Introduction

• The basics of semiconductor sensors and readout have been addressed, in depth, in a number of recent books and multi-day lecture series (see next slide).

• We will provide a brief summary of these topics.

• The rest of the lecture will focus on a variety of technical matters and recent developments.

• The hope is to provide a useful reference point.
Suggestions for further reading

• H. Spieler, Semiconductor Detector Systems, Oxford Science Publications, 2005
See also: http://www-physics.lbl.gov/~spieler/
• G. Lutz, Semiconductor Radiation Detectors: Device Physics, Springer (July 11, 2007)
• A.S. Grove, Physics and Technology of Semiconductor Devices, (1967) John Wiley & Sons;
  ISBN: 0471329983
• S. Sze, Physics of Semiconductor Devices, J. Wiley, 1981
• T. Ferbel, Experimental Techniques in High Energy Nuclear and Particle Physics, World
  Scientific, 1992

...and references therein
Outline

- Historical Perspective
- Basics
- Readout architectures
- Electronics Technology and Systems
- Mechanical and Metrological Aspects
- Radiation issues
- Future directions
Why Silicon?

• Microelectronics and lithography allow for the precise patterning of sensor and readout elements on the ~ 1 µm scale

• There exists a huge industrial and academic base which supports this technology, ever improving

• The natural scale maps well onto the experimental requirements for interesting physics measurements
  – Momentum determination at high $p_T$
  – Tracking in dense environments
  – Heavy flavor decay processes
Looking for charm in fixed target hadronic interactions…..b’s at lepton colliders

Late 1970’s surface barrier strip detector (Pisa)

~1980, 128 discrete channels, ~14 mW/channel (CERN)

~1985, “Microplex”, 1st 128 readout ASIC, 3 mW/chan (Parker, Hyams, Walker)
Circa 1980, state of the art, 256 channel strip detector for use in a fixed target experiment, (NA11 charm production) all strips are fanned out to a rack of discrete amplifiers and line drivers.
Finding top and bottom at the Tevatron ~1995.....

Two Vertex Views (note scales)

CDF Run II Preliminary

B⁺ → J/ψ K⁺

data
ct(Sig)
ct(Bkg)₁
ct(Bkg)₂
Fit prob: 44.2%
Prototype multi-modular silicon strip stave for use at the High Luminosity LHC

Present generation ATLAS pixel module in use today at the LHC…Higgs decays?

June 10, 2011  Silicon Detectors TIPP 2011  Carl Haber LBNL
~1980 single channel of discrete hybrid pre-amp, a few transistors, 14 mW/channel

2011 ATLAS FEI4 Chip

26880 pixels, 30 μW/pixel
3000 transistors/pixel

20 mm
CERN ATLAS tracker (4th generation, beam in 2008)

- Transition Radiation Tracker (TRT)
- Pixel Tracker
- Semiconductor Tracker (SCT)

2 m.
<table>
<thead>
<tr>
<th>generation</th>
<th>year</th>
<th>luminosity</th>
<th>$\Delta T$</th>
<th>chan/area</th>
<th>dose</th>
<th>readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CDF SVX</td>
<td>1990</td>
<td>$10^{29}$</td>
<td>3.5 $\mu$s</td>
<td>50K/ 0.68 m$^2$</td>
<td>25 Krad</td>
<td>3 $\mu$m CMOS</td>
</tr>
<tr>
<td>2 CDF SVX*</td>
<td>1995</td>
<td>$10^{30}$</td>
<td>3.5 $\mu$s</td>
<td>50K</td>
<td>100 Krad</td>
<td>1.2 $\mu$m RHCMOS</td>
</tr>
<tr>
<td>3 Run 2</td>
<td>2000</td>
<td>$10^{32}$</td>
<td>128 ns</td>
<td>600K / 5 m$^2$</td>
<td>1 Mrad, $10^{13}$/cm$^2$</td>
<td>0.8 $\mu$m RHCMOS</td>
</tr>
<tr>
<td>4 LHC</td>
<td>2009</td>
<td>$10^{34}$</td>
<td>25 ns</td>
<td>$5 \times 10^6$ / 68 m$^2$ 10$^8$ pixels</td>
<td>10 Mrad 10$^{15}$</td>
<td>0.25 $\mu$m CMOS RH Bi-CMOS</td>
</tr>
<tr>
<td>5 HL-LHC</td>
<td>2020</td>
<td>$10^{35}$</td>
<td>25 ns</td>
<td>$10^8$ / 200m$^2$ 10$^9$ pixels</td>
<td>100 Mrad 10$^{16}$</td>
<td>65 – 130 nm CMOS SiGe, Commercial</td>
</tr>
</tbody>
</table>
Technology

- The basic principles and structures have remained the same yet semiconductor detectors continue to function over a range of $\sim 10^6$

- Application specific integrated circuits
- Digital design and simulation tools
- Wafer size 2”,........,10”; feature size, circuit performance
- Interconnections, wire and bump bonding
- High density electronic packaging
- Advanced power management
- Composite mechanics
- Advanced thermal/mechanical materials
- Precision optical metrology
- Highly parallel DAQ with embedded processing (FPGA’s)
What drives the present and future developments?

