The Development of Silicon Carbide Low Gain Avalanche Detector

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Motivation

- Applications: high energy, high luminosity experiments on future colliders, requirements for irradiation resistance and time resolution

- Semiconductor detectors will face > $10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ (HL-LHC) and > $7 \times 10^{17} \text{n}_{\text{eq}}/\text{cm}^2$ (FCC-hh)

- HL-LHC will start in ~ 2029, the instantaneous luminosity $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, 5~7.5x increase

- Average number of interactions per bunch crossing (pile-up events) reach 200.
Silicon Low Gain Avalanche Detector

PIN and LGAD

- LGAD has long operating voltage range with low gain 10~100.
- The electric field in the gain layer could make carries multiplication but don’t reach the breakdown threshold.
- Si LGAD has been characterized by an excellent timing resolution < 50 ps benefited its great S/N.
Challenges for Silicon LGAD

- Most of silicon detectors must be cooled to -30 °C to compensate for the rapidly increasing leakage current in extreme irradiation environment.
- The time performance of Silicon LGAD degrades significantly when the radiation flux up to $2.5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$

Possible solution for higher radiation flux at room or high temperature with better time resolution:

**Silicon Carbide LGAD**
Silicon Carbide

As a wide-band semiconductor material, among many silicon carbide (SiC) polymorphs, 4H-SiC has potential applications in radiation detection, especially fast time detection.

Schematic structures of popular SiC polytypes: 3C, 4H and 6H

The parameters of Si and 4H-SiC

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Si</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>1.12</td>
<td>3.26</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>11.7</td>
<td>9.76</td>
</tr>
<tr>
<td>Thermal conductivity [W/K·cm]</td>
<td>1.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Average ionization energy [eV/e-h pair]</td>
<td>3.6</td>
<td>5-9</td>
</tr>
<tr>
<td>Average e-h pairs for MIP [μm⁻¹]</td>
<td>~78</td>
<td>~55</td>
</tr>
<tr>
<td>Breakdown Threshold [MV/cm]</td>
<td>~0.3</td>
<td>~2.0</td>
</tr>
<tr>
<td>Atom displacement energy [eV]</td>
<td>13-15</td>
<td>30-40</td>
</tr>
<tr>
<td>Funno factor</td>
<td>0.11-0.13</td>
<td>0.04-0.12</td>
</tr>
<tr>
<td>Electron mobility [cm²/Vs]</td>
<td>1450</td>
<td>800</td>
</tr>
<tr>
<td>Hole mobility [cm²/Vs]</td>
<td>450</td>
<td>115</td>
</tr>
<tr>
<td>Electron saturation velocity [cm/s]</td>
<td>1×10⁷</td>
<td>2×10⁷</td>
</tr>
<tr>
<td>Hole saturation velocity [cm/s]</td>
<td>0.6×10⁷</td>
<td>1.8×10⁷</td>
</tr>
</tbody>
</table>
Impact ionization coefficient $\alpha_{\text{Si}} > \alpha_{\text{SiC}}$

- In silicon carbide, it has smaller impact ionization coefficient than silicon at the same electric field. And the holes has larger impact ionization coefficient. Thus, the SiC LGAD should be designed with N-type drift layer and higher electric field (Si: 0.3 MV/cm; SiC: 2 MV/cm).
Minimum Ionizing Particle (MIP) Detection

- In the Si and SiC detectors with same thickness, the signal generated by the MIP in the SiC is smaller than that in the Si.

Silicon:  \( \sim 78 \text{ e-h pairs/um} \)
\( \sim 3.6 \text{ eV/ e-h pairs} \)

SiC:  \( \sim 55 \text{ e-h pairs/um} \)
\( \sim 7.8 \text{ eV/ e-h pairs} \)
Bevel Termination

Etched bevel termination for device isolation

- **Positive bevel** \((\theta > 90^\circ)\): more material is removed from the highly doped side to the lightly doped side of the PN junction.

- **Negative bevel** \((\theta < 90^\circ)\): less material is removed from the highly doped side to the lightly doped side of the PN junction.
SiC LGAD with Bevel Termination

• Ideal SiC LGAD with positive bevel termination

Feature:
Positive bevel termination with maximizing the breakdown voltage.

Difficulty:
Difficult to achieve ~75 µm bevel etch with existing technology.

• Realizable SiC LGAD with negative bevel termination

Feature:
Could achieve ~2 µm bevel etching with existing technology.

Difficulty:
The electric field at the bevel surface will be larger than the field in the bulk. It is easy to cause early breakdown of the device.
Silicon Carbide (SiC) Low Gain Avalanche Detector

- 50 µm P-type (~$1e^{13}$ cm$^{-3}$) drift layer
- electron drift and multiplication.
- Ion implantation for gain layer and JTE
- Electric field: ~0.3 MV/cm
- Gain layer doping: ~$1e^{16}$ cm$^{-3}$

- 75 µm N-type drift layer (~$2e^{14}$ cm$^{-3}$)
- hole drift and multiplication.
- Epitaxial stack with bevel termination
- Electric field: ~2 MV/cm
- Gain layer doping: ~$1e^{17}$ cm$^{-3}$
Electric Field Distribution

- Key point: suppress the electric field spike, make the drift layer depleted before breakdown

1) The electric field spike $E_B$ appears close to the bevel surface due to the negative bevel.

