Characteristics of Prototype Silicon Sensors for CDF Run2B

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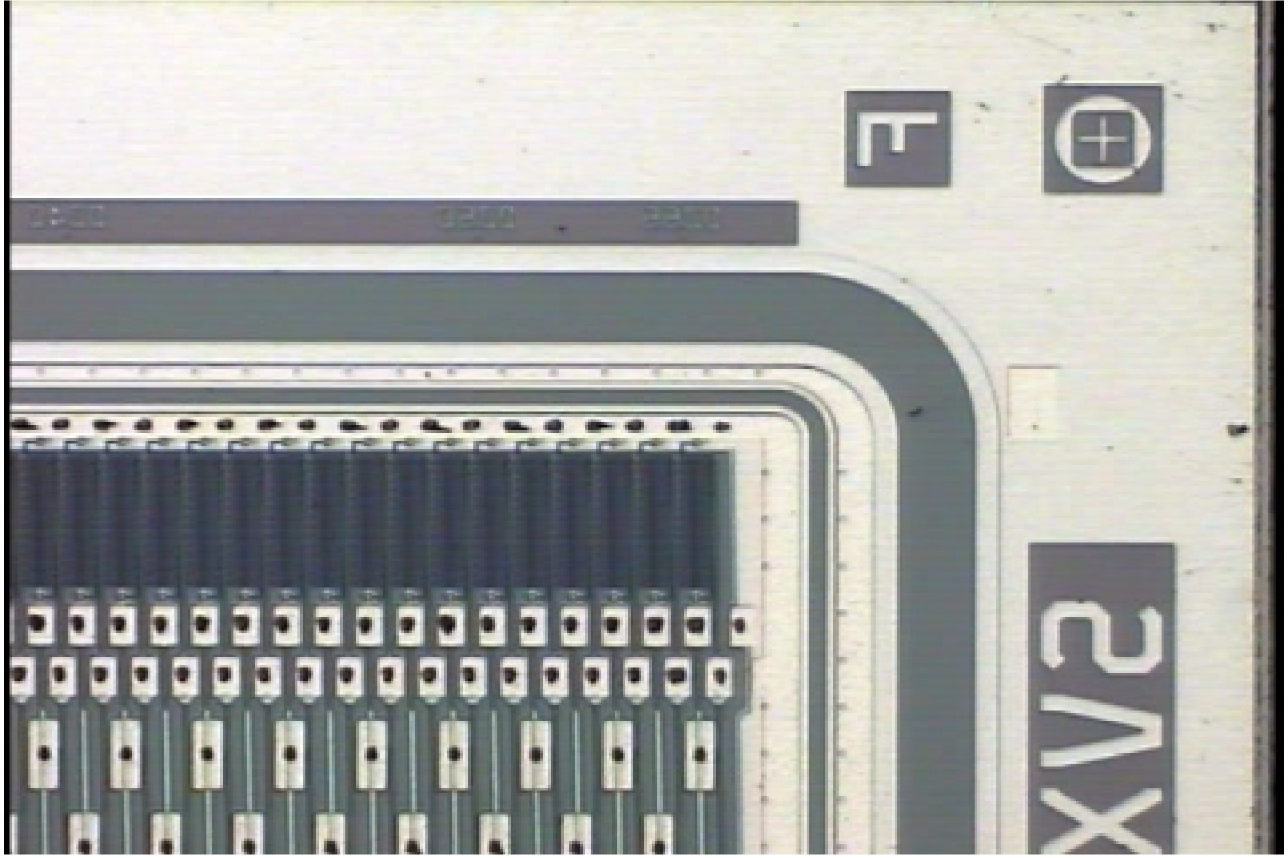
summarizing tests done at Tsukuba/Purdue/UNM

- **Prototype – Design and Delivery**
- **Sensor Characteristics (pre-radiation)**
  - **IV, CV, AC scan, DC scan…**
  - **comparison with HPK probing**
  - **limitations …**
- **Sensor Characteristics (post-radiation)**
- **Charge Up Issue**
- **Summary**

