

Sensor Quality Assurance for the ATLAS SCT

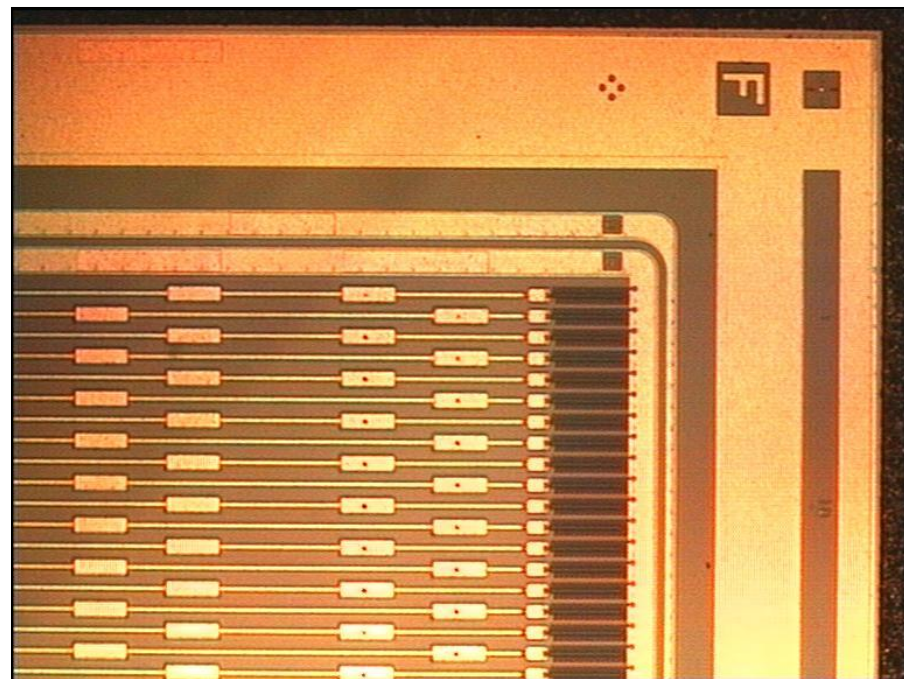
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Workshop on Quality Issues in Current and Future Silicon Detectors
CERN 3-4 November 2011

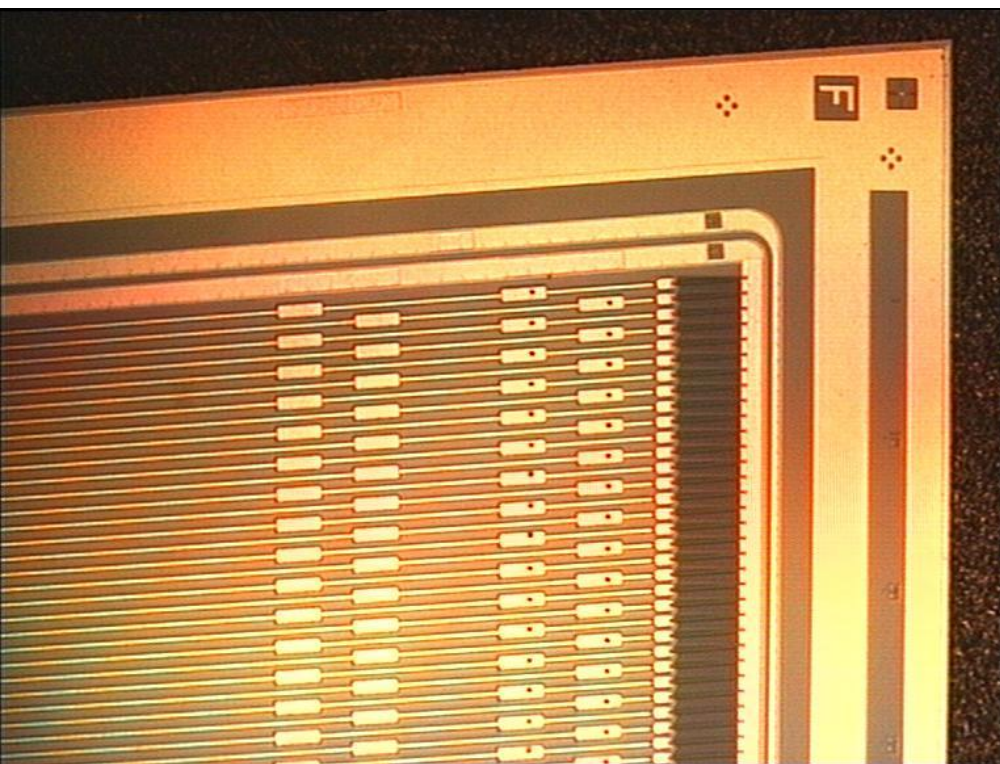
The Sensors
From Prototyping to Production
QA Strategy
Special Techniques & Procedures
Problems & Issues
Irradiations
Summary & Final Comments

The SCT Sensors

- Single sided p-on-n
- $\langle 111 \rangle$ substrate, $285\mu\text{m}$ thick
- 768+2 AC-coupled strips
- Polysilicon ($1.5\text{M}\Omega$) Bias
- Strips reach-through protection $5\text{-}10\mu\text{m}$
- Strip metal/implant widths $20/16\mu\text{m}$

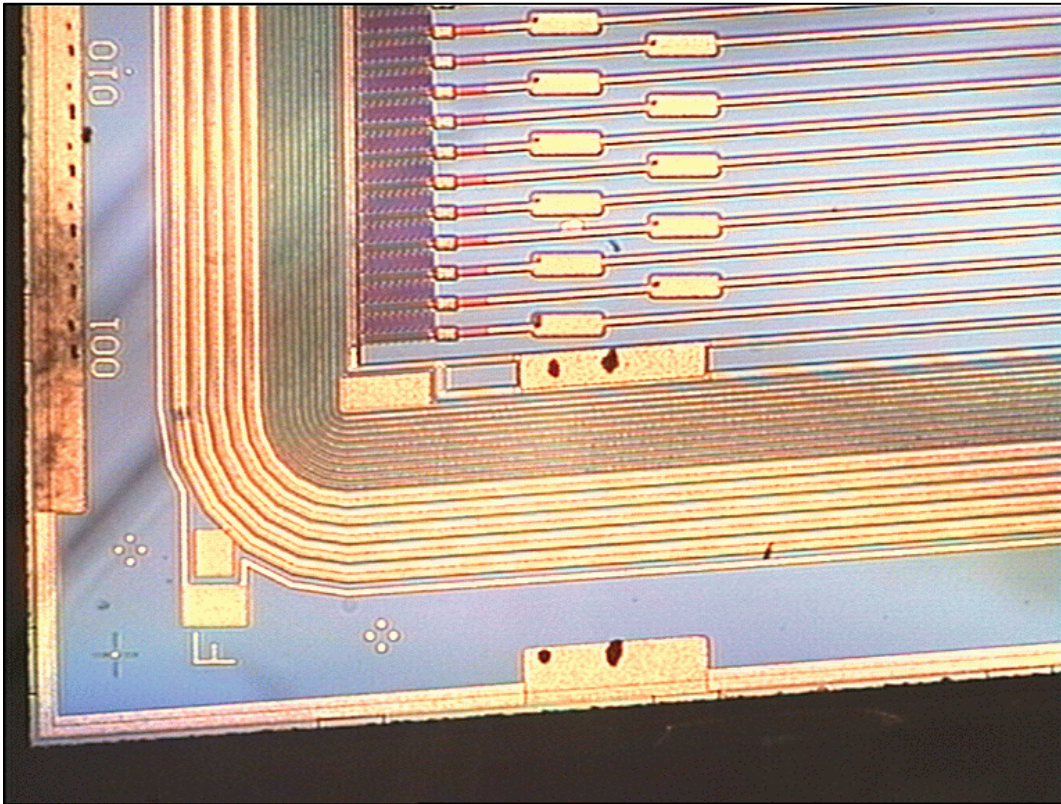


- 8448 barrel sensors
- $64.0 \times 63.6\text{mm}$
- $80\mu\text{m}$ strip pitch
- all supplied by Hamamatsu



- 6944 wedge sensors
- $56.9\text{-}90.4\mu\text{m}$ strip pitch
- 5 flavours
- 82.8% Hamamatsu
- 17.2% CiS

The SCT CiS Sensors – “Same spec, different species”



	Hamamatsu	CiS
Bias Resistors ($1.5\text{M}\Omega$)	Polysilicon	Implant
Strip metal/implant widths (μm)	20/16	16/20
Guard design	Single floating	Multi-guard
Barrels supplied	8448	0
Wedges supplied	6944	1196

From Prototyping to Production

Prototyping (1996-1999)

- The many silicon groups in ATLAS developed prototypes with their favorite manufacturer

Qualification (early 1999)

Only those manufacturers that had supplied *several* prototypes (nominally 10) with identical processing that gave consistent characteristics and were within all ATLAS specifications before and after irradiation were invited to bid during the tendering process.

Tendering (Summer 1999)

Two manufacturers (Hamamatsu and CIS) were awarded contracts to supply all sensors

PreSeries Production (Jan-Apr 2000)

~5% of total delivery to demonstrate that the quality of the produced sensors will be maintained, with characteristics consistent with the qualified sensors; the ability to comply with delivery schedules; the ability of both the manufacturer and ATLAS to effectively implement the QA procedures and use the database; compatibility of QA data between the manufacturer and different ATLAS institute; the effectiveness of packaging, labelling, transportation and other procedural and QA issues.

