First Results with the Prototype Detectors of the Si/W ECAL

David Strom – University of Oregon

- Physics Design Requirements
- Detector Concept
- Silicon Detectors - Capacitance and Trace Resistance
- Implications of Accelerator Technology Choice
- MIPS, sources and laser

Si-W work – personnel and responsibilities

M. Breidenbach, D. Freytag, N. Graf, G. Haller, J. Deng
SLAC
Electronics, Mechanical Design, Simulation

R. Frey, D. Strom
UO*

Si Detectors, Mechanical Design, Simulation

V. Radeka
BNL
Electronics

* This work includes contributions from Oregon students Tyler Neely and Eric Fitzgerald.
ECAL Design Requirements

• Optimal contribution to the reconstruction of multijet events:
  - Excellent separation of γ’s from charged particles
    
    \textit{Efficiency} > 95\% for energy flow

  - Excellent linkage of ECAL with tracker (important for SiD)

  - Good linkage of ECAL with HCAL

  - Good reconstruction of π\(^{\pm}\), detection of neutral hadrons

  - Reasonable EM energy resolution (\(< 15\%/\sqrt{E}\))

Physics case: jet reconstruction important for many physics processes.
• Longitudinal Sampling, 30 layers needed for EM energy resolution
\[ \frac{\sigma_E}{E} \sim 20\% \sqrt{\frac{X}{E}} \]

\(X\) is the sampling in radiation length.

• Useful for \(K^0\) tracking, etc.

• Can tolerate small, random inefficiency

See talks by Eckhard von Toerne
Importance of Granularity

- Figure of merit for energy reconstruction is

\[ f_E \approx \frac{\max(R_M, 4d)}{R_{cal}} \]

where \( R_M \) is the Molière radius, \( d \) is the detector pad size and \( R_{cal} \) is the inner radius of the calorimeter (factor of 4 somewhat arbitrary)

Example (OPAL SiW luminosity monitor, \( 1X_0 \) radiator, 3mm gap)

\[ d = 2.5\text{mm} \, , \, R_M \sim 17\text{mm} \]
• The costs of the calorimeters, coil, and muon system have

\[ \text{cost} \propto R_{\text{cal}}^n \]

where \( n \) is \( \sim 2 - 3 \).

• Thus a 10\% increase in the Molière radius of the calorimeter leads to a > 20\% increase in cost of the detector for constant \( f_e \).

• Conclusion: try and make the calorimeter as dense as possible.
Critical parameter: gap between tungsten layers.

<table>
<thead>
<tr>
<th>Config.</th>
<th>Radiation length</th>
<th>Molière Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% W</td>
<td>3.5mm</td>
<td>9mm</td>
</tr>
<tr>
<td>92.5% W</td>
<td>3.9mm</td>
<td>10mm</td>
</tr>
<tr>
<td>+1mm gap</td>
<td>5.5mm</td>
<td>14mm</td>
</tr>
<tr>
<td>+1mmCu</td>
<td>6.4mm</td>
<td>17mm</td>
</tr>
</tbody>
</table>

Assumes 2.5mm thick tungsten absorber plates

SD, Radius to calorimeter = 1.25m

Calice 3mm gap with 1.7m TESLA radius gives $\frac{R_M}{R_{Cal}} = 13\text{mrad}$
Si-W Calorimeter Concept

Inner Tracker 1.25m

Transverse Segmentation ~5mm
30 Longitudinal Samples
Energy Resolution ~15%/E^{1/2}

Layer Assembly
3.6 Meters
1.1-1.3 Meters
Silicon Wafers
Circuit Board
Rolled Tungsten

ECAL

Si-W Calorimeter Concept
Transverse Segmentation ~5mm
30 Longitudinal Samples
Energy Resolution ~15%/E^{1/2}
Silicon Concept

- Readout each wafer with a single chip
- Bump bond chip to wafer
- To first order cost independent of pixels / wafer
- Hexagonal shape makes optimal use of Si wafer
- Channel count limited by power consumption and area of front end chip
- May want different pad layout in forward region
Critical parameter: minimum space between tungsten layers.

Evolving capacitor packaging may eliminate need for dimples.
Can we get the heat out?

Back of the envelope calculation of change in temperature:

- Thermal Conductivity of W alloy 120W/(K-m)
- Thermal Conductivity of Cu 400W/(K-m)

Need to reduce heat to below 100mW/wafer.
Silicon Detector Design

- DC coupled detectors (avoids bias resistor network)
- Two metal layers
- Keep Si design as simple as possible to reduce cost
- Cross talk looks small with current electronics design
- Trace capacitances (up to 30pF) are bigger than the 5pF pixel capacitance
Ten Hamamatsu detectors are in hand
Measurements on Silicon Detector Prototypes

Leakage Current Looks Fine:

(10nA for 1µs gives only 250 electrons noise)
NB: Neighboring pixels are not grounded.
Expected contributions to detector capacitance:

- 5.7pF from pixel capacitance ($C_{geom}$)

- $\sim 20pF$ for sum of trace capacitance and capacitance from other traces connecting to other pixels. ($C_{stray}$)

