode
  – A peak at 360ADC in $3 \times 3$ pixel cluster mode
  – CVF: 123.3uV/e$^-$ @source follower input

![Graph showing SF gain mean: 0.87]
Noise

• Temporal noise and FPN
  – S-curve measured on full pixel array
  – TN ~6e⁻
  – Threshold dispersion (FPN) ~114e⁻
  – Offset cancellation is needed
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Experiment setup

- 1064nm laser beam
  - optical lens to focus laser
- 3-dimensional stepping motor
  - accuracy: 0.1um
- Thinning chip
  - wire-bonding on sub-board
  - illuminate from backside (no aluminum)
Laser beam

• Timing
  – Triggered by the frame start signal
  – Synchronized with rolling shutter readout

• Focusing with analog pixel as a monitor
  – Achieve the smallest beam cluster
  – Calibrate the equivalent electron number of laser energy

• beam waist diameter
  – 3.4μm
sensor test by laser

- Laser signal versus bias voltage
  - Inflection point $V_{bias} = -27V$
  - An evidence of fully-depleted sensor
  - Slow increasing maybe caused by signal collection efficiency
  - Choosing $V_{bias} = -100V$ in the following laser scan test
Laser scan with different laser intensity

- Scan two adjacent digital pixels
  - Step size of 1um
  - Threshold is fixed (no noise hits)

\[ \text{Signal charge} = 1574e^- \]
\[ \text{Signal charge} = 2308e^- \]
\[ \text{Signal charge} = 3148e^- \]
\[ \text{Signal charge} = 4722e^- \]

Normalized response = number of hit/number of pulse
Spatial resolution by laser

- Actual position decided by motor
- Responding position reconstructed by Center of Gravity

Signal charge = 1574e⁻

Signal charge = 2308e⁻

Signal charge = 3148e⁻

Signal charge = 4722e⁻

residual of position measurement
Spatial resolution by laser

- Spatial resolution versus signal level
  - Get the best resolution of 2.3μm at around 3000e⁻ signal level

![Graph showing spatial resolution by laser with signal level on the x-axis and spatial resolution on the y-axis, indicating a minimum resolution of 2.3μm at around 3000e⁻ signal level. The graph includes a formula: \( \frac{0.5 \text{pitch}}{\sqrt{12}} \), which represents the theoretical resolution limit.](image-url)
Conclusion and outlook

• A prototype SOI pixel sensor for CEPC vertex
  – 16um pitch and 75um thickness D-SOI chip
  – Validate the feasibility of thinning process
  – Fully depleted sensor @\( V_{\text{bias}} = -30\text{V} \)
  – Low noise (6e\(^{-}\)) of single pixel is achieved
  – The demonstration of a single point resolution below 3um

• CPV3 will follow up
  – Fix the problems in CPV2
  – Reduce the threshold distribution
  – Compatible with 3D integration
  – Characterized by particle beam test
Thanks for your attention!
Backup

- CPV2 pixel schematic
Backup

- I-V curve measurement

<table>
<thead>
<tr>
<th>diode</th>
<th>Pix_rng</th>
<th>Bpw_cir</th>
<th>IO_bpw</th>
<th>I_all</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>m</td>
<td>×</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>m</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

[Diagram of a silicon-based device with labels for diode, Pix_rng, Bpw_cir, and IO_bpw]
Backup

- TCAD simulation for charge sharing in SOI sensor
Backup

• Calculation for beam waist diameter

\[ \tan \frac{\theta_0}{2} = \frac{D}{2F} \]

\[ 2\omega_0 = \frac{4\lambda}{\pi \theta_0} \approx \frac{4\lambda}{\pi D} \]