Production (Apr 2000-Aug 2002)

Manufacturers were contractually obliged to deliver detectors in regular monthly shipments, distributed to the 7 module-building clusters in ATLAS:

- CE: Freiburg, **MPI**, Nikhef, Prague, Potvino
- UK-V: Glasgow, **Lancaster**, Liverpool, Manchester, RAL, **Sheffield**, **Valencia**
- CS: Australia, CERN, Cracow, Geneva, Ljubljana, MSU, **Prague**, **MPI**
- Nordic: **Bergen**, Oslo, Uppsala
- Japan: **Hiroshima**, **Tsukuba/KEK**, Kyoto edu, Okayama
- USA: LBL, UCSC
- UK-B: Birmingham, **Cambridge**, QMW, RAL

red indicates sensor QA institute

Each of the module-building clusters had one or two institutes that received the detectors and performs all the QA. The receiving ATLAS institute had three months to perform all QA tests before payment is due.

Eg: Schedule at Cambridge:

- *total delivery: 2500 Hamamatsu barrels, monthly batch size: 120.*

QA Strategy

The Manufacturer

Following the process of qualification of a detector from a particular manufacturer, it was the responsibility of the manufacturer to ensure no changes in processing occur during production that may modify:

- any parameters relevant to ATLAS specifications
- any pre- and post-irradiation electrical behaviour

from that observed during the qualification program.

ATLAS

Verification: a visual examination and IV measurement on every detector as the basic check on quality. On a subset of detectors (~5%), an extensive evaluation of detector characteristics was performed as a check on processing consistency and as a verification of the manufacturers tests.

In parallel, small (~1%) samples of sensors throughout production were regularly irradiated and tested to ensure that the post-irradiation behaviour of sensors remained consistent with those in the qualification process.

QA Acceptance Criteria

The acceptance criteria for both mechanical and electrical sensor parameters are listed in the backup slides

Not all properties are easily quantifiable, and some may be quantified somewhat arbitrarily. However, it is important to state all possible problems and to set reasonable limits where possible to ensure that manufacturers are contractually obliged to take back detectors that are mechanically or electrically defective

QA Actions

Exact instructions for QA institutes defined in FDR/99-7 available at
<http://www.hep.phy.cam.ac.uk/~silicon/docs/detectortests.html>

1. General Actions

Action or Measurement	Manufacturer	SCT all	SCT 5%
Serial number in barcode, in database and on scratch pads	✓	✓	
Visual inspection	✓	✓	
Sensor thickness	✓		✓
IV Data	✓ (350V)	✓ (500V)	
Current stability (24hr @ 150V)	✗		✓
Depletion Volts	✓		✓

QA Actions - Strips

Sensor Property	Manufacturer	SCT all	SCT 5%
List strips with oxide pinholes at 100V	✓		✓
List strips with strip metal opens	✓		✓
List strips with metal shorts to neighbours	✓		✓
List strips with defective bias resistors	✗		✓
List strips with implant breaks	✗		✓
Bias Resistor Range	✓		✓

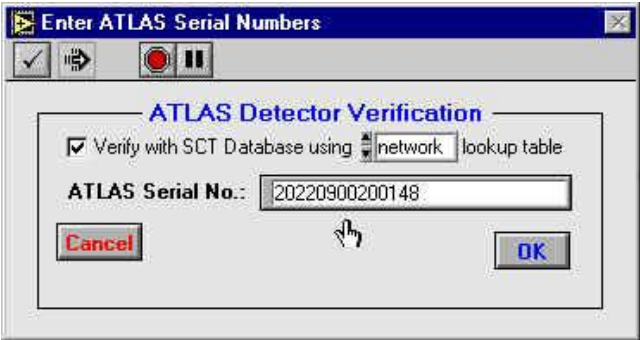
Key Points in SCT QA

- Central database for accessibility of data and information
 - Used by both SCT and manufacturers
- Precisely defined procedures
 - With the right people for the job, following exactly the same procedures
- Development of special techniques and tests
 - Frames to minimise handling and risk for those ~5% of sensors subjected to intense testing
 - The “full strip” test

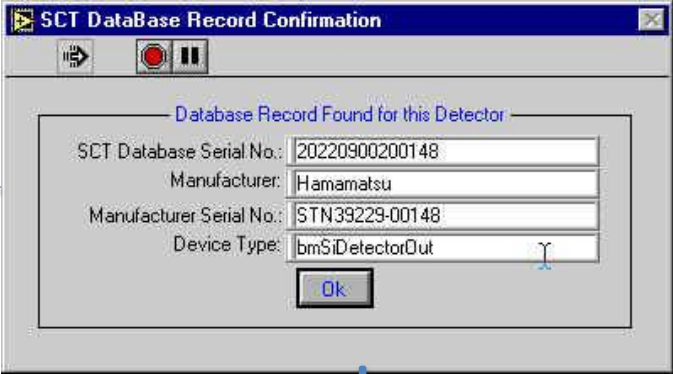
SCT Production Database

- ORACLE database developed and hosted by Geneva University
 - Direct write access from all QA institutes AND manufacturers, via java uploader utilities (provided by Geneva)
 - Labview s/w responsible for tests and uploads closely coupled with the database
 - Centrally provided java uploader tools (invoked by locally written labview s/w) ensures validity of data entries and formats
 - Direct read access with extensive java interface (provided by Cambridge)
 - Essential to develop the right tools for easy access to data in the format that people actually need

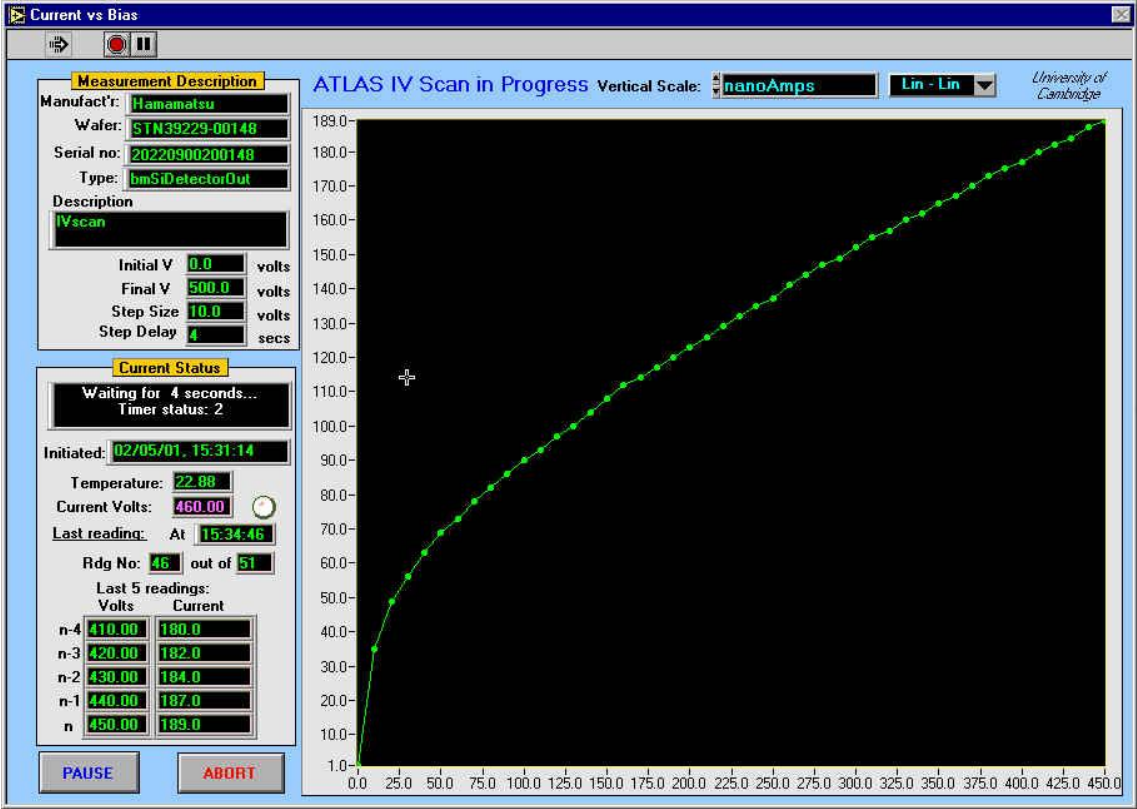
Example: IV scan for barrel sensor 20220900200148



1. Authentication of serial number



2. Confirmation (or otherwise!) of valid serial number



3. IV test performed

CreateIVscanfile.vi

Creating IVscan Database file

Detector Serial No.: 20220900200148

Operator: DR

Location: Cambridge

Date: 02/05/2001

Temperature: 22.88

I@150V: 0.11

I@350V: 0.17

Run Number: A0000225.dat

Optional updates

PASS

Upload raw datafile? ☒

Create IV Plot Image? ☐

Select this box if there was a problem: ☐

Comments: [Add Comment](#)

Radiation Dose: 0.00

Anneal time: 0.00

[Quit](#) [Create file](#)

4. On completion, local raw data file is saved, and database entries are confirmed to operator, who is prompted for optional entries (comments, problems etc)

```
%NEWTEST
SERIAL NUMBER : 20220900200148
TEST MADE BY : DR
LOCATION NAME : Cambridge
TEST DATE : 02/05/2001
PASSED : YES
PROBLEM : NO
RUN NUMBER : A0000225.dat
%DetIVscan
Temperature : 22.88
I LEAK 150 : 0.11
I LEAK 350 : 0.17
%Test RawData
FILENAME : Z:\sctdb\rawdata\RA3071658984.dat
```

5. Local database file is created and “swept” into database

Read-only Database Interface (Cambridge)

Version 10.07

File Tools Preferences

SCT Database Interface

Stocks Items Shipments **Test Data**

Sensors ASIC Wafers ASICs Barrel Modules EndCap Modules SctRodDaq

Detector Type Selection

Manufacturer: Hamamatsu Type: Barrel SiDet Outer Institute: Cambridge

Serial Nos From: 1 To: 99999 Current Locn: Anywhere

Manufacturer Data **ATLAS Data**

Select ATLAS Test Data

☐ Summary ☒ IV ☐ Visual ☐ Defects

☐ Depletion ☐ I Stability ☐ Coupling Cap ☐ Bias Resistance

☐ Metal Resistance ☐ Interstrip Cap ☐ Include manufacturer data if possible?