• Today’s silicon trackers are large systems typically in use at colliders for momentum vertex measurement
  – Physical size ~ 1 m radius
  – Channel counts ~10^7
• High rate of interactions and track density: 40 MHz
• High radiation levels: 10^{15} - 10^{16}/cm^2
• Inaccessible: few years
• Mass ruins the response of other systems
• As the field progresses all of these aspects increase!
Specs and Optimizations

• Physics Goals
• Design Parameters
  – Resolution
  – Layout
  – Segmentation
  – Mass
  – Rate, L
• Radiation exposure

• Sensor
  – thin: lower voltage
  – thick: increased signal
  – smaller segment: less capacitance, leakage, more channels

• Electronics
  – fast: high power, noise
  – readout architecture

• Cooling
• Mechanical Support
Silicon Detectors

- Semiconductor band structure’s energy gap
- Asymmetric diode junction: example p(+) into contact with n ($N_A >> N_D$)
- Space charge region formed by diffusion of free charges, can be increased with "reverse bias"

junction width: $W = \sqrt{2 \mu \rho \varepsilon (V_{BI} + V_{RB})} = 0.5 \mu m \sqrt{\rho (V_{BI} + V_{RB})}$

$\mu$ = electron mobility, $\varepsilon = 11.9 \varepsilon_0$

$\rho = \text{resistivity of n type material} = \frac{1}{e\mu N_D} \approx 1 - 10k\Omega \ cm$

$V_{BI} = \text{built in potential (} \sim 0.8 \ V)$  $V_{RB} = \text{applied reverse bias}$
Response to Ionization

- Electron-hole pairs formed in the depletion zone drift under the influence of the electric field
- Signal depends on width of depletion zone
- Drift time determined by mobility and field
  - ~7 ns to cross 300 microns
- Drifting charge is a current which can be measured
Planar Processing

- Using micro-lithographic techniques arrays of diode structures can be patterned on silicon wafers.
- The “Silicon Microstrip” detector was introduced in the late 1970’s and is the basis of all precision types in use today.
Point Resolution: Segmentation

- Discrete sensing elements (binary response, hit or no hit), on a pitch $p$, measuring a coordinate $x$
- Discrete sensing elements (analog response with signal to noise ratio $S/N$) on a pitch $p$, where $f$ is a factor depending on pitch, threshold, cluster width

\[ \sigma_x = \frac{p}{\sqrt{12}} \]

\[ \sigma_x \sim fp\left(\frac{N}{S}\right) < \frac{p}{\sqrt{12}} \]
2D Pixel Structure

Single sided configuration
Pixel readout

Charge sensitive
Preamp + shaping, signal processing, pipelines, digitization

Diagram courtesy of Z.Li and V.Radeka
Further Variants

Silicon drift detector

Double sided detector

p+ in n
n+ in p
n+ in n
Pixel Detector Types

CCD
Charge Coupled Device
Relatively slow
Low noise, Low mass

Monolithic Active Pixel
electronics and charge
formation/collection in a
thin epitaxial layer, diffusion
Moderate speed
Low noise, Low mass

Hybrid pixel
FE IC and sensor joined
by a bump bond
Fast
Radiation Hard
Signal Processing Issues

- **Signal**: expressed as input charge, typically 25,000 electron-hole pairs (4 fC)
- **Gain**: determined by feedback and capacitance
- **Noise**: various sources, must be small compared to signal ($S/N > \sim 10$)
Leakage Current

- **Leakage current**
  - DC component blocked by oxide capacitor
  - If DC coupled then must be compensated by filter, feedback, or injection
  - Before (after) radiation damage ~ 1 nA (1 ma)
  - AC component is seen by pre-amp: noise source

\[ I_L = \frac{en_i(\sigma v_{\text{thermal}}N_T)WA}{2} \]

- \( n_i \) = intrinsic carrier concentration
- \( \sigma \) = recombination cross section
- \( v_{\text{thermal}} \) = carrier thermal velocity
- \( N_T \) = trap density
- \( A \) = junction area

\[ I_L(T) \propto T^2 e^{-E_a/2kT} \]
Noise

• Fluctuations ~ Gaussian $\sigma_N$
  - Leakage Current
  - Preamp “input noise charge”, white noise, decreases with pre-amp current, increases with faster risetime, $a, b$ are constants and $C_D$ is the detector capacitance
  - Bias resistor: source of thermal noise
  - Radiation activated

• Extraneous Noise

\[
\sigma_N \propto \sqrt{I_{LEAK} T_M}
\]

\[
\sigma_N \propto a + bC_D
\]

\[
\sigma_N \propto \frac{1}{R_{BIAS}}
\]
Full Evaluation of S/N

Noise model

Shaping models

June 10, 2011

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Readout Electronics

- Large channel count and complexity require custom readout chips (ASICs)
- On-chip complexity increases with process evolution
- Impact of powerful design and simulation tools
- Mixed analog-digital signals on the same chip
- Speed and noise performance have kept up with requirements but S/N often remains an issue, particularly with longer strips and irradiation
Readout Architectures

- Experimental conditions, have, to some extent driven the development of a variety of readout architectures
- Accommodate properties and limitations of available IC processes, a moving target
- Subjective aspects have entered as well
- Analog: process analog pulse heights off detector, full resolution, diagnostics
- Digital: digitize on detector, full resolution
- Binary: on detector threshold, simplify readout
Double Correlated Sample and Hold

- Original MOS monolithic architecture, no resistors
- High frequency bandwidth limited by pre-amp
- Low frequency limited by $\Delta T = T_2 - T_1$
- Can be generalized to N samples but incurs a noise penalty factor of $\sqrt{2}$ for each pair
Analog

- Example is the APV25 chip developed for CMS
- Readout all analog pulse heights, no sparsification
- Dual function: fast time mode, slow low noise mode
- Utilize analog signal processing on-chip to measure pulse time
Digital

- Example is the SVX4 chip developed for CDF
- Switched capacitor analog pipeline
- Combined analog threshold + 8 bit digitization
- Sparse readout
Binary

- Example is the ABCD chip developed for ATLAS, BiCMOS
- AC coupled pre-amplifier shaper for 25 ns collisions
- Comparator + trim DAC per channel
- 1 bit pipeline clocked at 40 MHz, L1 buffer
- Data compression
- Control and configuration protocol
- DSM CMOS version exists as well, 130 nm underway
• Example is ATLAS FEI3 pixel cell
• DC couple preamp with leakage current compensation
• Pulse height is measured by “Time over Threshold”
• Additional architecture organizes the data in columns for readout
Going to the next level

- Module Control Chip
- Readout ASIC
- Hybrid
- Sensor
- Power Control Circuit
Diagnostics

