Testing Silicon Detectors in the Lab

Thomas Bergauer (HEPHY Vienna)
Schedule of my talk during 1\textsuperscript{st} detector school

- Semiconductor Basics (45’)
- Detector concepts: Pixels and Strips (45’)
- Strip Detector Performance (45’)
- \textit{Quality Control on strip detectors} (45’)
- Radiation Damage (45’)

15 June 2012  
Thomas Bergauer (HEPHY Vienna)
Quality Control on strip detectors

- Introduction
- Measurement techniques
  - Electrically
  - Optically
  - Mechanically
  - Aging Studies
- Construction of Detector Modules
  - Wire Bonding
- Beam Tests
What is Quality control?

• Characterize devices
  – Electrically: currents, capacitances
  – Mechanically: bondability, sag, bow
  – Optically: dust, dirt, lithography issues, dimensions

if they comply to the specifications

• Define acceptance criteria
  – E.g. CMS: number of non-working strips <1%
  – non-working strips to be excluded from being used

• What means “not working”?
  – Outside parameter range (e.g. $200\text{pF} < C_{ac} < 220\text{pF}$)
Silicon Detectors in High Energy Physics

Electrical parameters

• Typical Setup at HEPHY Vienna
  – Light-tight box
  – Instruments
  – Computer running NI Labview

15 June 2012
Mechanical parameters

• Measurement of
  – Sag
  – Bow
  – Thickness
Using 3D mechanical measurement system

• Coordinate measurement machine (CMM)
Optical measurements

Optical microscopy
Olympus BX60+DP21

Electron microscopy
FEI Quanta 200 FEG SEM

HEPHY cleanroom
USTEM Vienna UT

15 June 2012
Thomas Bergauer (HEPHY Vienna)
ELECTRICAL MEASUREMENTS
Silicon Detectors in High Energy Physics

Instruments

- Electrometer (precise Amp-meter)
- LCR Meter
- Source Measure Unit (SMU)

15 June 2012
What is a Source Measure Unit?

- Source
  - Voltage source
  - Constant current source
- Amp-meter
- Volt-meter
in one device

Keithley 237

GS610 construction

*1 DUT : Device Under the Test
*2 For DUT voltage measurement
What is a Source Measure Unit? (cont.)

- High precision Amp-meter
- K237: 250fA at 700V
- High precision needs Triax connectors
STRIP-BY-STRIP CHARACTERISATION
Strip-by-strip Test Setup

• Sensor in Light-tight Box
• Vacuum support jig is carrying the sensor
  – Mounted on movable table in X, Y and Z
• Needles to contact different structures on sensor
• What do we test?
  – Electrical parameters
  – strip failures

Thomas Bergauer (HEPHY Vienna)
Common strip failures

Open Strip:

Shorted Strip:

Open bias resistor:

Open implant at via:

Open implant:

“Pinhole” (short between implant and metal):
Silicon Detectors in High Energy Physics

What do we test?

- Global parameters:
  - **IV-Curve**: Dark current, Breakthrough
  - **CV-Curve**: Depletion voltage, Total Capacitance

- Strip Parameters e.g.
  - strip leakage current $I_{\text{strip}}$
  - poly-silicon resistor $R_{\text{poly}}$
  - coupling capacitance $C_{\text{ac}}$
  - dielectric current $I_{\text{d}}$

---

Thomas Bergauer (HEPHY Vienna)
Measurement validation

Direct measurement of oxide thickness by electron microscopy

SEM result: 355 nm
average from C_ac measurement: 354.2 nm
Vendor average: 391.8

Graph showing oxide thickness measurements

15 June 2012

Thomas Bergauer (HEPHY Vienna)
Measurement of the inter-strip resistance

SMU 1
-100V
GND
applies bias voltage

SMU 2
0...3V (5V)
A
GND

Current at 0V is strip leakage current, interstrip resistor value from slope of current when ramping

ramps potential on neighbouring DC pad -> Bias resistor value from slope of current
Measurement of the inter-strip resistance