Order results by: Serial Number

List Data Overall Test Status

Downloadable Java executable, can access Geneva DB from any networked computer

Eg visual inspections, listed in a spreadsheet

Query Results

Please right-mouse click on a row to view the available options (if any) for further information.

Query Result (3315 records):

Serial Number	Date	Location	Status	Remarks	Pictures
20220900209181	"	"	"	"	Implant defect at edge, r...
20220900209182	06-JUN-02	Cambridge	Ok	Edges and resistors insp...	
20220900209183	06-JUN-02	Cambridge	Ok	Light chipping along edg...	
20220900209184	06-JUN-02	Cambridge	Ok	Edges and resistors insp...	
20220900209185	06-JUN-02	Cambridge	Ok		Grazing, strips 95-105
20220900209186	06-JUN-02	Cambridge	Ok	Edges and resistors insp...	
20220900209187	06-JUN-02	Cambridge	Ok		
20220900209188	07-JUN-02	Cambridge	Ok	Edges and resistors insp...	Marks across top left han...

Save spreadsheet Close

Serial Nos From: 1 To: 99999 Current Locn: Anywhere

Manufacturer Data ATLAS Data

Select ATLAS Test Data

☐ Summary ☒ IV ☐ Visual ☐ Defects

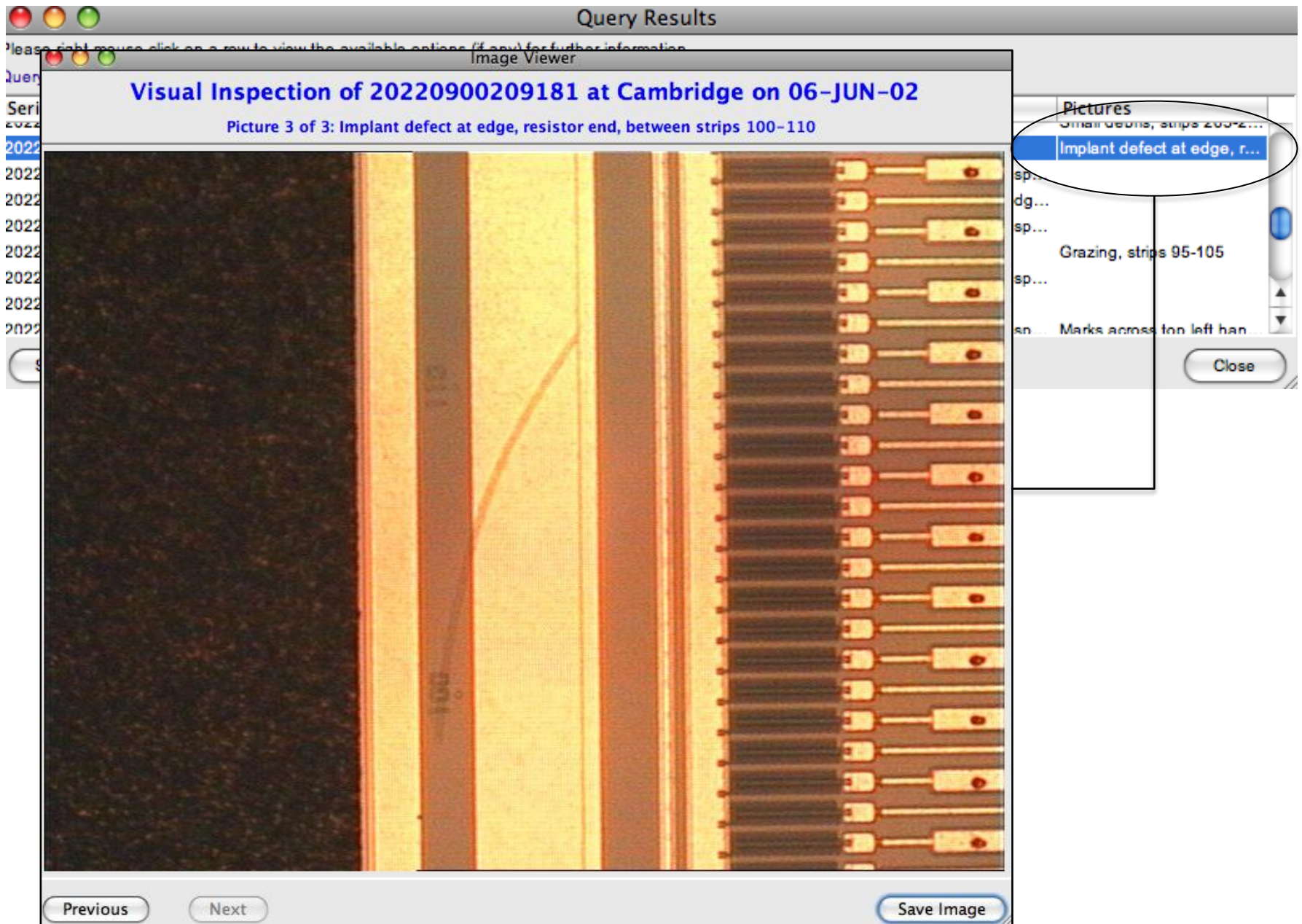
☐ Depletion ☐ I Stability ☐ Coupling Cap ☐ Bias Resistance

☐ Metal Resistance ☐ Interstrip Cap ☐ Include manufacturer data if possible?

Order results by: Serial Number

List Data Overall Test Status

Popup options from spreadsheet, eg to view uploaded images



Tests on Every Sensor

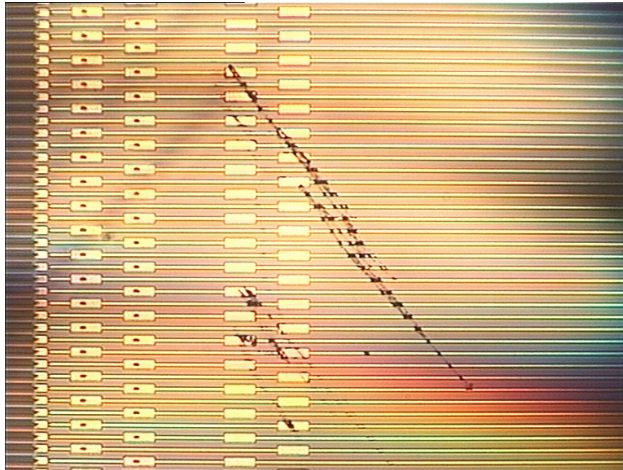
- Sensor placed on chuck
- Aligned
- Full visual inspection with automated chuck movements
 - Every part of sensor inspected under microscope
- Chuck raised to needle, IV performed
- 10-15 minutes in total

Needs precisely defined control software, and a rather special “breed” of operator: dedicated, conscientious, attention to detail and a certain level of stamina!

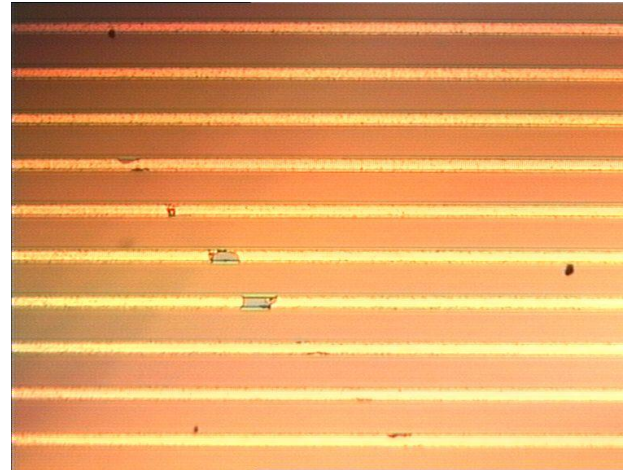
Visual Inspections

Full sensor area scanned under a microscope (automated probestation). Sensor must be free from “gross defects and scratches” and edge chips must not exceed 50µm. But what is a “gross defect”?

