Moisture sensitivity of AC coupled silicon sensors

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on behalf of the ATLAS SCT collaboration
Introduction

◆ AC coupled silicon strip sensors used for the ATLAS SCT
  ● 86% made by Hamamatsu, including all the barrel region
    ■ These perform very well, without problem
  ● 14% made by CiS
    ■ These show some moisture sensitivity
      ◆ Implying more difficulty in commissioning parts of the endcap SCT, but OK for operation in ATLAS

◆ According to common specification given by SCT community (p-on-n technology), with design details optimised by each manufacturer

◆ Hamamatsu
  ● SiO₂ passivation
  ● metal strips are broader than implants (Field plate geometry)

◆ CiS
  ● SiON passivation
  ● metal strips are narrower than implants (Non-field plate geometry)
  ● Bulk oxidized (SCT inner endcap modules only) to improve radiation tolerance
Radiation tolerance

- Radiation load in the CERN LHC for the scheduled 10 y of operation
  - Neutrons: \( \leq 2 \times 10^{14}/\text{cm}^2 \)
  - Protons: \( \leq 3 \times 10^{14}/\text{cm}^2 \)

- After moderate irradiation \( n \rightarrow p \) type inversion
  - \( p/n \) junction moves from strip side to backside

- Required bias voltage to get full depletion including safety margin
  - Initially only 150 V
  - Decreasing to a low value at type inversion
  - From type inversion on increasing until 450 V

- Both fabricates (Hamamatsu and CiS) have shown in extensive irradiation studies to give satisfactory performance
Breakdown problems for CiS non-field plate sensors

- For the majority of the unirradiated non-field plate CiS sensors a strange IV behaviour was observed during module production
  - Problems ranging from a bit unpractical in use until bad
  - Problems almost not observed for the field plate sensors from Hamamatsu (<1%)

- Nature of the problems with CiS sensors
  - Early IV breakdown
  - Awkward and irreproducible IV curves
  - IV results did not correspond to measurements by manufacturer

- Continued studies show clear moisture dependence of CiS IV behaviour
  - wet (45 – 50% RH) gives good IV curve
  - dry (< 10% RH) may give breakdown
  - transition region (30 – 40 % RH) => strange results

- Breakdown only occurs at strip side
  - => no breakdown problem after type inversion
  - Confirmed by irradiation tests by MPI (Ladislav Andricek, MPI Halbleiterlabor, Munich)
  - => breakdown is no problem for operation in ATLAS

- Simple qualitative explanation of the phenomenon will be given
  - Based on ideas from Rainer Richter (MPI-Munich)
Properties investigated CiS silicon sensor

- Geometry: non-field plate
- Sensor type: W12 (inner endcap modules)
- Technology: p-on-n
- Additional oxygen dope: $10^{17}$/cm$^3$
- Orientation $<111>$
- Wedge shape 55.5 x 61 mm$^2$
- 768 AC coupled strips
- Average pitch 70.5 µm

- Tested until $V_{\text{bias}} = 450$ V
Two different sensor geometries in use at the SCT inner modules

**Field plate geometry**
- 70.5 µm
- AC coupled strip
- p+ implant
- n bulk <111>

**Non-field plate geometry**
- 70.5 µm
- AC coupled strip
- p+ implant
- n bulk <111> oxygenated
Two sensor geometries

Field plate geometry (Hamamatsu)

Non-field plate geometry (CiS)

Metal shields

Implant edge not

shields

implant

16

22

16

20

n_{bulk} <111>

\text{c(O)} = 5 \times 10^{15}/\text{cm}^2

\text{c(O)} = 10^{17}/\text{cm}^2
Two examples of moisture dependence for CiS non-field plate geometry

- In dry atmosphere (< 6% RH) breakdown
- In wet condition (RH = 45 – 50%) no problem
- $I_{bias}$ lower in dry atmosphere before breakdown
- Effect of lower $I_{bias}$ in dry atmosphere also observed for Hamamatsu sensors with the field plate geometry but here < 1% breakdown

A.Chilingarov, Lancaster University, talk on Vertex 2004, Menaggio, on 17 September 2004
Measurement in the transition region for CiS W12 sensors

- Measured at 39% RH => transition region dry/wet behaviour
- Breakdown sets in but disappears during measurement
Other examples of IV behaviour of CiS non-field plate geometry in dry atmosphere

- Altogether there is a wide spectrum of breakdown voltages ranging from ~ 50 V to 400 V
- But often strong correlation within the same batch

![IV behaviour of narrow strip geometry for two batches](image-url)

- RH = 3 - 6%

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Test box used for IV studies

- Small volume probe box
- Rapid moisture sensor
  - type SHT15 with $\tau = \text{few s}$ from Sensirion
- IV measurement with Keithley 2410
  - Steps of 10 V, ramping at 10V/s
  - 10 s waiting time prior to measurement

- Simple moisture control by water bubbler
- $\Rightarrow$ rapid switching of moisture level possible (< 1 min)
Study on the moisture dependence of the CiS non-field plate silicon sensors

- What do we see if we change from dry to wet while $V_{\text{bias}}$ is on?

- And when going back again?
  - Non breakdown situation
  - Breakdown situation

- Can we train a module by ramping $V_{\text{bias}}$ up in wet and subsequently switch to dry?