- Single channels can be studied in detail “on the bench”
- Channels are integrated in chips, chips into modules, etc…..
- Large detector systems require extensive monitoring and calibration
  - Parasitic collective effects and external noise can occur at the system level
- Much effort to develop meaningful procedures which can be implemented efficiently
- These will differ for the various architectures due to the limitations imposed.
Full Response Study: Module

S-curve threshold

VT50 gain noise

Input Noise vs Strip Length

Electrons

0 2 4 6 8 10 12 14

Strip Length [cm]
Noise and Correlations

- Interstrip capacitance $C_c$ dominates
- Total noise charge at an input $N$ is due to that channel and a coupled contribution from $N-1,+1$, with a negative correlation
- A useful statistic is to histogram the instantaneous difference between channels separated by $J=1,2,3,...$ strips (\(\sqrt{2}\))
- For $J \sim 5$ the mean approaches 1 in a system with no extra noise
Noise Interference

- Deadtimeless systems: simultaneous integration & readout
- Test: Consider a 132 cell pipeline, collected at 40 MHz, issue a trigger, readout, discard, wait 132 cycles, issue a trigger, readout
- Operate at onset of low occupancy
- Vary grounding, shielding, and filtering configuration
High Density Packaging

• Electronic packaging is often the only “reducible” part of the detector mass
• Advances in packaging have allowed us to integrate increasing complexity into denser footprints
• Maintain necessary thermal performance with minimized mass and high reliability
• Key technologies are based upon commercial processes
• Avoid the homemade syndrome
Key Technologies

• Surface mount technology (SMT), pick & place
• Flexible circuits
• High density multilayer PCB and flex
  – Trace widths/space approaching 25 µm
• Large area flexible circuits > 1 meter length
• Chip on Board (COB) and Chip on Flex
• Thin film on ceramic, glass, and polyimide
• Thick film on ceramic, BeO and AlN substrates
• Lamination onto high-TC carbon substrates
## Electrical Materials

<table>
<thead>
<tr>
<th>material</th>
<th>Resistivity ($\mu\Omega$cm)</th>
<th>dielectric constant</th>
<th>$X_0$(cm)</th>
<th>Thermal C. (W/m°C)</th>
<th>CTE (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>11.9</td>
<td></td>
<td>9.37</td>
<td>149</td>
<td>2.6</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.65</td>
<td></td>
<td>8.9</td>
<td>237</td>
<td>23.9</td>
</tr>
<tr>
<td>Copper</td>
<td>1.67</td>
<td></td>
<td>1.43</td>
<td>398</td>
<td>16.6</td>
</tr>
<tr>
<td>Gold</td>
<td>2.44</td>
<td></td>
<td>0.335</td>
<td>297</td>
<td>14.2</td>
</tr>
<tr>
<td>Carbon</td>
<td>1375</td>
<td></td>
<td>19.32</td>
<td>varies</td>
<td></td>
</tr>
<tr>
<td>Kapton</td>
<td>3.4</td>
<td></td>
<td>28.4</td>
<td>0.2</td>
<td>~20</td>
</tr>
<tr>
<td>SiO₂</td>
<td>3.9</td>
<td></td>
<td>10</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>BeO</td>
<td>$10^{21}$</td>
<td></td>
<td>6.6</td>
<td>230</td>
<td>8.3</td>
</tr>
<tr>
<td>AlN</td>
<td>$&gt;10^{20}$</td>
<td>9</td>
<td>8.4</td>
<td>170</td>
<td>4.3</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>$&gt;10^{20}$</td>
<td>9.0</td>
<td>7.55</td>
<td>24</td>
<td>7.2</td>
</tr>
<tr>
<td>G-10</td>
<td>4.7</td>
<td></td>
<td>19.4</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>
Technology examples
# Emerging Interconnects

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Standard</th>
<th>HDI: Dense (Particle Filled Epoxy)</th>
<th>HDI: LCP (liquid crystal polymer)</th>
<th>HDI: PTFE (PTFE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line width</td>
<td>75 microns</td>
<td>25 microns</td>
<td>37.5 microns</td>
<td>25 microns</td>
</tr>
<tr>
<td>Line space</td>
<td>75 microns</td>
<td>25 microns</td>
<td>37.5 microns</td>
<td>33 microns</td>
</tr>
<tr>
<td>Via type</td>
<td>mechanical</td>
<td>laser</td>
<td>Laser</td>
<td>laser</td>
</tr>
<tr>
<td>Via diameter</td>
<td>200 microns</td>
<td>50 microns</td>
<td>50 microns</td>
<td>50 microns</td>
</tr>
<tr>
<td>Stacked vias</td>
<td>Build up only</td>
<td>Build up only</td>
<td>In 2010</td>
<td>In 2010</td>
</tr>
<tr>
<td>Capture pad diameter</td>
<td>400 microns</td>
<td>100 microns</td>
<td>110 microns</td>
<td>110 microns</td>
</tr>
<tr>
<td>Surface finish</td>
<td>E-less Ni / I Au, ENEPIG</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Solder mask</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Thickness</td>
<td>&lt;1mm</td>
<td>0.4 - 0.7mm</td>
<td>0.5mm</td>
<td>0.5mm</td>
</tr>
<tr>
<td>Layers</td>
<td>10</td>
<td>12</td>
<td>4, 6 in 1\textsuperscript{st} article</td>
<td>11</td>
</tr>
</tbody>
</table>
Wirebonding

- Mainstay of microelectronic interconnection
- Typically uses 25 \(\mu\)m Al or Au wire, ultrasonic welding process
- Requires particular control of materials, cleanliness, and process
- Automated (5 bonds/sec) machines are commercially available and in widespread use in the HEP and related communities
- 75 \(\mu\)m pitch is achievable with good process control, a typical HEP “module” might contain ~5000 bonds
Bump or Flip Chip Bonding