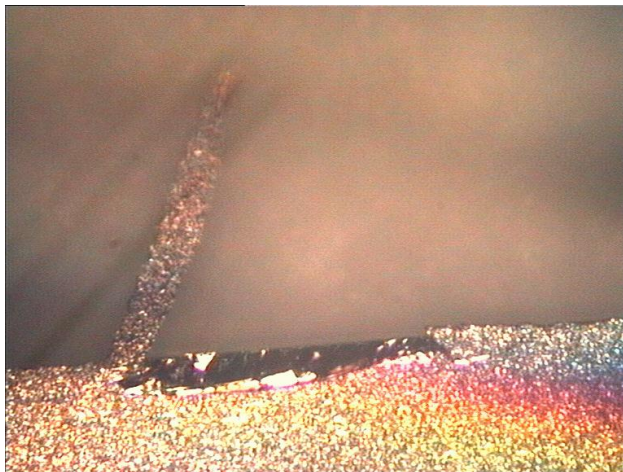
Requires consistent judgement by operator, and agreement with manufacturer:



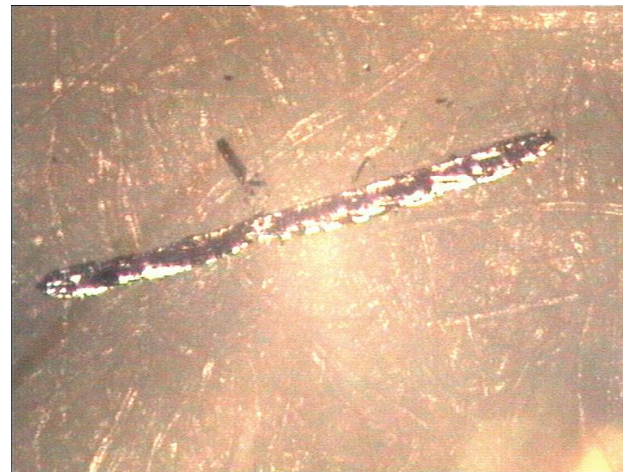
REJECT



ACCEPT

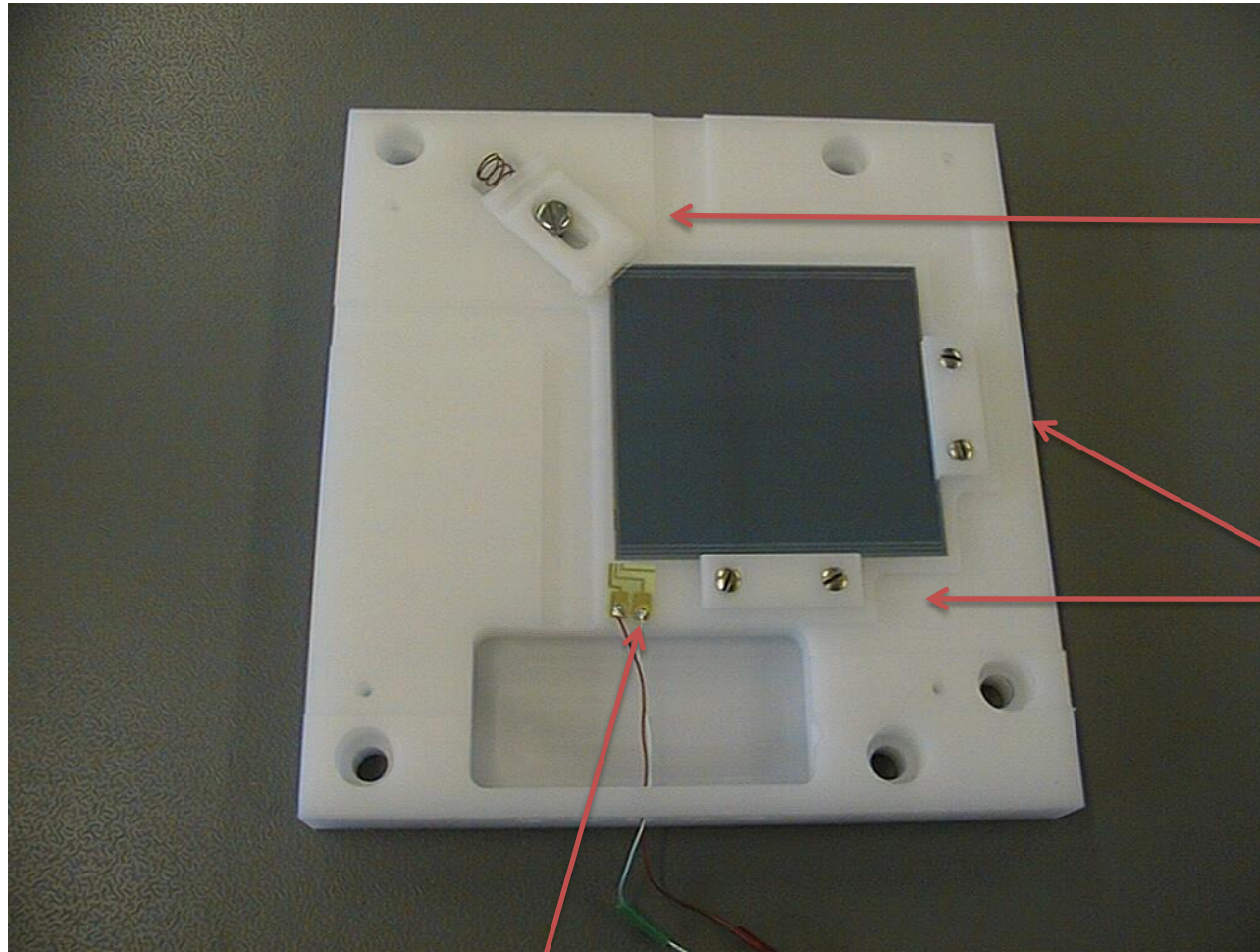


Rear Edge Chip REJECT



Debris in packaging REJECT

Sensor Support Frame for full tests

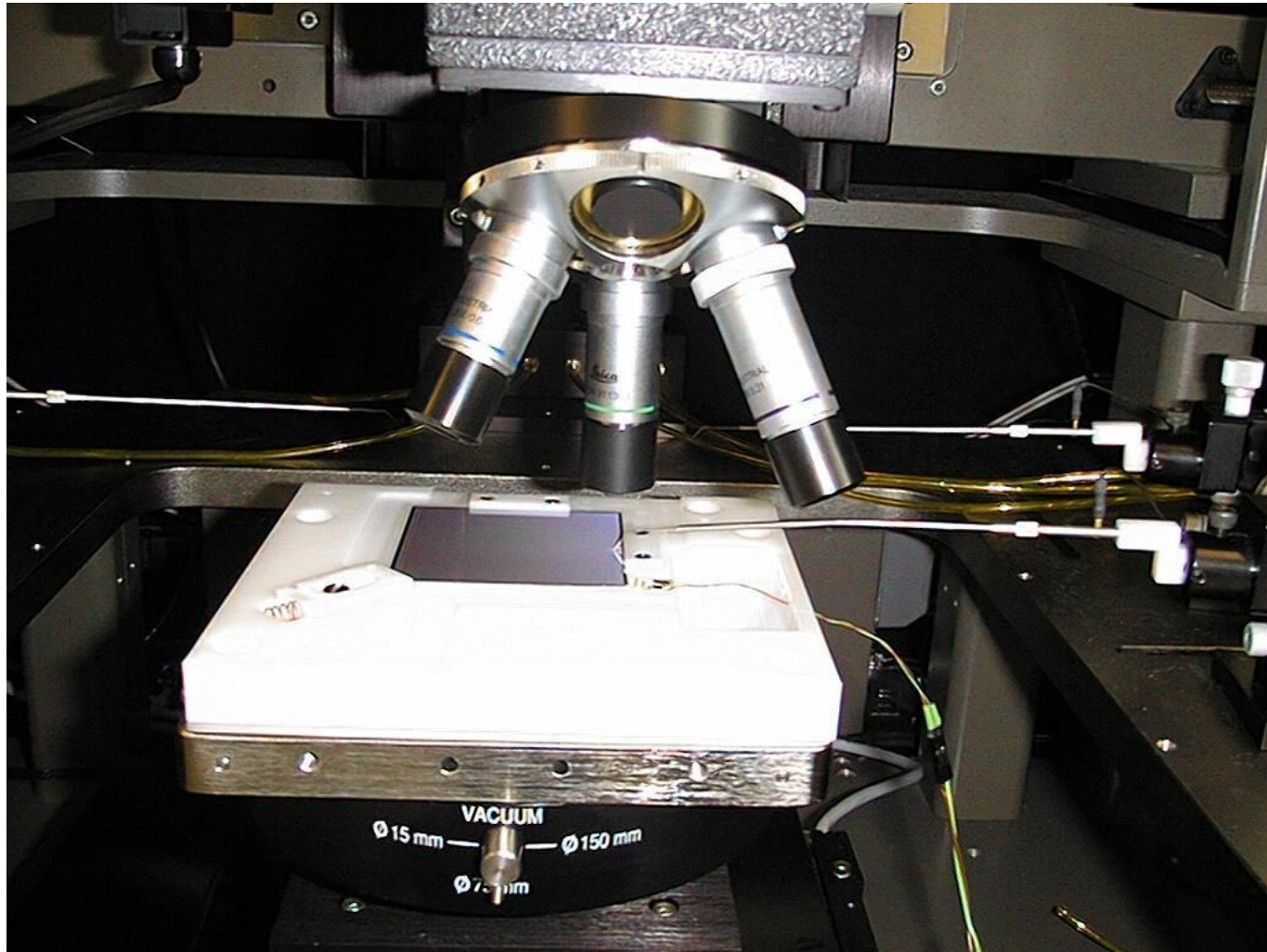


Delrin clamp with
spring loading

Delrin blocks

Bias Connection (two bonds)

Frame supported sensor on chuck during sensor strip test



Machining tolerance of delrin block means sensor is perfectly flat
O-ring on underside of block ensures grip by chuck vacuum

Leakage current stability tests of multiple sensors in parallel (using Keithley with switching matrix)