HPK sensor, **n-side**, strip 1-2

- $I_{\text{strip}} = -5.14 \text{ nA}$
- $R_{\text{int}} = 92.6 \text{ G}\Omega$
- $R_{\text{poly}} = 2.8 \text{ M}\Omega$

HPK sensor, **p-side**, strip 6-7

- $I_{\text{strip}} = 1.498 \text{ nA}$
- $R_{\text{int}} = 158.4 \text{ G}\Omega$
- $R_{\text{poly}} = 17.9 \text{ M}\Omega$

- First strip scan using this method currently ongoing

15 June 2012

Thomas Bergauer (HEPHY Vienna)
Spreading Resistance Profiling

**Polishing:** 0,5°
**Needle:** r=7µm, 3g
**Stepsize:** 10µm
**Resolution:** ~110nm

~ 1,4µm
What is Process Monitoring?

- Each wafer hosts additional test structures around main detector
- “standard” set of test structures is called “half moon” (because of its shape)
- Test structures used to determine one parameter per structure
- Assuming that sensor and test structures behave identically

- Some parameters are not accessible on main detector (e.g. flatband voltage of MOS), but important for proper operation
Test Structures Description

- **TS-CAP:**
  - Coupling capacitance $C_{AC}$ to determine oxide thickness
  - IV-Curve: breakthrough voltage of oxide

- **Sheet:**
  - Aluminium resistivity
  - $p^+$-implant resistivity
  - Polysilicon resistivity

- **GCD:**
  - **Gate Controlled Diode**
  - IV-Curve to determine surface current $I_{surface}$
  - Characterize Si-SiO$_2$ interface

- **CAP-TS-AC:**
  - Inter-strip capacitance $C_{int}$

- **Baby-Sensor:**
  - IV-Curve for dark current
  - Breakthrough

- **CAP-TS-DC:**
  - Inter-strip Resistance $R_{int}$

- **Diode:**
  - CV-Curve to determine depletion voltage $V_{depletion}$
  - Calculate resistivity of silicon bulk

- **MOS:**
  - CV-Curve to extract flatband voltage $V_{flatband}$ to characterize fixed oxide charges
  - For thick interstrip oxide (MOS1)
  - For thin readout oxide (MOS2)
Measurement Setup

- Probe-card with 40 needles contacts all pads of test structures in parallel
  - Half moon fixed by vacuum
  - Micropositioner used for Alignment
  - In light-tight box with humidity and temperature control
- Instruments
  - Source Measurement Unit (SMU)
  - Voltage Source
  - LCR-Meter (Capacitance)
- Heart of the system: Crosspoint switching box, used to switch instruments to different needles
- Labview and GPIB used to control instruments and switching system

Thomas Bergauer (HEPHY Vienna)
Silicon Detectors in High Energy Physics

Setup

Probestation

Probe Card with support

Half moon on sliding table

15 June 2012

Thomas Bergauer (HEPHY Vienna)
Silicon Detectors in High Energy Physics

Blue Fields:
Obtained results extracted from graph by linear fits (red/green lines)

Yellow Fields:
Limits and cuts for qualification
Passed/Not Passed Lights

- After all measurements finished
- Window pops up
- One light for each test
  - Green: within limits
  - Red: out of limits
- Allows immediate judgment about quality
- Pressing “OK” button writes data directly into central database (CMS used Oracle)

15 June 2012  Thomas Bergauer (HEPHY Vienna)
Example measurement: CV on MOS

- Metal Oxide Semiconductor
- Used to determine fixed oxide charges by measuring so-called flat-band voltage
- Measurement by taking capacitance vs. voltage
  a) $V_{\text{flat band}} = 0$
     (Ideal oxide without any charges)
  b) Accumulation layer
  c) Depletion
  d) Inversion
Process monitoring on irradiated structures

Needs measurement at **low temperatures** (-20 degC)

Dedicated setup:
- Sensor support is cooled by Peltier elements and liquid cooling circuit
- Dry atmosphere to avoid condensation (Nitrogen or dry air)