- Wirebonding is impractical for large 2D arrays
- ATLAS pixel cell is 50 x 250 µm
- At this density FE interconnect is made with a conductive “bump”
- This is an industrial process and requires expensive technology, therefore has not become “in-house”
Bump Bonding Processes

**SOLDER BUMPING**

1. Sputter Etching and Sputtering of the Plating Base / UBM
2. Spin Coating and Printing of Photoresist
3. Electroplating of Cu and PbSn
4. Resist Stripping and wet Etching of the Plating Base
5. Reflow

**INDIUM BUMPING**

1. Wafer Cleaning
2. Photolithography
3. Plasma activation
4. Evaporated Indium
5. Wet Lift off process

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Issues for Large Systems

- Grounding and Shielding
- Powering
- Bias
- Control and Data Transmission
  - Cables
  - AC Coupling
- Monitoring and fast/slow control
  - Interlocks, safety
Grounding and Shielding

- Front end is a mixed analog and digital system
- Data transmission and control introduces long range signals with drive
- Sensor has a capacitance of pf’s, so mV of noise is an issue
- Rules apply but also thorough diagnostics before installation
- Trace down and control coupling paths and impedances
- Control locations where grounds are connected
Power Distribution

- Conventional wisdom stated that each “module” of tracker should be serviced independently
  - isolate single point failures
  - Avoid electrical interference and ensure low noise

- For large trackers this has led to a cabling (mass and access) limitation

- Future trackers may be larger by x5 or more

- An active R&D effort in alternative powering approaches
Powering Alternatives

• Independent Power
  – One cable with current $I_{\text{mod}}$, and $V_{\text{mod}}$ for each module

• Serial Power
  – Reuse current, connecting $N$ modules in series, one cable carries current $I_{\text{mod}}$, $V=NV_{\text{mod}}$
  – Practical implementation utilizes shunt regulation and active bypass protection, requires extensive AC coupling of control and data

• DC-DC Conversion
  – Step down voltage by factor $R$ at each module, one cable carries $I_{\text{tot}}=NI_{\text{mod}}/R$ at $V=RV_{\text{mod}}$
  – Practical implementation utilizes switching converters either charge pumps or inductive

• These alternative approaches can be very efficient compared to linear regulation
**Power architectures**

- **Independent powering**
  
  Hybrid current = I  
  Number of hybrids = n  
  Total current = nI  
  Power lines = n

- **Serial powering**
  
  Hybrid current = I  
  Number of hybrids = n  
  Total current = I  
  Power lines = 1

- **DC-DC powering**
  
  Hybrid current = I  
  Number of hybrids = n  
  Total current = n(I/r)  
  Power lines = 1
Serial Power

- Many variations on this have been studied in the R&D efforts, custom ASICs exist and are in development
- Large systems (>30 drops) have been operated with AC coupling
- Stable, low noise behavior obtained
- Failure recovery and control circuits have already been tested
- Most efficient when current per module is uniform
DC-DC Conversion

- DC-DC converters require high frequency clocks
- Realistic circuits have been operated in close proximity to sensor/modules with excellent noise performance, when adequately shielded.
- Main concern is the mass and size of required components

Buck converter with custom air core inductor

Charge pump
Control and Data Transmission

- Efficient low mass cabling requires a high degree of multiplexing
- Low power differential protocols – LVDS
- Clock and command distribution looks like a “multidrop” system (MLVDS and other variants)
- Bandwidth: fast clocks on copper 40-160 MHz or greater
- Transmission line structures in large flex circuits
- Much use of optical transmission, reliability concerns remain....
- Serially powered systems require AC coupling
- Much of this looks like a departure from standard practice
Bus Cable Geometry and Impedance

Materials: Al foil 2mil, Dupont LF0100, Shinetsu CA333 2 mils, Cu 18 um, Kapton 1 mil, Adhesive

>>Matches measured impedance

Differential Stripline Impedance Calculator

Notes:
1) Calculation assumes traces are centered vertically.
2) S/T > 5.0

Enter dimensions:
- Trace width (W) 3 mils
- Trace thickness (T) 0.7 mils
- Trace spacing (S) 4 mils
- Distance between planes (B) 5 mils
- Relative Dielectric constant (Er) 3.6

Differential Trace Impedance 72.9 ohms
Signal Dispersion in a Large AC Coupled Multidrop System

BCO out Position 2

AC coupled LVDS receiver, driver, controller

BCO in [mV] vs Position

BCO in at Position 23

BCO in Position 0
Monitoring, Fast/Slow Control

- Temperature, humidity, flow, radiation
- Voltages and currents
- Local on module monitoring, dedicated ASICs: fast
- Dedicated nearby process controllers
- Online logging
- Machine interlocks
- Service interlocks
Mechanical Aspects

• Precision tracker requires support structure which is stable and low in mass (Xo).

• There are two key materials/classes which come into consideration here
  – Beryllium: structural grade metal, low Z, metallic CTE, expensive, and hazardous to machine, probably impractical for very large structures
  – Carbon composites: tremendously flexible class of materials, reasonable Xo, good thermal properties, variable CTE
<table>
<thead>
<tr>
<th>material</th>
<th>Density (gr/cc)</th>
<th>Xo (cm)</th>
<th>Young’s Mod (GPa)</th>
<th>CTE (ppm/°K)</th>
<th>TC: W/m°K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>2.33</td>
<td>9.37</td>
<td>130-185</td>
<td>2.8-7.3</td>
<td>149</td>
</tr>
<tr>
<td>Beryllium</td>
<td>1.85</td>
<td>35.27</td>
<td>255</td>
<td>12.4</td>
<td>201</td>
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<tr>
<td>Aluminum</td>
<td>2.70</td>
<td>8.9</td>
<td>69</td>
<td>23.9</td>
<td>237</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>7.9</td>
<td>1.76</td>
<td>193</td>
<td>11.7</td>
<td>95</td>
</tr>
<tr>
<td>Titanium</td>
<td>4.54</td>
<td>3.56</td>
<td>116</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>2.21</td>
<td>19.32</td>
<td></td>
<td>0.6-4.3</td>
<td></td>
</tr>
<tr>
<td>Carbon fiber frac 70-40%</td>
<td>~1.7-2</td>
<td>23-27</td>
<td>180-125 along fibre</td>
<td>Varies with layup</td>
<td>10’s – several 100’s</td>
</tr>
<tr>
<td>CF: K13D2U</td>
<td>2.2</td>
<td></td>
<td>135 Msi</td>
<td></td>
<td>800</td>
</tr>
<tr>
<td>POCO</td>
<td>0.5</td>
<td>~100</td>
<td>low</td>
<td>0.7</td>
<td>45/135 in/out</td>
</tr>
<tr>
<td>Graphite foam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boron Nitride</td>
<td>2.25</td>
<td>20.8</td>
<td></td>
<td>&lt;1</td>
<td>250-300</td>
</tr>
</tbody>
</table>