Prototype - Design



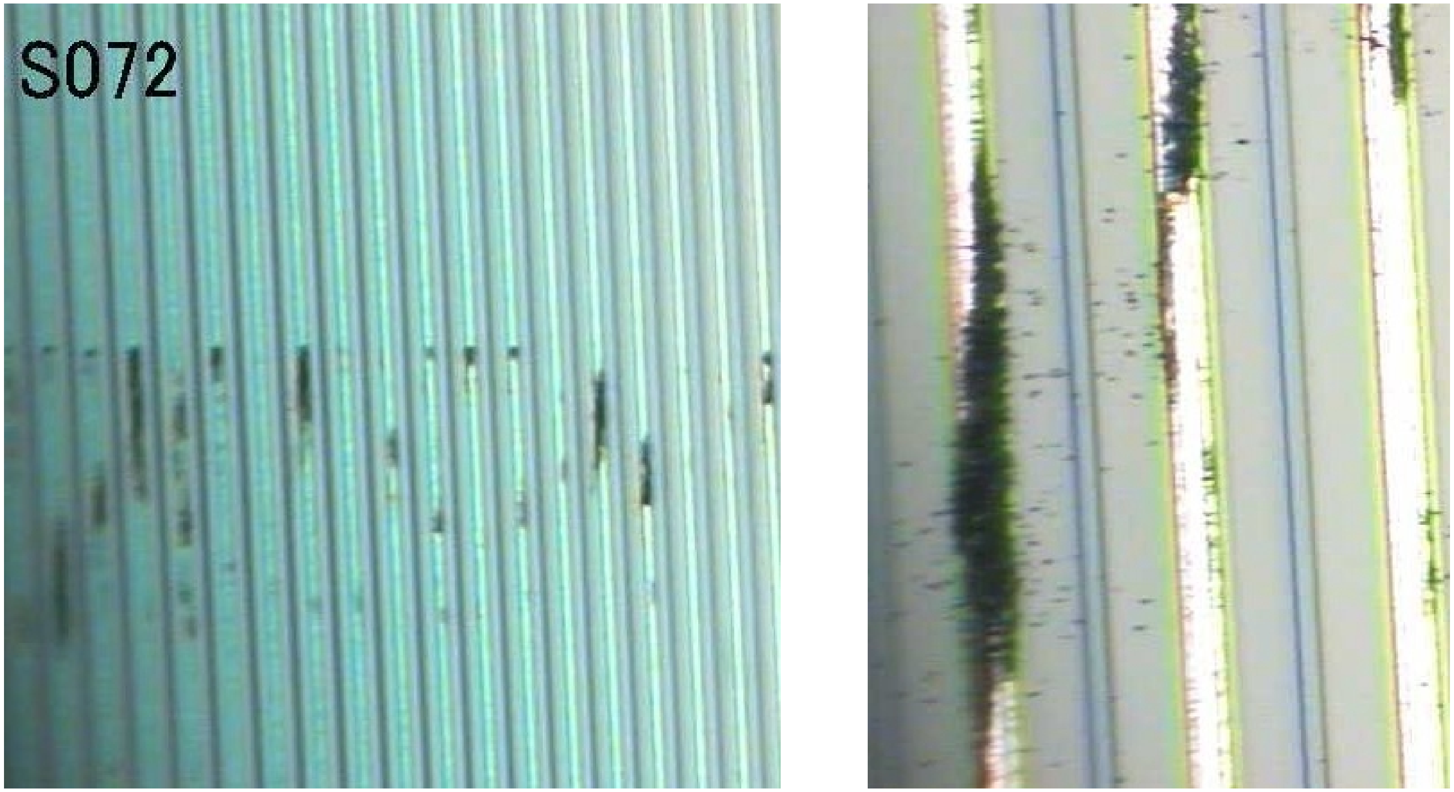
Dimensions -
axial:40.6 x 96.4 mm^2
1.2°: 41.1 x 96.4 mm^2

- **p^+n single sided on 6” (two sensors per wafer)**
- **256 AC coupled readout strips (75um/80um pitch)**
  p^+ width = 8 um; Al width by 14 um
- **single intermediate strip**
- **poly-Si bias resistors of 1.5MΩ**
- **single guard ring**

Prototype - Delivery

Prototypes fabricated by Hamamatsu Photonics

- **60 Axial Prototypes (delivered in July 2002)**
- **53 Stereo Prototypes (delivered in Oct 2002)**



~1/3 of stereo: unusual stains
no apparent effects on sensor performance

Sensor Characterization

- I-V up to 1000V: All
- C-V: 23+53 (23 axial+53 stereo)
- Stability of I-V: 7+9
- Long-term stability: 6+4 biased at 500V
- AC scan: Coupl. Cap (Ccp), ~Rbias (R), oxide leak(Icp) :(18+4)+18
- DC scan: I_strip: 0+2, only for leaky sensors
- Interstrip resistance: 3+0
- Interstrip capacitance: (9+4)+2

used for strip integrity
comparison (HPKvsTsukuba)