2) High bias voltage (~1000 V) should be applied to deplete N-type drift layer ($d=75\,\text{um}, N_{\text{eff}}=2e14\,\text{cm}^{-3}$)

$$V_{\text{dep}} = \frac{q|N_{\text{eff}}|d^2}{2\epsilon\epsilon_0}$$

3) The $E_B$ exceeds the breakdown threshold easily when the bias voltage increase, that caused the device breakdown before full depletion – early breakdown.

- Gain factor dominated by $E_G$
- Breakdown dominated by $E_B$
Bevel Angle Optimization

- To maximize the breakdown voltage (minimize the electric field spike on the bevel), two methods can be used based on the existing silicon carbide process technology:

1) make the angle as close to 90° as possible.
2) make the angle as small as possible, less than 5°.
First SiC LGAD Prototype of LBNL-NCSU:

- The SiC LGAD prototype fabricated by a custom epitaxial stack on an N-type substrate.

The results by secondary ion mass spectrometry (SIMS) indicate the epitaxial growth of silicon carbide has large fluctuations. It caused the device characteristics deviate from expectations. As LGAD requirement, we hope that the variation of thickness and doping density can be limited to 10% in the future.

- Bevel termination

70°~80° bevel termination is adopted to devices isolation.
First SiC LGAD Prototype of LBNL-NCSU:

- There is no significant difference in leakage current for devices with different areas. The surface leakage current is the possible dominant factor. 
  \[ I = I_{\text{bulk}}(\propto \text{area}) + I_{\text{surface}} \]

- Early breakdown where \( V_{\text{BD}} < V_{\text{GL}} < V_{\text{FD}} \)
  
  LGAD requirement : \( V_{\text{GL}} < V_{\text{FD}} < V_{\text{BD}} \)

High doped and thick gain layer with high electric field which exceeds the breakdown threshold, it also makes the \( V_{\text{GL}} \) be very large (~450 V).
Summary:

- Positive bevel termination ensure that the surface electric field is below that in the bulk of the device, but not realizable for SiC LGAD stack structure which has thick drift layer (~75 µm).
- Vertical trench (90°) and small bevel angles (< 5°) can significantly increase breakdown voltage. They can be achieved by existing technology.
- Process feasibility for SiC LGAD was verified, but the prototype devices did not work as LGAD due to early breakdown.

New epitaxial stack designs have been proposed based on results from the existing SiC LGAD prototype. We will use different doping concentrations and thicknesses to ensure coverage of a wide breakdown voltage range while accounting for the fluctuations of epitaxial growth.

R&D in progress...
Thanks for your attention
Backup
PIN and LGAD

- **Bias Voltage**
- **Current**
- **1/C²**

**Graphs and Diagrams**:
- PIN and LGAD characteristics
- Breakdown voltage
- Low gain regions

**Key Points**:
- PIN and LGAD in different bias voltage scenarios
- Breakdown mechanism
- Current-voltage relationship
- Inverse of charge density
Optimize S/N ratio by Gain factor

Obtain the best S/N ratio when the gain factor is about 10~100

\[
\left( \frac{S}{N} \right)^2 = \frac{(I_L M)^2}{2e \left[ (i_{dg} + i_L) M^2 FB \right] + i_{NonGain}^2} = \frac{(I_L M)^2}{2e \left[ (i_{dg} + i_L) M^{2+\times} B \right] + i_{NonGain}^2}
\]

(Nicolo Cartiglia, Topics in LGAD Design, Trento, Tredi 2015)
Model of Positive Bevel Termination

Baliga, Fundamentals of Power Semiconductor Devices, 2019

- **Simple model**

  \[ W_S = \frac{W_B}{\sin(\theta)} \]

  \[ E_{mPB} = E_{mB} \left( \frac{W_B}{W_S} \right) = E_{mB} \sin(\theta) \]

- **Enhanced model**

  \[ a = \frac{W_B}{\sin(\theta)} \]

  \[ b = \frac{W_B}{\tan(\theta)} \]

  \[ W_S = a + b = W_B \left( \frac{1}{\sin(\theta)} + \frac{1}{\tan(\theta)} \right) \]

  \[ E_{mPB} = E_{mB} \left( \frac{W_B}{W_S} \right) = E_{mB} \left( \frac{\sin(\theta)}{1 + \cos(\theta)} \right) = E_{mB} \tan\left(\frac{\theta}{2}\right) \]

PB termination ensure that the surface electric field is below that in the bulk of the device.
Model of Negative Bevel Termination

- A significant reduction of the surface electric field can be achieved by using a very small negative bevel angle.

\[
W_S = \frac{W_P}{\sin(\theta)}
\]

\[
E_{mNB} = E_{mB} \left( \frac{W_N}{W_S} \right) = E_{mB} \frac{W_N}{W_P} \sin(\theta)
\]