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Beryllium

- Bulkhead which supports vertex detector layers, radius ~ 7 cm
- Costly, precision machined component
- Modest temperature excursion from RT
Carbon Composites

- Carbon fiber “sheets” consist of filaments or woven layers impregnated with epoxy.
- By arranging layers in various “lay-ups” and configurations, a great variety of components can be created with enhanced mechanical and thermal properties.
- Other advanced carbon based materials can be combined in structure as well.
Basic Issues

• Sag in a uniform composite beam

\[
\delta(\text{bending}) = \frac{wL^4}{384EI}
\]

\[
I = 2 \frac{bt^3}{12} + 2bt \left( \frac{c+t}{2} \right)^2 = \frac{bt^3}{6} + \frac{btc^2 + 2bct^2 + bt^3}{2} \approx btc \left( \frac{c}{2} + t \right)
\]

\[
\delta = \frac{wL^4}{384Ebtc \left( \frac{c}{2} + t \right)}
\]

• Stress in the “bi-material” strip

\[
\kappa = \frac{6E_1E_2(h_1 + h_2)h_1h_2\epsilon}{E_1^2h_1^4 + 4E_1E_2h_1^3h_2 + 6E_1E_2h_1^2h_2^2 + 4E_1E_2h_2^3h_1 + E_2^2h_2^4}
\]

\[
\epsilon = (\alpha_1 - \alpha_2) \Delta T
\]
Example: Carbon Fiber Beam

- Structure consists of 2 CF facings laminated on either side of a “soft” core w. embedded metal cooling lines: sandwich beam
- Symmetry keeps the structure flat
- Facing contains multiple sheets in order to tune mechanical and/or thermal properties
- Core may have enhanced thermal properties to improve cooling efficiency
- Subsequent (or co-)lamination of electrical circuitry and sensors
- Issue of stress between carbon and other unlike materials as composite is cooled from lamination temperature to RT and to operating temperature
Bus cable

Hybrids

Carbon honeycomb or foam

Coolant tube structure

Carbon fiber facing

Readout IC's
Composites Facility
Some assembly steps

June 10, 2011  Silicon Detectors TIPP 2011  Carl Haber LBNL
Prototype Core Construction

BNL, Yale
LBNL
RAL
Oxford
Example thermal performance for various material selections, calculated.
Advanced Materials

- Processed carbons
  - Carbon-Carbon: CF reinforced C by pyrolysis
  - Pyrolytic Graphite: TC>1000
- Graphite Foams: of varying density, conductivity
  - Pocofoam
  - Allcomp foam
- Boron Nitride: fillers
  - Varying particle size, shape
- Thermal adhesives: rigid, compliant, radiation hard
- Silicon Carbide: solid, foam, also an electrical material
Metrology

• Precision, non-contact mechanical measurement
• R&D, construction, in-situ alignment & monitoring
• Optical and touch probe CMM’s
• ESPI/TV Holography
• Frequency Scan Interferometer (FSI)
• Laser rangefinding displacement sensor
• Confocal probe
## Metrology

<table>
<thead>
<tr>
<th>Technology</th>
<th>Application</th>
<th>Resolution</th>
<th>Interface</th>
<th>Ease/Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMM-touch</td>
<td>Large objects</td>
<td>x/y/z ~ µm’s</td>
<td>commercial</td>
<td>Teach mode</td>
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<tr>
<td>CMM-optical</td>
<td>In plane location</td>
<td>x/y/z ~ µm’s</td>
<td>commercial</td>
<td>same</td>
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<tr>
<td></td>
<td>Small heights</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESPI</td>
<td>Dynamics</td>
<td>x/y/z ~ µm’s</td>
<td>commercial</td>
<td>R&amp;D tool</td>
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<tr>
<td>FSI</td>
<td>In-situ alignment</td>
<td>One axis</td>
<td>custom</td>
<td>System design</td>
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<tr>
<td></td>
<td>Stability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser Displacement</td>
<td>Flexible heights</td>
<td>z ~ µm’s</td>
<td>User defined</td>
<td>User defined,</td>
</tr>
<tr>
<td></td>
<td>R&amp;D tests</td>
<td></td>
<td></td>
<td>1 KHz</td>
</tr>
<tr>
<td>Confocal Probe</td>
<td>Precision heights</td>
<td>10-100 nm</td>
<td>Limited use</td>
<td>User defined,</td>
</tr>
<tr>
<td></td>
<td>Small area</td>
<td></td>
<td>commercial or user</td>
<td>100 Hz–2 KHz</td>
</tr>
</tbody>
</table>
Metrology: Coordinate Measuring

Good for repetitive, feature driven surveying

These devices have been used extensively in the development and construction of silicon trackers
Metrology: ESPI

Electronic Speckle Pattern Interferometry
Also called TV Holography

Modes of a clamped metal plate
Metrology: Laser Displacement

The measurement principle uses triangulation. The position of the reflected light on the Li-CCD moves as the position of the target changes. The displacement amount of the target is measured by detecting this change.