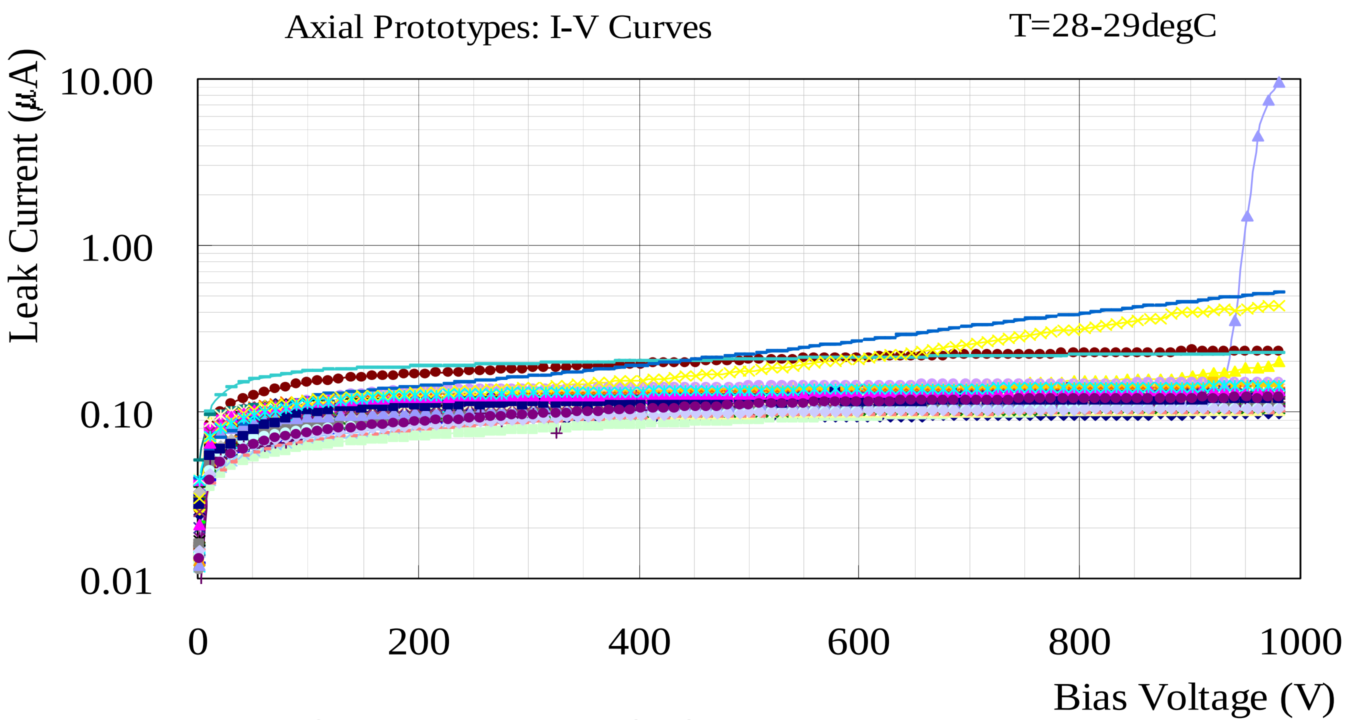
+4: strips sampled covering
the full region