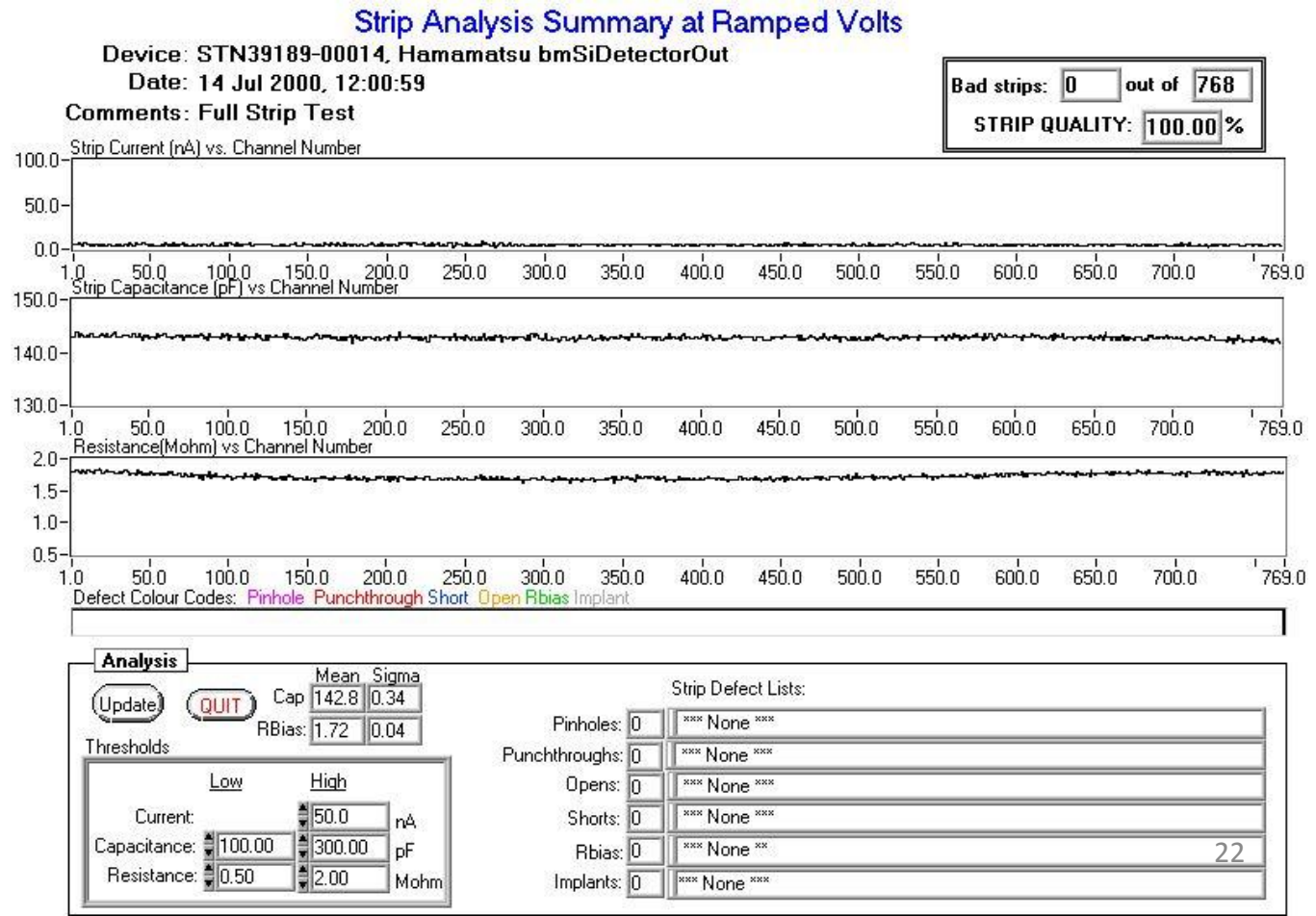
Full Strip Test

The “flagship” test for highlighting strip side processing defects

With the sensor partially biased (to ~50% of full depletion voltage), step through every strip to probe the strip metal. For every strip, apply 100V across strip dielectric to determine robustness of dielectric, then return strip metal to ground and model CR in series on the measured impedance @100 Hz between strip metal and bias rail

$$C = C_{\text{coupling}} \quad R = R_{\text{bias}}$$

Sensitive to any strip defect, and any general processing defect that may effect operation of sensor, and yields the bias resistance and coupling capacitance for every strip.



Strip Analysis Summary at Ramped Volts

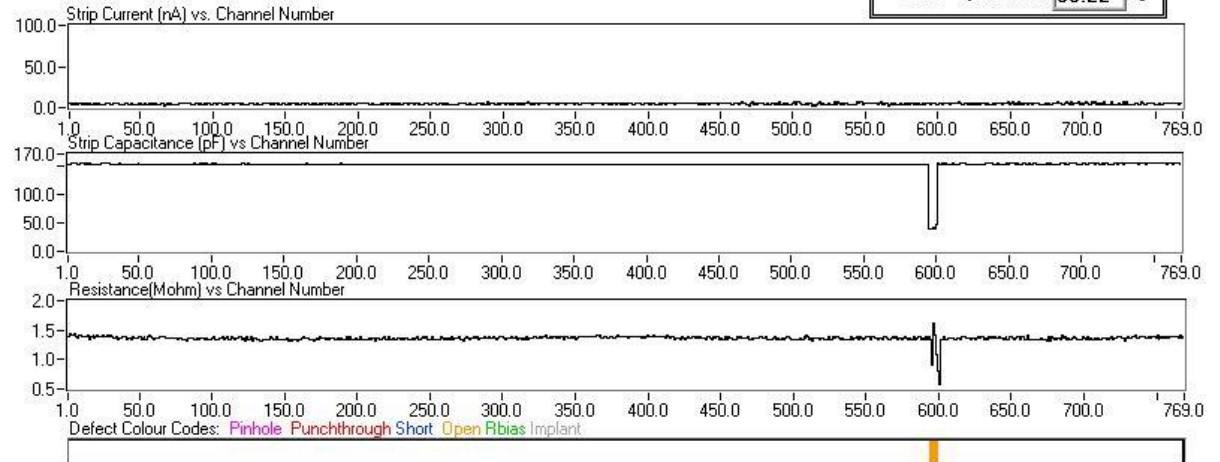
University of Cambridge

Device: STN39229-00149, Hamamatsu bmSiDetectorOut

Date: 09 Aug 2000, 15:54:06

Comments: Full Strip Test

Bad strips: 6 out of 768
STRIP QUALITY: 99.22 %



Strip Defect Lists:	
Pinholes:	0 None
Punchthroughs:	0 None
Opens:	6 595, 596, 597, 598, 599, 600
Shorts:	0 None
Rbias:	0 None
Implants:	0 None

Example 1

Detection of resistor breaks

Example 2

Detection of resistor processing defects

Strip Analysis Summary at Ramped Volts

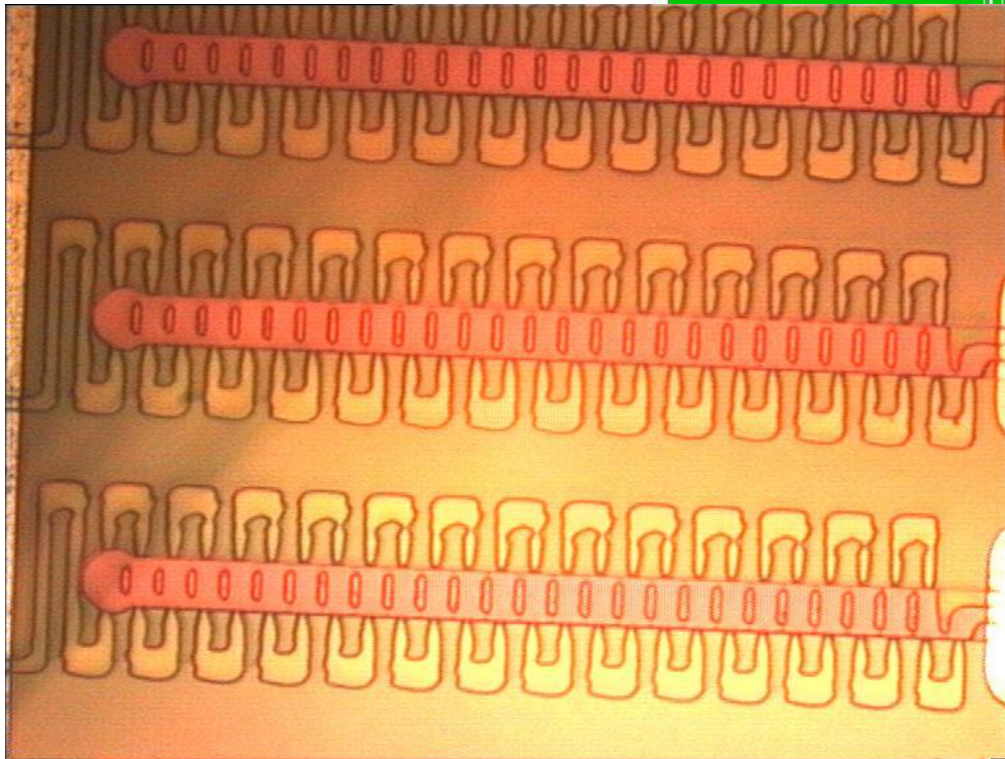
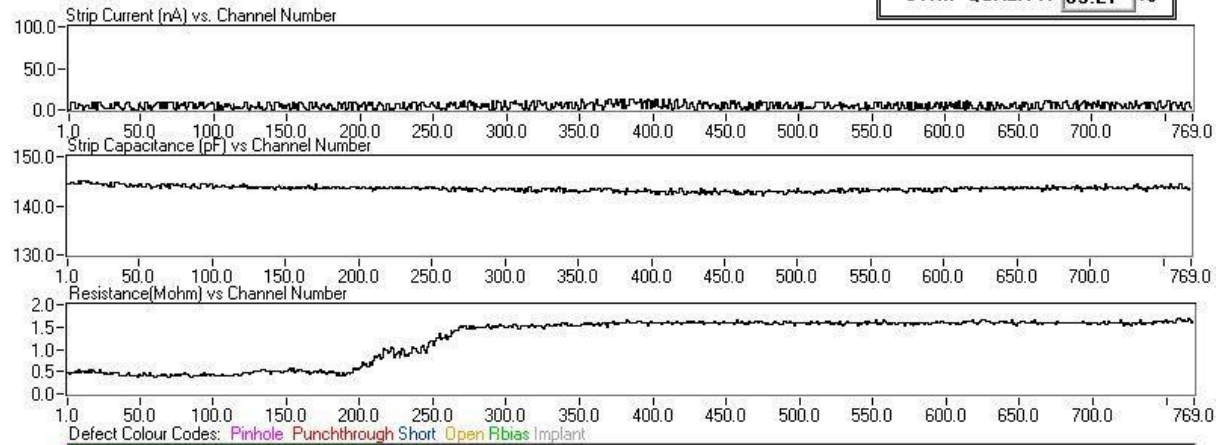
University of Cambridge