Composite Yale B Side Warm

Minimum = 20.363 mm.  
Maximum = 20.624 mm.  
$\Delta = 0.261$ mm.  
$\sigma_{meas} = 0.004$ mm.

Measured Warm-Cold Difference

Minimum = -0.115 mm.  
Maximum = 0.126 mm.  
$\Delta = 0.241$ mm.

Fit

Minimum = 20.384 mm.  
Maximum = 20.444 mm.  
$\Delta = 0.060$ mm.

Fit of Difference

Minimum = -0.008 mm.  
Maximum = -0.008 mm.  
$\Delta = 0.008$ mm.

Warm

Warm – Cold

No significant distortion
Metrology: Confocal Probe

Application 2: Mold for microlens array

Aims:
- Quality control of a mold for fabricating microlens arrays,
- Control of the shape, the spacing and the position of individual array cells,
- Control of polishing quality.

Click on image to improve definition

Measurement parameters
- Measurement system: MICROMESURE 2 Profilometer
- Controller: OP 20
- Optical pen: CHR 150
- Sample: Mold for microlens array
- Material: Metal
- Picture size: 150 µm x 150 µm
- Measurement pitch: 0.5 µm x 0.5 µm
Radiation Environment

• Primary source are collision products
  – High energy charged particles + neutrals
• Additional component due to “accidents”
• Primary field falls with radius as $\sim r^{-(1-2)}$
• Each interaction yields $\sim 7$ particles/angular unit: sum crossings and interactions
• Fluence and dose have increased $>10^4$ since mid-80’s
  – Near future expect unprecedented dose due to increased luminosity and energy
    • 100 Mrad absorbed energy (units)
    • $10^{15}$-$10^{16}$ particles/cm$^2$
    • Compare to: space ($\sim 1$ MRad), nuclear weapons ($\sim 10^{13}$)
Radiation Effects: Ionizing

- Incident particle interacts with atomic electrons
- Measure in energy absorbed (rads (Si))
- e/h pairs created, recombine or trap
- Transient effect
  - Actual signal formation
  - Single event upset condition in circuits
- Electronics: charge trapping at Si/SiO2 interface (largely controlled by rad-hard circuit designs or thinner oxides)
- Detectors: surface effects, oxides
Electronics

• For presently operating systems commercial rad-hard CMOS has provided sufficient resistance.

• New chips use commercial deep submicron CMOS
  – Thin oxides provide automatic hardness, verified in test
  – Augment design rules with enclosed gate geometries to block radiation induced leakage paths

• Certain bipolar technologies are also rad-hard (analog)
Radiation Effects: Non-ionizing

- Incident particle interacts with nucleus
  - Displacement damage – permanent or slow to reverse
  - 2^{nd} order effects as defects interact over time
- Depends upon particle type and energy
- Measure in particles/cm²
Radiation Effects: Detectors

- Damage to the periodic lattice creates mid-gap states
- Increased leakage
  - Shot noise
  - Power
  - Heat

\[ I_L = \frac{en_i(\sigma v_{thermal} N_T)WA}{2} \]

- \( n_i \) = intrinsic carrier concentration
- \( \sigma \) = recombination cross section
- \( v_{thermal} \) = carrier thermal velocity
- \( N_T \) = trap density
- \( A \) = junction area

\[ I_L(T) \propto T^2 e^{-E_a / 2kT} \]
Reverse current with fluence and time

\[ \Delta I = \alpha V \Phi \]

Damage constant \( \alpha \approx 2 \times 10^{-17} \frac{Amp}{cm} \)

Volume \( V \approx 2 \times 10^{-3} \text{ cm}^3 \)

Incident Flux \( \Phi \approx 10^{14} - 10^{15} \text{ particles/cm}^2 \) @ LHC

\( \Rightarrow \Delta I \approx 2 \mu A @ 0^\circ C \) (current doubles every 7 degrees)
Thermal Run-away

Increased current → Power dissipation → Increased temperature → Increased current
Change in effective acceptor concentration

Effective space charge ($N_{\text{eff}} \Rightarrow V_{fd}$) with fluence and time

- Creation of acceptor states or removal of donor states
  - Effective change of resistivity
  - Type inversion: $n \rightarrow p$
  - Depletion voltage changes in proportion to $|N_{\text{eff}}|$ → higher voltage operation required
  - Dramatic time and temperature dependence
Charge Collection

• Reduction in charge collection efficiency (CCE)
  – \( N_{e,h}(t) = N_0 \exp\left(-\frac{t}{\tau_{\text{trap}}}\right) \)
  – Ratio of collection and charge trapping time constants evolves with fluence

Gregor Kramberger, Ljubljana
Excess Radiation Induced Noise

- An effect seen in AC coupled or double sided sensor which are biased with punchthrough structures (this approach has been widely abandoned)
- Functional dependence is like shot noise but magnitude is 4X too large
- Scales linearly with integration time
- Only induced by heavy particle flux
- Actual mechanism is not understood but phenomenology is consistent

Methods to Control Radiation Effects

- Most represent some tradeoff
- Size matters
  - Smaller volumes generate less leakage current (but require more channels, power, heat...)
  - Thinner detectors deplete at lower voltage (usually means less signal)
- Temperature
  - Low temperature (-10 C) operation can “stabilize” reverse annealing for $<10^{14}$
  - Reduce leakage current effects
- Integration time
  - Current noise is reduced for short shaping times at the expense of increased pre-amp noise, power.
• Biasing schemes
  – Reduce value of parallel biasing resistor to reduce voltage drop due to $I_{\text{Leak}} R_{\text{bias}}$ at the expense of increased thermal noise

• HV operation
  – Configure detectors to withstand higher voltage operation
  – Tolerate increased depletion voltage
  – Operate in partial depletion (collection issues)

• Low noise electronics
  – Tolerate reduced signal due to CCE and partial depletion

• Configuration
  – p in n substrate – simple, type inverts
  – n in n substrate – 2 sided process, can be operated in partial depletion after inversion
  – n in p – non-traditional process, does not invert
Strip detectors with multiple guard ring structures to tolerate HV=500 V operation