- Pixels under the bump-bond array have additional stray capacitance from probing and bonding pads (currently $\sim 100pF$)

Expected curves

$$C_{tot} = C_{stray} + C_{geom} \sqrt{\frac{V_{dep}+V_{bi}}{V_{bias}+V_{bi}}} \quad V_{bias} < V_{dep}$$

$$C_{tot} = C_{stray} + C_{geom} \quad V_{bias} > V_{dep}$$
Typical CV curve as measured in lab
Relative depletion depth as a function of voltage.
Mean stray capacitance measurement obtained from a fit to the CV curve:

<table>
<thead>
<tr>
<th>Expected</th>
<th>100kHz</th>
<th>1 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.0 ± 0.2 pF</td>
<td>21 ± 1 pF</td>
<td>22 ± 1 pF</td>
</tr>
</tbody>
</table>

⇒ Measurement agrees with expectation for 0.9 µm thick oxide and 6µm wide traces (3.1 pF/cm).

Series resistance for 1µm by 6 µm:

<table>
<thead>
<tr>
<th>Expected (pure Al)</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>47 Ω/cm</td>
<td>(57 ± 2)Ω/cm</td>
</tr>
</tbody>
</table>

⇒ Measurement slightly larger than nominal
Impact of Detector Technology on Detector Design

⇒ In a warm machine, exceptional pixels with large capacitance or series resistance lead to degraded time tag measurements

- Small impact on tagging performance since bad channels can be de-weighted in determining the average time of a track

⇒ In a cold machine, exceptional pixels with large capacitance or series resistance lead to a higher rate of noise events in buffers

- Could lead to inefficiency late in the bunch train due to buffer overflow
Location of high resistance and capacitance pixels

a.) Longest trace $\sim 10$ cm

b.) Radial trace $\sim 7$ cm

c.) Congested area near bump bond array
• For areas $a$ and $b$ fundamental limit to noise is given by (for e.g. correlated double sampling)

$$ENC_{Rs} \sim C_{tot} \sqrt{\frac{4KT}{q^2e} R_s \frac{1}{2\tau}}$$

where $R_s$ is the series resistance, $C_d$ and $\tau$ is the shaping time of the electronics.

• For $\tau = 1\mu s$, $R_s = 580 \Omega$ and $C_{tot} = 40 \text{ pF}$ this gives $\sim 600$ electrons noise, which is not really a problem.

• We can slightly improve noise performance by decreasing the trace width, perhaps by a factor of 2, i.e.

$$ENC_{Rs} \propto \sqrt{w}$$

where $w$ is the trace width.
In region \( c \), near the bump bonding array, we will have a large number of traces crossing a pixel. No series resistance, but amplifier FET noise similar:

Possible ways to decrease capacitance in region \( c \):

- Move probing pads on to pixels.
- Decrease trace width in area near central pixels, here
  \[
  ENC_{amp} \propto w
  \]
- Use a long skinny chip (e.g. 100 \( \mu \text{m} \) x 600 \( \mu \text{m} \) grid)

After these three measures, worst case capacitance is \( \sim 70 \text{ pF} \).
Other more radical alternatives

- Polyimide (kapton) can be used instead of SiO$_2$ as insulator for traces
- Oxide thickness to 5$\mu$m possible.
- Minimum trace with probably 10$\mu$m
- Could reduce stray capacitances by a factor of 2 or more

Hamamatsu does not currently provide metal-on-polyimide products, but we could increase the thickness of the wafer and the SiO$_2$.

SINTEF (Norway) may be producing detectors based on 6 inch wafers with metal-on-polyimide within the next year. (Possible collaboration with Brookhaven to produce masks.)
Test Setup for Cosmics, Sources and Laser

- Modified probe station, allows laser to be target on entire detector

- IR microscope objective used to focus laser to $\sim 10 \, \mu m$ spot

- Bias applied to backside of detector using insulated chuck
Test Setup – detector probing

• Contact made to test pads on bump bonding array using an AC probe

• Cables add $\sim 20$ pF of additional capacitance, but noise performance is somewhat better than readout chip

• Use AMPTEK 250F preamp, shapers with $\tau \simeq 1\mu s$ and a digitizing oscilloscope to mockup expected electronics

• PC board with $1\text{ cm} \times 1\text{ cm}$ silicon pad detector used for cosmic trigger visible under chuck
Response of detectors to Cosmics
(Single 5mm pixel)
Simulate LC electronics
(noise somewhat better)

Errors do not include $\sim 10\%$ calibration uncertainty (no source calibration)
Response of Detectors to 60KeV Gamma’s from Am$^{241}$

Possible $\sim 1\%$ wafer-wafer calibration?

Width of distributions corresponds to $\sim 970$ electrons noise. Pixels under test are on outer edge of wafer – includes larger series resistance contribution than cosmic data.
Laser Studies

$\lambda = 1064$ nm

IR penetrates into wafer

Allows controlled study of large and small pulses
Conclusions

• A narrow gap silicon–tungsten detector for LC physics is attractive

• First round of prototype silicon detectors perform as expected

• Detectors can be produced with workable values of stray capacitance and series resistance
  ⇒ some changes need for cold design