- Has an IV discharge impact on the sensor signal?
Switching dry to wet level when $V_{\text{bias}}$ is on

Non-breakdown situation

◆ $V_{\text{bias}}$ ramped up to 150 V in dry atmosphere
  - No breakdown yet for this module

◆ $I_{\text{bias}}$ increasing when switching to 50% RH

◆ But $I_{\text{bias}}$ does not return to original level when switching back to dry
Switching dry to wet level when $V_{\text{bias}}$ is on

- $I_{\text{bias}}$ initially in a discharge mode
  - $I_{\text{bias}} > 6 \mu\text{A}$
  - Normal: $< 1 \mu\text{A}$

- Discharge mode disappears instantaneously in moist atmosphere

- And discharge mode does not return when dry atmosphere is restored

- $\Rightarrow$ module is well capable of operating in dry atmosphere
Training by switching from wet to dry while $V_{bias}$ is on

- No breakdown if moisture level is switched at $V_{bias} = 150$ V instead of $V_{bias} = 0$

- => sensor is well capable of operating in a dry atmosphere if properly trained

![Memory effect of the moisture sensitivity](image-url)
What happens if we train at a lower voltage than 150 V?

=> For this sensor breakdown can be avoided if we keep it at 40 V background voltage
Impact of breakdown current on signal properties

- Module at low temperature (~ 0 °C)
  - => bulk current low
    - (« 1 µA)
  - V_{bias} = 150 V
- Decaying breakdown current
- Two noise characterisations done
  - immediately after biasing
    - => I_{bias} ~ 2 µA
  - 40 min later
    - => I_{bias} « 0.5 µA

I_{bias} during characterisation of module N027
Noise spectrum at 1st characterisation with a module using CiS sensors

- Discharge currents are not stable (stochastic process)
  - Number of huge noise spikes are visible indicating the breakdown spots
- Discharge currents are not evenly distributed across the surface but occur at a small number of critical points
Most spikes gone at 2nd characterisation
Schematic potential distribution at CiS non-field plate surface

- Dry $\Rightarrow$ non-conductive surface assumed
- Positive potential is induced by backplane across the interstrip surface
- High field occurs near edge of implant $\Rightarrow$ breakdown
Avoiding breakdown with field plate geometry of Hamamatsu

- Non conductive surface (dry)
- Metal strip capacitively coupled to implant
  - Implant shielded by metal => field near edge of implant reduced
  - No breakdown

\[ V \]

[Diagram showing field distribution]

\[ V \]

\[ 0 \]

\[ \text{low field} \]

\[ p^+ \text{ implant} \]

\[ \text{Al} \]

\[ \text{SiO}_2 \]

\[ \text{n bulk} \]
Effect of wire bonding for non-field plate sensors

- Measured in dry condition

- Wire bonding generally improves breakdown behaviour but often not sufficiently

- Improvement is minor for low breakdown voltages (< 100 V) but substantial for higher (>150 V) breakdown voltages

- Explanation: metal strips are no longer floating when bonded
Moisture film on insulator surface

- Moisture films of atomic thickness are formed on all insulators starting
  - Well known behaviour for insulators
  - Continuous decrease of surface conductivity for decreasing relative humidity †

- Moisture effect on surface conductivity material dependent (hygroscopic materials)
  - => There may be a difference between the SiO₂ passivation (used for field plate sensors)
    and the SiON passivation (used for non-field plate sensors)

- My own observation: dry air removes moisture film within seconds

† A.Chilingarov, talk on Vertex 2004, Menaggio, on 17 September 2004.
Partially depleted situation in **dry** atmosphere

- Assumed depleted area for **non-field plate** geometry
- Surface not conductive $\Rightarrow$ positively charged by induction
  - Positive space charge in SiO$_2$ layer neglected
  - Undepleted zone between strips
  - High interstrip capacitance (A.Chilingarov, talk on Vertex 2004, Menaggio, on 17 September 2004)
  - Lower bias current
  - For non-field plate geometry high field at edge of implant $\Rightarrow$ **Breakdown**
Partially depleted in **moist** atmosphere

- Assumed depleted area for non-field geometry
- Surface conductive $\Rightarrow$ no external charge
  - Fully depleted zone between strips $\Rightarrow$ low interstrip capacitance
  - Higher bias field $\Rightarrow$ higher bias current
  - Reduced field at edge of implant $\Rightarrow$ **No breakdown**
- When switching from wet to dry then the negative charge on the insulated surface is preserved
  - $\Rightarrow$ we do get the same charge distribution back if we test $V_{\text{bias}}$ on a later moment as long as the sensor is permanently kept in a dry atmosphere
Summary and conclusions

- Sensors with early breakdown can be trained by applying bias voltage in a moist atmosphere followed by switching to dry while $V_{bias}$ is on.

- Breakdown currents show themselves as a small number of high spikes in the noise spectrum.
  - => discharges probably confined to small spots.

- The lower bias current in a dry atmosphere compared to moist for both detector geometries can be explained from reduced field strength in the dry atmosphere.

- Observed breakdown phenomena in CiS sensors are unpractical in during commissioning of the ATLAS SCT endcaps but do not affect operation in the ATLAS SCT.