Simulation of 10 year operating scenarios for silicon tracking at the LHC

$L = 10^{33}-10^{34}$
New developments

• Engineered materials
• New configurations, 3D electrodes, interleaved strips
• Cryogenics
• Alternate materials: Diamond, SiC,…
• RD efforts organized at CERN
  – RD42: development of diamond as detector
  – RD48: radiation damage to silicon
  – RD50: development of radiation resistant detectors
  – RD39: cryogenic detectors and systems
  – http://rdXY.web.cern.ch(rdXY
Engineered Silicon

• Microscopic understanding of damage mechanisms, defects, and kinetics
  – Modeling
  – Measurements
  – Time and temperature dependence

• Engineer the silicon for greater radiation resistance
3D Detectors

3D silicon detectors were proposed in 1995 by S. Parker, and active edges in 1997 by C. Kenney.

Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.

Electrodes are processed inside the detector bulk instead of being implanted on the Wafer’s surface.

The edge is an electrode! Dead volume at the Edge < 2 microns! Essential for
- Large area coverage
- Forward physics

1. NIMA 395 (1997) 328
7. NIMA 509 (2003)86-91

S. Parker

June 10, 2011

Silicon Detectors TIPP 2011

Carl Haber LBNL
1. 3D lateral cell size can be smaller than wafer thickness, so
2. in 3D, field lines end on cylinders rather than on circles, so
3. most of the signal is induced when the charge is close to the electrode, where the electrode solid angle is large, so planar signals are spread out in time as the charge arrives, and
4. Landau fluctuations along track arrive sequentially and may cause secondary peaks (see next slide)
5. if readout has inputs from both n+ and p+ electrodes,
6. for long, narrow pixels and fast electronics,

S.Parker
Examples of etching and coating with polysilicon.

An early test structure by Julie Segal, etched and coated (middle, right), showing conformal nature of poly coat.

An electrode hole, filled, broken (accidentally) in a plane through the axis, showing grain structure (below). The surface poly is later etched off.
Alternate Materials

• Very active R&D effort for >10 years

• Most work has been on pCVD diamond material
  – Significant improvement in charge collection

• New results on single crystal materials – but small samples

• Issue of industrial capacity vs silicon

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>4H-SiC</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap (eV)</td>
<td>5.5</td>
<td>3.3</td>
<td>1.12</td>
</tr>
<tr>
<td>Breakdown field (V/cm)</td>
<td>$10^7$</td>
<td>$4 \times 10^6$</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>Resistivity (Ω-cm)</td>
<td>$&gt;10^{11}$</td>
<td>$10^{11}$</td>
<td>$2.3 \times 10^6$</td>
</tr>
<tr>
<td>Intrinsic Carrier Density (cm$^{-3}$)</td>
<td>$&lt;10^3$</td>
<td>$10^3$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>Electron Mobility (cm$^2$V$^{-1}$s$^{-1}$)</td>
<td>1800</td>
<td>800</td>
<td>1350</td>
</tr>
<tr>
<td>Hole Mobility (cm$^2$V$^{-1}$s$^{-1}$)</td>
<td>1200</td>
<td>115</td>
<td>480</td>
</tr>
<tr>
<td>Saturation Velocity (km/s)</td>
<td>220</td>
<td>200</td>
<td>82</td>
</tr>
<tr>
<td>Mass Density [g cm$^{-3}$]</td>
<td>3.52</td>
<td>3.21</td>
<td>2.33</td>
</tr>
<tr>
<td>Atomic Charge</td>
<td>6</td>
<td>14/6</td>
<td>14</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>5.7</td>
<td>9.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Displacement Energy [eV/atom]</td>
<td>43</td>
<td>25</td>
<td>13-20</td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>8.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Radiation Length [cm]</td>
<td>12.2</td>
<td>8.7</td>
<td>9.4</td>
</tr>
<tr>
<td>Spec. Ionization Loss [MeV/cm]</td>
<td>4.69</td>
<td>4.23</td>
<td>3.21</td>
</tr>
<tr>
<td>Ave. Signal Created/100 μm [e]</td>
<td>3600</td>
<td>5100</td>
<td>8900</td>
</tr>
<tr>
<td>Ave. Signal Created/0.1% X₀ [e]</td>
<td>4400</td>
<td>4400</td>
<td>8400</td>
</tr>
</tbody>
</table>

- Low dielectric constant - low capacitance
- Large bandgap - low leakage current
- Large energy to create an e-h pair - small signal
Characterization of Diamond:

Signal formation

- $Q = \frac{d}{\tau} Q_0$ where $d =$ collection distance = distance e-h pair move apart
- $d = (\mu_e \tau_e + \mu_h \tau_h) E$
- $d = \mu E \tau$

with $\mu = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$

and $\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$

Charge Collection in DeBeers CVD Diamond

Collection Distance (microns)

Time (year)

RD42 Goal
Cryogenic operation

- Palmieri et al (1998) recovery of lost CCE at cryogenic temperatures
- “Lazarus Effect” due to freeze-out of traps
- R&D activity centered at CERN (RD39)
- Practical difficulty for “low mass” tracker if substantial cryogenic engineering and infrastructure is required.
Technology Development Shopping List

- Radiation resistance of silicon and other solids
- **Radiation hard electronics – smaller feature size, larger IC’s**
- Signal processing and circuit design
- **Pixel architectures, monolithic and active pixel sensors**
- Alternative powering schemes. serial power, DC-DC conversion
- **Real time fast trigger processors**
- Large area and precision low mass mechanics
- **Alignment and survey technology (metrology, lasers, sensors)**
- Low mass electrical and mechanical components including discretes & substrates
- **Cooling technology – materials, coolants, delivery systems**
- Finite element thermal and mechanical simulations
- **Pattern recognition and data reduction methods**
- Reliability and redundancy methods
- **Large area, fine line, lithographic methods**
- Robotic methods for assembly and test
- **Wireless data transfer**
- Optical readout methods
Real time momentum trigger