Dark current scales with temperature:
- Lowered to 50% when temperature drops by 7 degrees
Low noise measurements

IV measurement T=−20degC

Voltage (V)

Current (pA)

Silicon Detectors in High Energy Physics

15 June 2012 Thomas Bergauer (HEPHY Vienna)
Low noise measurements (2)

- Shielded cables necessary for whole conduction path
- Coax often sufficient
- For extreme sensitive measurements (e.g. pA):
  - Triax cables necessary
Long-term Stability and Thermal Cycling

AGING STUDIES
Long-term stability

- Monitoring of leakage current over certain timescale
- Certain effects cause instabilities
  - Micro-discharges
  - Chemical reactions

Thomas Bergauer (HEPHY Vienna)
Silicon Detectors in High Energy Physics

Corrosion

Chemical reaction with Potassium

- Leftover from SiO₂ etching
- serving as a catalyst for Al -> Al₂O₃ reaction

15 June 2012 Thomas Bergauer (HEPHY Vienna)
OPTICAL INSPECTION
Round scratches
- occur on every sensor
- maybe due to automatic sensor handling?
Residues and other optical issues
MECHANICAL MEASUREMENTS
Mechanical parameters

- Measurement of
  - Sag
  - Bow
  - Thickness

Using 3D mechanical measurement system

- Coordinate measurement machine (CMM)
Sensor Thickness

- Grid of 7 by 13 measurement points
- Measure exact same points on sensor and on jig alone (with vacuum applied)
- Graphic right: difference of the two runs
- Calculate average thickness

The average thickness is 0.320 mm

<table>
<thead>
<tr>
<th>Tolerance zone</th>
<th>Upper tol.</th>
<th>Lower tol.</th>
<th>No. of pts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.018</td>
<td>0.010</td>
<td>-0.008</td>
<td>91</td>
</tr>
<tr>
<td>Flatness</td>
<td>Std dev. * 4</td>
<td>Y</td>
<td>Min/Max Pnt.</td>
</tr>
<tr>
<td>0.018</td>
<td>0.019</td>
<td>Y</td>
<td>45 / 1</td>
</tr>
<tr>
<td>Min. dist.</td>
<td>X</td>
<td>Y</td>
<td>0.311</td>
</tr>
<tr>
<td>-0.008</td>
<td>-88.831</td>
<td>-91.778</td>
<td>Z</td>
</tr>
<tr>
<td>Max. dist.</td>
<td>X</td>
<td>Y</td>
<td>0.326</td>
</tr>
<tr>
<td>0.010</td>
<td>-106.722</td>
<td>-152.896</td>
<td>Z</td>
</tr>
</tbody>
</table>
Sag of the vacuum jig

- Hold sensor with vacuum through porous stone

15 June 2012

Thomas Bergauer (HEPHY Vienna)
Sensor Flatness

- Run 1 without vacuum
- Run 2 with vacuum
  - Graphic on the right is difference
- Maximum difference: 42µm
- Subtracting sag of vacuum jig: 13µm

15 June 2012 Thomas Bergauer (HEPHY Vienna)
MODULES
Module Construction

Connecting a bare sensor with a readout chip onto a mechanical support structure
Detector Modules

- A detector module consists of
  - Front-end hybrid containing readout chips (CMS: APV25)
  - Pitch adapter
  - Silicon Sensor
  - frame/support

- Wire bonding for connections
Silicon Detectors in High Energy Physics

15 June 2012  Thomas Bergauer (HEPHY Vienna)
Basic Element of the Tracker: Module

Components:
- Carbon fiber/graphite frame
- Kapton flex circuit for HV supply
- Front End Hybrid housing readout chip
- Pitch Adaptor
- One or two silicon sensors

Total:
- 29 module designs
- 16 sensor designs
- 12 hybrid designs
Module Assembly

Module assembly for CMS was manual process in Vienna:

- CF frame was fixed with vacuum support
- Glue dispensed
- Sensor put onto frame using gantry positioning system
- Glue curing
- Using 3D coordinate measurement machine for measurement of assembly precision (<10 micron)