Device: 20220900200202, Hamamatsu bmSiDetectorOut

Date: 01 Nov 2000, 11:04:36

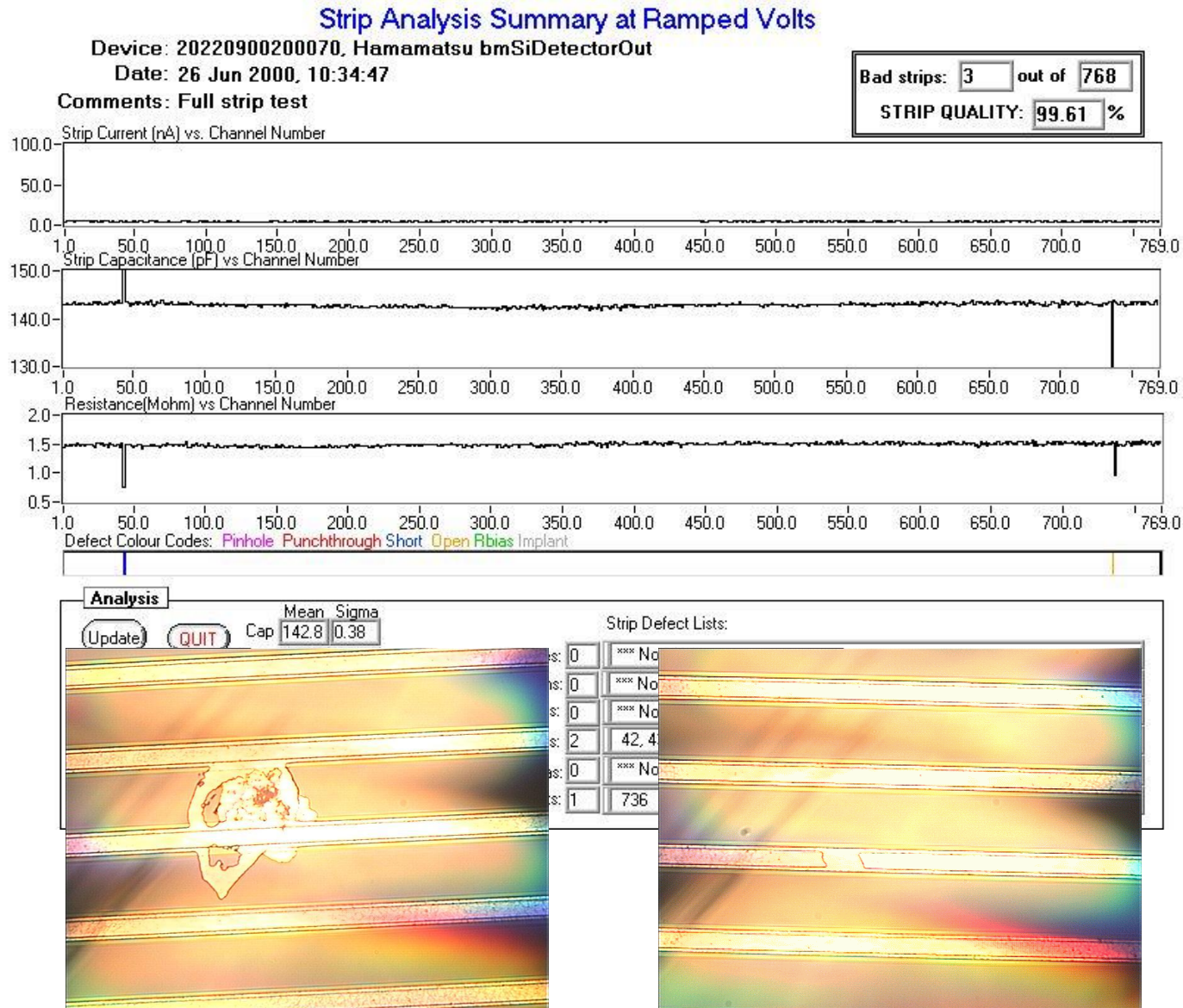
Comments: Full Strip Test

Bad strips: 236 out of 768
STRIP QUALITY: 69.27 %



Strip Defect Lists:	
Pinholes:	0 None
Punchthroughs:	0 None
Opens:	0 None
Shorts:	0 None
Rbias:	236 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,
Implants:	0 None

Example 3: Detection of metals shorts and strip implant breaks



Early Hamamatsu Issues

- The overall quality and consistency of the Hamamatsu sensors were outstanding, with a negligible number rejected for use by SCT.
- Two issues identified during preseries stage, never observed again during production:
 - Poorly diced edges, with Si debris in sensor envelopes
 - Deformed polysilicon resistors, unnoticed until identified by full strip test

Hamamatsu made QA easy – once early mistakes were acknowledged and rectified, sensors were delivered in their thousands with almost identical properties

The CIS Leakage Current Problem

- It became clear that the CIS SCT sensors were very sensitive to humidity
 - A significant subset displayed poor IV and early (<150V) breakdown in dry conditions
 - Need humidity to maintain a 'healthy looking' IV
 - Became more apparent during module tests which (unlike sensor QA) were typically conducted in nitrogen environment
 - Problem identified as microdischarge from strips, due to lack of field plate (strip metal narrower than implant)
- As this became an issue rather late in the delivery program, SCT adopted a pragmatic strategy:
 - Only accept sensors with no sign of breakdown below 150V in dry air
 - OK for the short term, and then strip micro-discharge becomes less relevant after type inversion

CIS Leakage Current Problem

Consequences during SCT operation

- We have had a small but significant (~30) number of modules which have developed anomalously high leakage currents this year
- Almost all were constructed with CIS sensors, and all showed IV breakdown above 150V during production QA tests
- We believe that oxide charge buildup from ionising radiation is shifting the breakdown voltage downwards
 - Decreasing HV and increasing current limits means we can keep operating these devices with full efficiency so far

Irradiation Program

A small (~1%) sample of sensors were selected regularly throughout the production deliveries for irradiation with 24 GeV/ protons to $3 \times 10^{14} \text{p.cm}^{-2}$ at the T7 irradiation facility at the PS. During irradiation, sensors were chilled in nitrogen to -8°C , and biased at 100V with all strip metals grounded. The irradiation took typically 6-10 days, and following irradiation the detectors were annealed for 7 days at 25°C to bring them to the minimum of the anneal point.



Strips wire bonded to 6cm/12cm pitch adaptors.