Half Pitch vs Momentum

0 10 20 30 40 50

Momentum GeV

1 2 3 4 5 6 7 8 9 10

Half Pitch Units (37.5 um)

4.5 mm

6 mm

4.5 mm

See WIT2010 pub in JINST

2 x DC coupled strip detectors
SS, 100um pitch < 8CHF/cm2

Strip Read Out Chip
2 x 100um pitch with on-chip correlator
Conclusions

• Huge progress ~30 years to build silicon trackers using a broad suite of advanced technologies

• Much significant science done, and to be done, with these devices

• Progress in understanding and compensating for effects of radiation over a range of $10^4$

• R&D underway for next generation
EXTRA SLIDES
Multi-hit performance

- Binary response (hit or no hit), on pitch $p$, two hit separation requires an empty element.
  - Wide pitch $\Rightarrow$ most hits are single element, separation $= 2p$
  - Narrow pitch $\Rightarrow$ double element hits, separation $= 3p$
- Analog response: can use local minima in a merged cluster
Lower Mass

• Large area and precision low mass mechanics

• Alignment technology (lasers, sensors)
  – Drop stiffness requirements in favor of active monitoring and feedback (lesson from the telescope builders).

• Low mass electrical and mechanical components including discretes & substrates
  – Power distribution schemes, serial power, DC-DC conversion, less redundancy, grounding issues
  – Technologies for hybrid circuits – thick, thin films, laminates

• Cooling technology – materials, coolants, delivery systems
  – High thermal conductivity materials
  – High pressure CO2
  – Cooling integrated with FE electronics
  – Reduced power consumption
Trajectory

- Charged particle in a magnetic field $B = Bz$
- 3D Helix: 5 parameters
  - $C =$ half curvature $(1(\text{sgn})/R)$
  - $z_0 =$ offset
  - $D =$ signed impact parameter (distance of closest approach)
  - Azimuth $\phi =$ angle of track at closest approach
  - $\theta =$ dip angle

\[
\begin{align*}
x &= x_0 + R \cos \lambda \\
y &= y_0 + R \sin \lambda \\
z &= z_0 + R \lambda \tan \theta
\end{align*}
\]
Momentum Resolution

Simple case: Measure sagitta $s$ of track with radius $R$, over projected arc length $L$ (cm, KGauss, MeV/c), assuming $R \gg L$

$$p = \frac{0.3BR}{\cos \theta} = \frac{0.3BL^2}{8s \cos \theta} \quad \text{using} \quad R = \frac{L^2}{8s} \Rightarrow \left( \frac{\Delta p}{p} \right)_{\text{sagitta}} = \frac{8p\Delta s}{0.3BL^2 \cos \theta}$$

where $Ds$ is the error on the sagitta measurement.

Effect of material: multiple scattering

$$(\Delta s)^2 = \frac{\sigma_{MCS}^2}{16} \frac{L^2}{3 \cos^2 \theta} \Rightarrow \left( \frac{\Delta p}{p} \right)_{\text{MCS}} = \frac{52.8}{B \sqrt{LX_0} \cos \theta}$$

$$\frac{\Delta p}{p}_{\text{TOTAL}} = \left( \left( \frac{\Delta p}{p} \right)_{\text{sagitta}}^2 + \left( \frac{\Delta p}{p} \right)_{\text{MCS}}^2 \right)^{\frac{1}{2}}$$
Effect of Material

\[
\frac{\Delta p}{p}_{\text{sagitta}} = \frac{8 p \Delta s}{0.3 B L^2 \cos \theta}
\]

\[
\frac{\Delta p}{p}_{\text{MCS}} = \frac{52.8}{B \sqrt{LX_0} \cos \theta}
\]

\[
\frac{\Delta p}{p}_{\text{TOTAL}} = \left( \left( \frac{\Delta p}{p} \right)_{\text{sagitta}}^2 + \left( \frac{\Delta p}{p} \right)_{\text{MCS}}^2 \right)^{\frac{1}{2}}
\]

- Minimize sagitta error
- Maximize B, L
- Minimize material
Vertex Resolution

\[ x_1, x_2 = \text{measurement planes} \]
\[ y_1, y_2 = \text{measured points, with errors } \delta y \]
\[ y = a + bx \]
\[ b = \text{slope} = \frac{y_1 - y_2}{x_1 - x_2} = \frac{y_1 - y_2}{\Delta x} \]
\[ a = \text{intercept} = \frac{1}{2} (y_1 + y_2) - \frac{1}{2} (y_1 - y_2) \left( \frac{x_1 + x_2}{\Delta x} \right) = \bar{y} - b\bar{x} \]

\[ (\delta b)^2 = \left( \frac{\partial b}{\partial y_1} \right)^2 (\delta y)^2 + \left( \frac{\partial b}{\partial y_2} \right)^2 (\delta y)^2 \implies \delta b = \frac{\sqrt{2}\delta y}{\Delta x} \]

\[ \delta a = \frac{\delta y}{2} \sqrt{1 + \frac{8\bar{x}}{\Delta x}} \]

for good resolution on angles (f and q) and intercepts (d, z_0)

- Precision track point measurements
- Maximize separation between planes for good resolution on intercepts
- Minimize extrapolation - first point close to interaction

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Effect of Material

\[ x_1, x_2 = \text{measurement planes} \]
\[ y_1, y_2 = \text{measured points, with errors } \delta y \]
\[ \delta a = \frac{\delta y}{2} \sqrt{1 + \frac{8 \bar{x}}{\Delta x}} \]

for good resolution on angles (f and q) and intercepts (d, z_0)

- Precision track point measurements
- Maximize separation between planes for good resolution on intercepts
- Minimize extrapolation - first point close to interaction
- Material inside 1\textsuperscript{st} layer should be at minimum radius (multiple scattering)