- Throughput: 4 modules per day
Silicon Detectors in High Energy Physics

Automatic Module Assembly

Robotic assembly system which:
1. Apply glue on frame
2. Place hybrid onto frame
3. Place sensor onto frame
4. Optical measurement of placement precision
5. Glue curing
6. Second measurement of alignment precision

Displacement data entered in TrackerDB and used for correction during track reconstruction
(more precise: as starting point of track-based alignment)

Assembly precision $\sigma \approx 9\mu m$
Wire bonding

- Ultrasonic welding technique
- 17 or 25 micron bond wire of Al-Si-alloy
- Pull-tests to verify bond quality
Silicon Detectors in High Energy Physics

Tracker Outer Barrel (TOB)

- Tracker Outer Barrel (TOB) mainly produced in US

Tracker Support Tube:

- 5550 modules

- 688 Rods

- (24 different species)

- 1.1m

15 June 2012

Thomas Bergauer (HEPHY Vienna)
Tracker Inner Barrel (TIB)

- TIB mainly produced in Italy

16 shells + 6 disks

3800 modules

4 layers
2 units

15 June 2012

Thomas Bergauer (HEPHY Vienna)
Tracker End Caps (TEC)

- TEC modules and petals mostly from Central Europe (Belgium, Germany, France, Austria)

6850 modules
(10 different species)

288 petals
(8 different species)
TEC Installation

15 June 2012  Thomas Bergauer (HEPHY Vienna)
BEAM TESTS
Purpose of beam tests

Realistic test of detector plus readout system. Results are:

- **SNR** (could also be obtained with radioactive source on lab test bench)
- **Residuals/resolution** studies only with high-energy beam
  - Multiple scattering at low energy does not allow such measurements
  - Beam telescope needed

- Also realistic test of
  - Cooling system
  - slow control
  - Mechanical stages
  - Data Acquisition
Beam test impressions

15 June 2012

Thomas Bergauer (HEPHY Vienna)
Example 1: resolution studies

**TESTAC:**

<table>
<thead>
<tr>
<th>strip width [μm]</th>
<th>intermediate strips</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>no</td>
</tr>
<tr>
<td>10</td>
<td>no</td>
</tr>
<tr>
<td>12.5</td>
<td>no</td>
</tr>
<tr>
<td>15</td>
<td>no</td>
</tr>
<tr>
<td>20</td>
<td>no</td>
</tr>
<tr>
<td>25</td>
<td>no</td>
</tr>
<tr>
<td>5</td>
<td>single</td>
</tr>
<tr>
<td>7.5</td>
<td>single</td>
</tr>
<tr>
<td>10</td>
<td>single</td>
</tr>
<tr>
<td>12.5</td>
<td>single</td>
</tr>
<tr>
<td>15</td>
<td>single</td>
</tr>
<tr>
<td>17.5</td>
<td>single</td>
</tr>
<tr>
<td>5</td>
<td>double</td>
</tr>
<tr>
<td>7.5</td>
<td>double</td>
</tr>
<tr>
<td>10</td>
<td>double</td>
</tr>
<tr>
<td>12.5</td>
<td>double</td>
</tr>
</tbody>
</table>
Example 1 (cont.): Resolution Studies
Example 2: Performance before/after irradiation
Example 2 (cont.): Sensor design

- **Belle II sensors**
- **Double sided**
  - Structures for strip separation on n-side needed → „p-stop“
  - 3 design with 4 different layouts

1) atoll p-stop
2) common p-stop
3) combined p-stop
Example 2 (cont.): Analysis of data

Comparison of p-stop geometry

<table>
<thead>
<tr>
<th>p-stop type</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>common</td>
<td>40</td>
</tr>
<tr>
<td>combined</td>
<td>35</td>
</tr>
<tr>
<td>atoll</td>
<td>30</td>
</tr>
</tbody>
</table>

15 June 2012 Thomas Bergauer (HEPHY Vienna)
Part 4: Quality Control on strip detectors

END