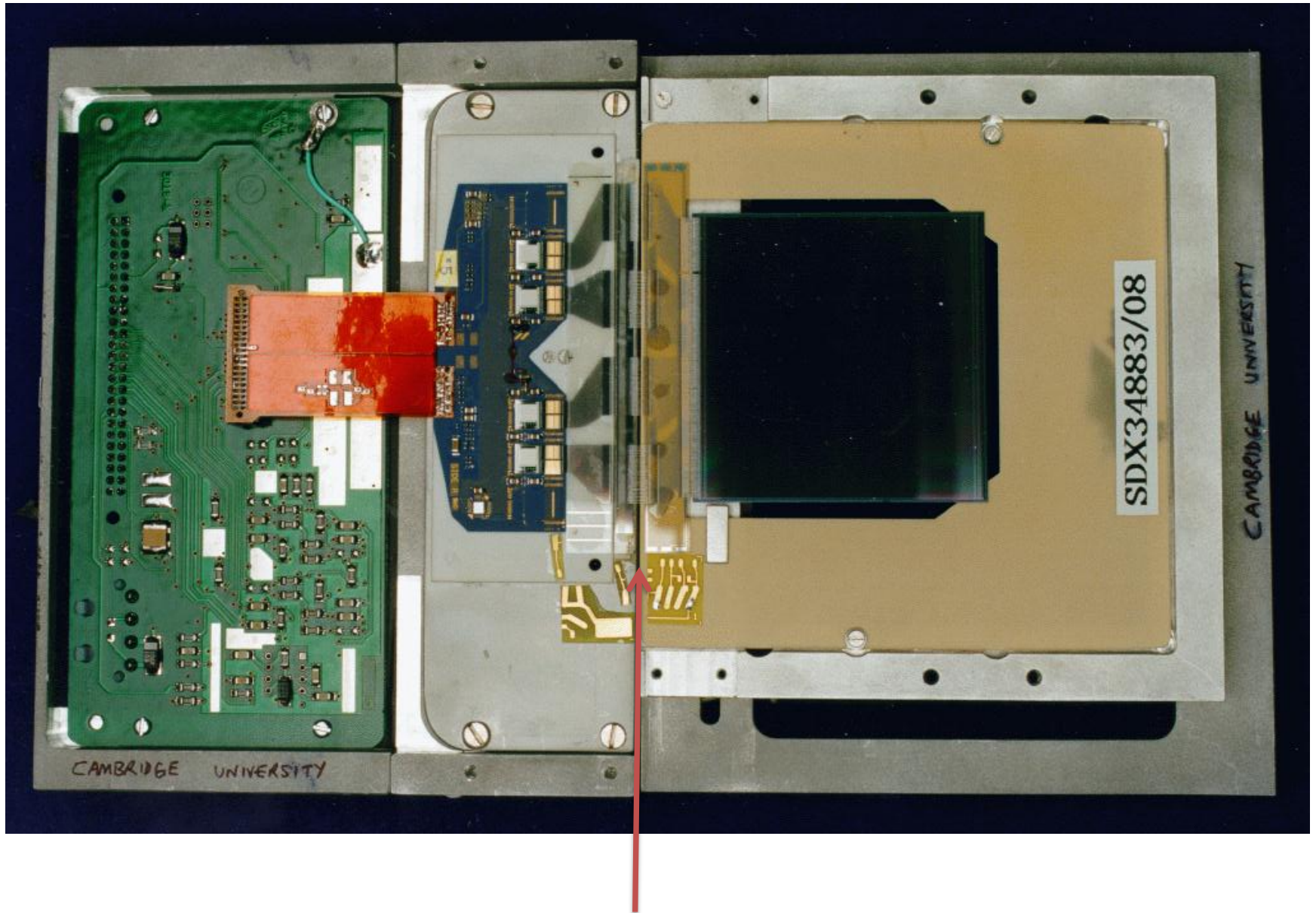
Bias and gnd bonded via Al tab.

Ceramic frame for sensor irradiation, sensor spot glued in all 4 corners.

Pre- and post-irradiation assembly and tests mostly by Cambridge

Post-Irradiation acceptance criteria listed in backup slides

Strip noise measurements of irradiated sensors



Rebondable interface

Bonding Details – Remountable sensors

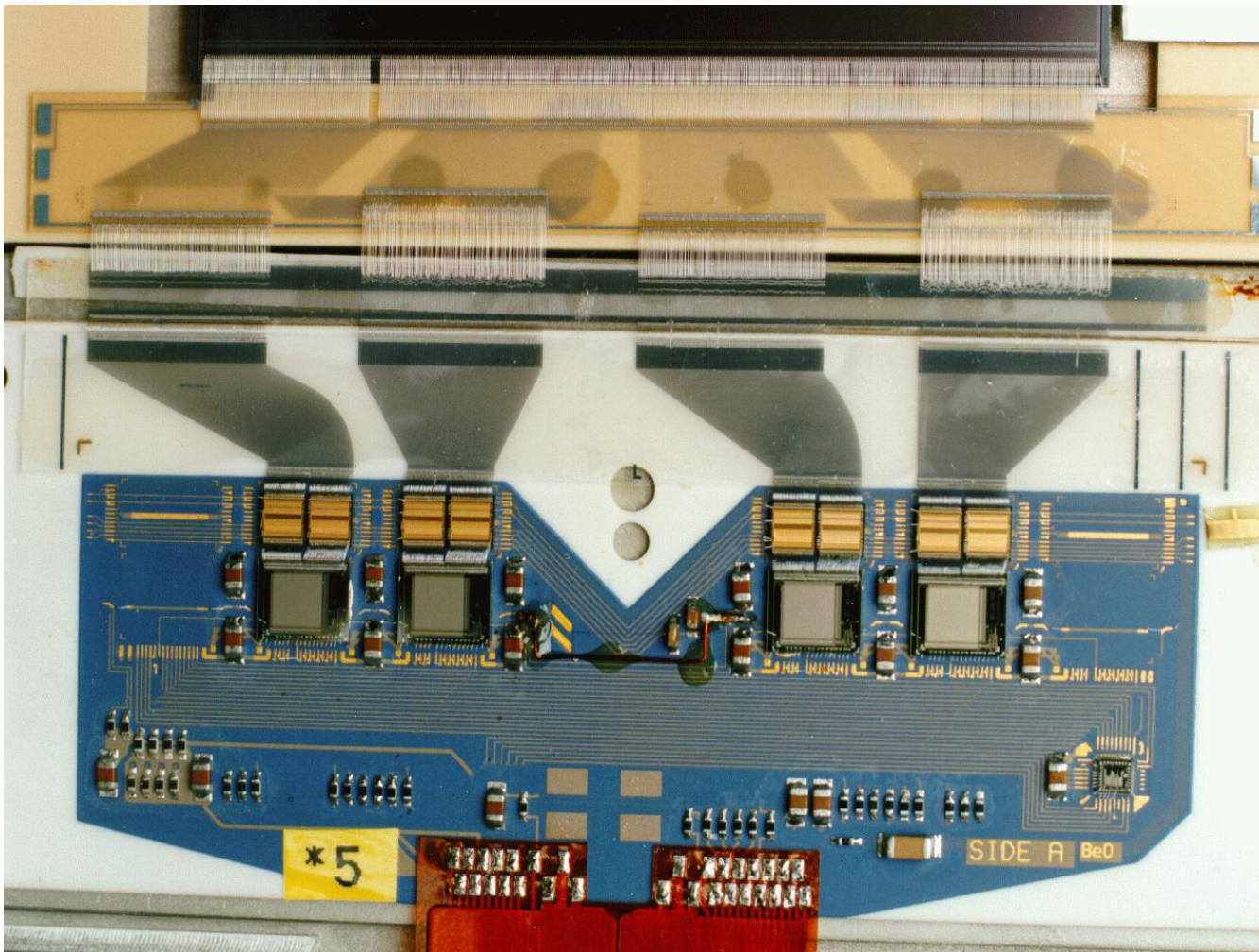
Effective strip length connected to chip:

6cm

12cm

6cm

12cm



6/12cm adaptor

Replaceable
intermediate
adaptor
(100µm pitch)

Cambridge

Summary

- The ATLAS SCT sensor QA was a major success
- Key factors:
 - Definition of all possible mechanical and electrical characteristics resulted in a “no quibbles” relationship with the vendors
 - Very closely defined testing procedures adopted by the entire community
 - Full strip test played an important role
 - Responsible for discovery of polysilicon processing defects in preseries
 - Pre-series production resolved all QA issues at an early stage
 - Globally accessible database with the optimal tools for data insertion and reporting
- No sensor issues (excepting the CIS leakage currents) have impacted on SCT operations
- Few aspects will change with a future SCT production

Final Comments

- IV testing in ambient clean-room humidity meant the CIS IV issue was not immediately apparent
 - Better preproduction qualification procedures
 - Establish small production sampling of IV in N₂
- Visual inspections were very time and labour intensive, but any significant defects were visible by eye
 - Very useful though to correlate channel noise issues with images of strip defects in the database!
- Irradiations gave confidence in consistency of sensor characteristics after ~1.5x lifetime fluence
 - But have yielded no clues of the anomalies we are currently observing at short term fluence levels
- Baby detectors were intended to be used for irradiations, but lack of correlation with large sensor behaviour meant they were not used
 - Useful for R&D, but not for production tests

Backup Slides

Acceptance Criteria – Mechanical Properties

Not all mechanical properties are easily quantifiable, and some may be quantified somewhat arbitrarily. However, it is important to state all possible problems and to set reasonable limits where possible to ensure that manufacturers are contractually obliged to take back detectors that are mechanically defective

- **Quality of cut edges:** Edge chipping to be avoided, no chips or cracks to extend inwards by $> 50\mu\text{m}$
- **Damage and Defects:** Device free from scratches and other defects that ATLAS judges could compromise the detector performance during the lifetime of the experiment. The criteria were mainly established in collaboration with the manufacturer during the pre-series production, and may continue to evolve.
- **Thickness:** $285 \pm 15\mu\text{m}$
- **Uniformity of thickness:** $10\mu\text{m}$
- **Flatness:** Sensors must be flat to $200\mu\text{m}$ when unstressed
- **Mask alignment tolerance:** $< 3\mu\text{m}$ misalignment
- **Bond Pads:** Metal quality, adhesion and bond pad strength to be such as to allow successful uniform bonding to all readout strips using standard bonding techniques.
- **Alignment fiducials:** Must be visible

Acceptance Criteria – Electrical Properties

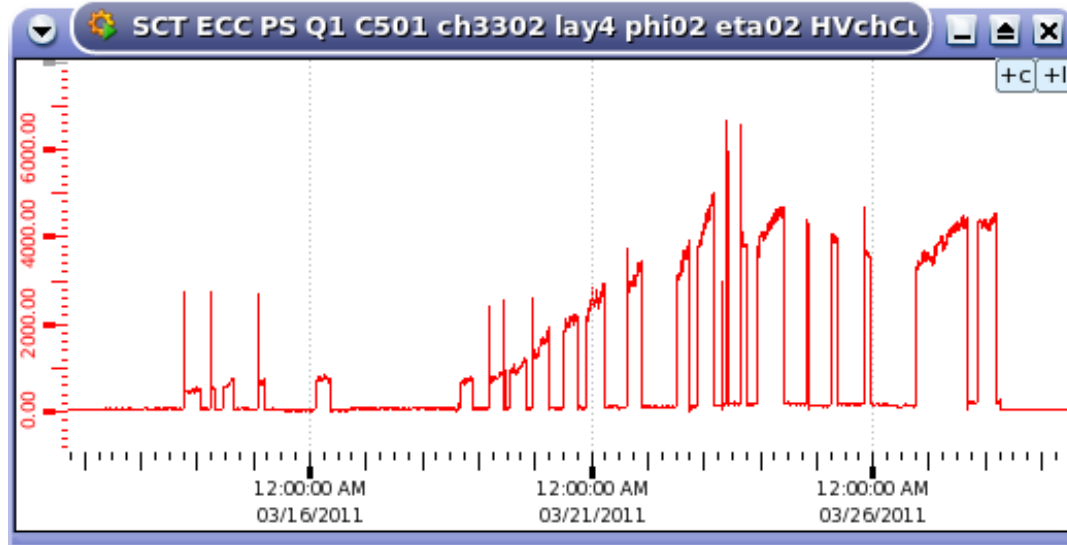
Property	Specification
Leakage Current at 20°C	$<6\mu\text{A}@150\text{V}$, $<20\mu\text{A}@350\text{V}$
Leakage Current Stability in Nitrogen	$<2\mu\text{A}$ deviation over 24hr
Depletion Voltage	$<150\text{V}$
R_{bias}	$1.25\pm 0.75\text{M}\Omega$
C_{coupling} (@100kHz)	$>20\text{pF/cm}$
$C_{\text{interstrip}}$ (@100kHz @150V bias)	$<1.1\text{pF/cm}$
$R_{\text{interstrip}}$	$>2 \times R_{\text{bias}}$ at operating Bias
Strip metal resistance	$<15\Omega/\text{cm}$
Strip quality	$>99\%$ good strips per sensor

Acceptance Criteria – Post Irradiation Properties

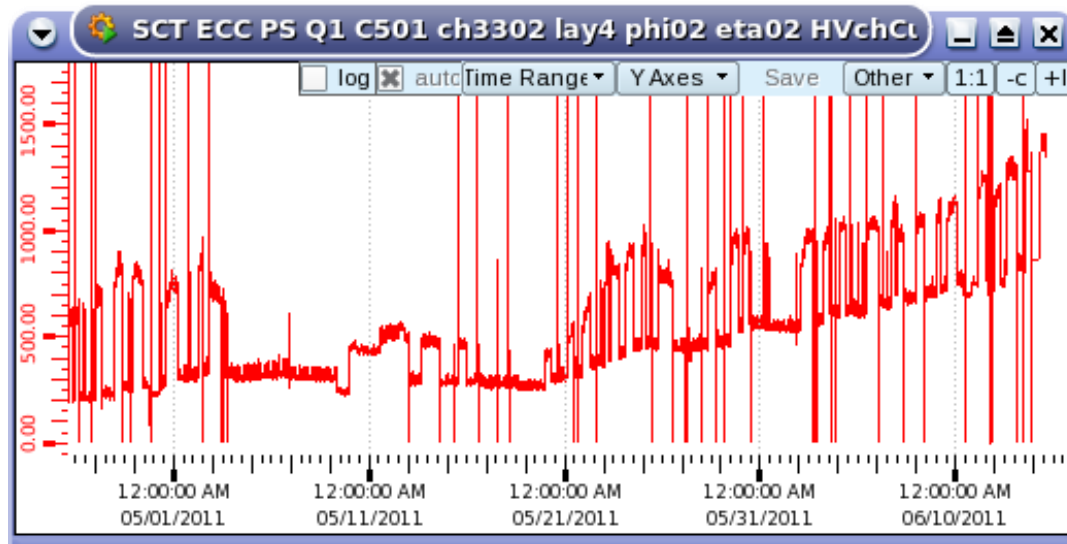
After $3 \times 10^{14} \text{p.cm}^{-2}$ and 7 days equivalent annealing at 25°C

Property	Specification
Leakage Current during irradiation	Increases in stable and monotonic fashion
Leakage current	$< 250 \mu\text{A}$ up to 450V at -18°C
Leakage current stability	Vary by no more than 3% over 24 hours at 350V at -10°C
Strip defect count	Within pre-irradiation acceptance level
Rbias	Within pre-irradiation acceptance level
Charge Collection with SCT128A	Max operating voltage for >90% of achievable charge $< 350\text{V}$
Microdischarge	$< 5\%$ increase in measured noise on any channel when raising HV from 300V to 400V

Example of leakage current deterioration from anomalous CIS-equipped modules

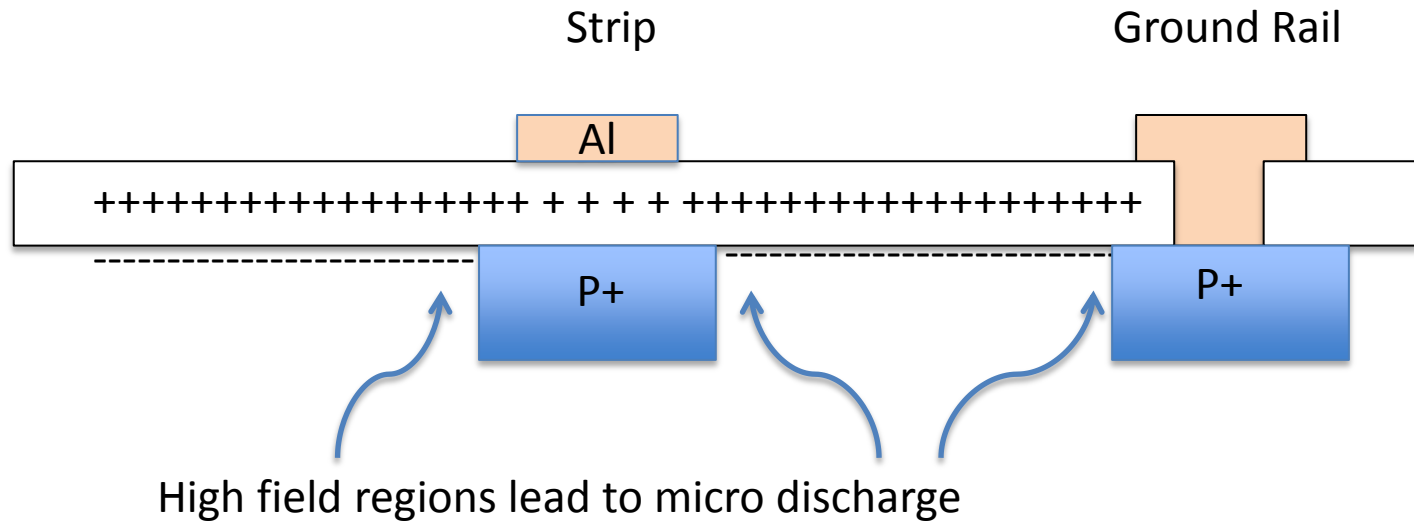


Dramatic increase in current at 150V in April 2011 (but not for 50V) - breakdown



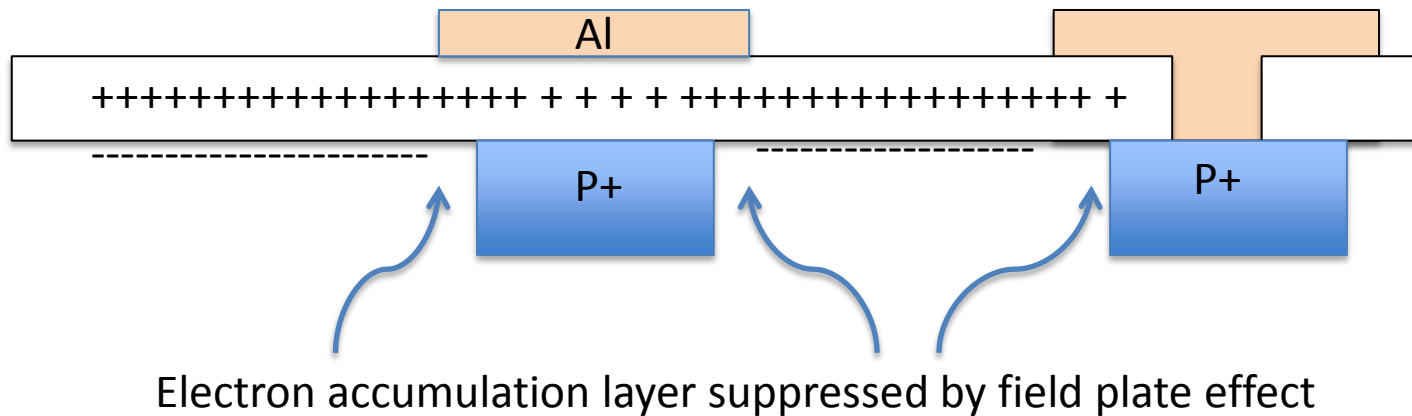
“Normal” behavior in June, albeit at 80V – bulk damage

CiS Sensor strip schematic



Build up of positive charge in oxide (which starts from a non-zero offset and steadily increases and eventually saturates with ionising radiation) leads to increasing electron accumulation layer at the Si-SiO interface, giving high field region at the edge of the implant. CiS sensors were known to have improved breakdown at high humidity because surface charge is always negative which suppresses the electron accumulation layer.

Hamamatsu Sensor strip schematic



Field plate effect suppresses electron accumulation layer (because strip metal is at negative potential wrt implant underneath it), lower field strength at edge of P+ implant, much less prone to micro discharge and less sensitive to humidity.