Diagnostic tests when irregularities are found

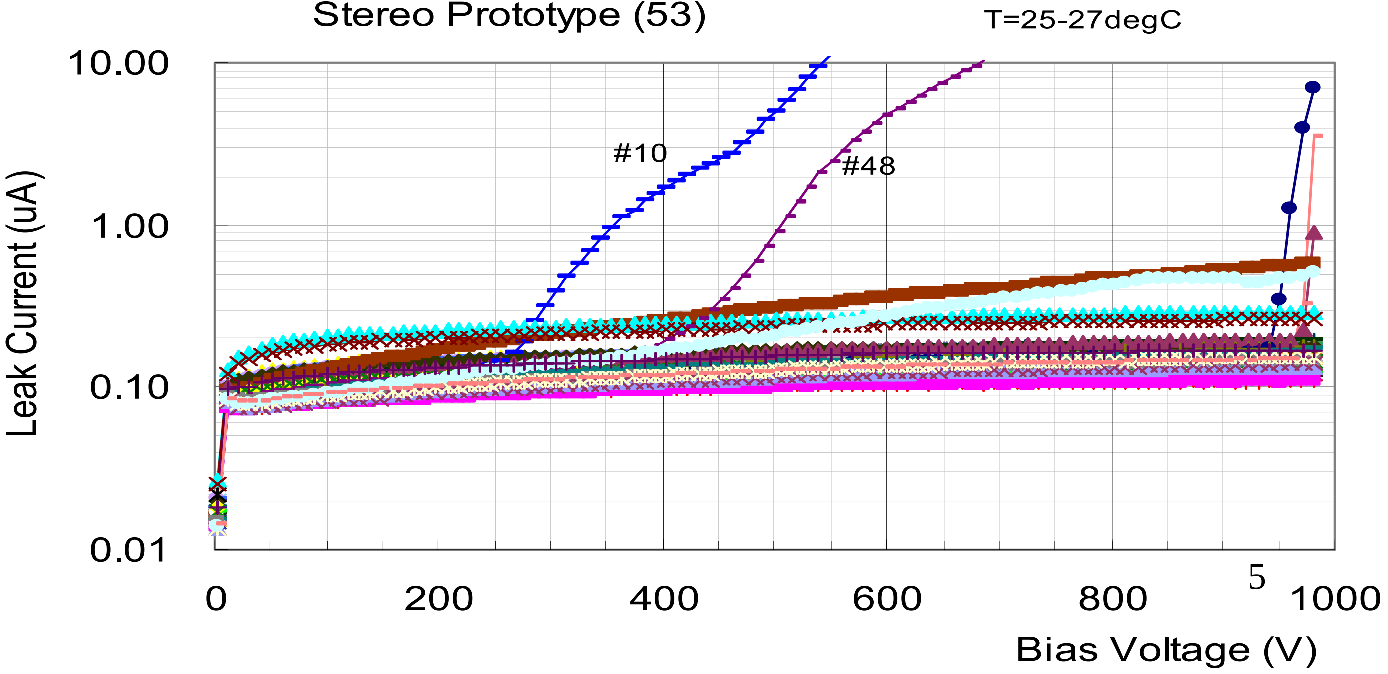
- n irradiation: 3 sensors @ $1.4\text{x}10^{14}$ n/cm^2
  2 sensors @ $0.7\text{x}10^{14}$ n/cm^2

I -V curve

60 axial



53 stereo

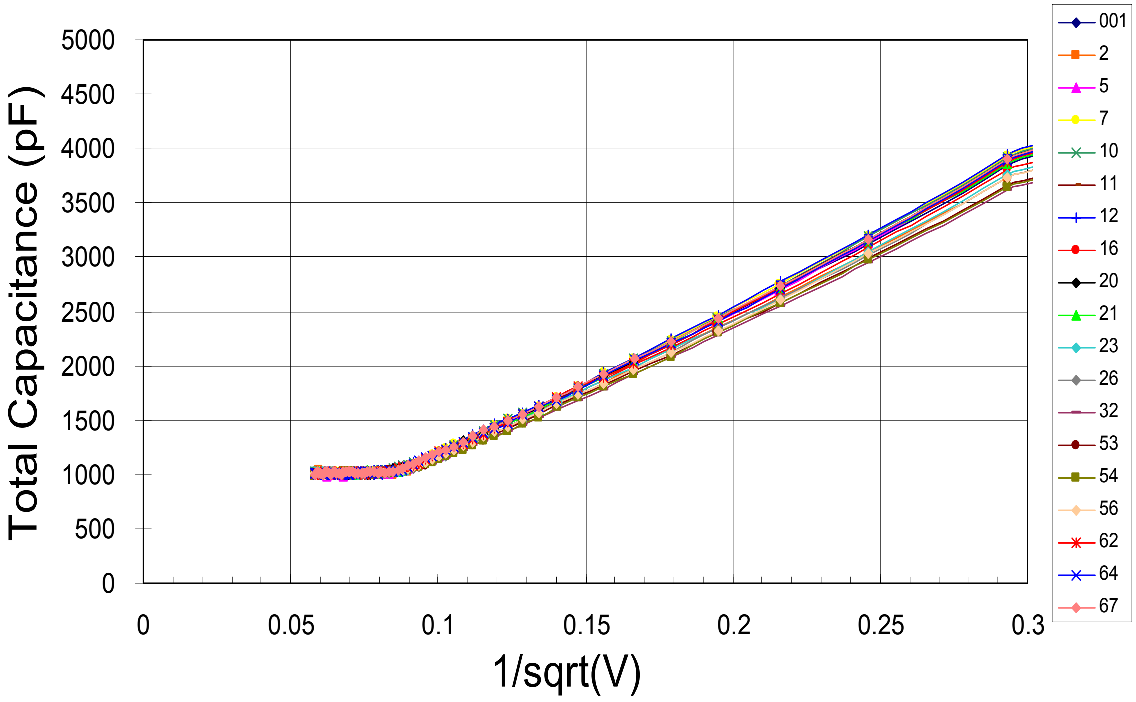


IV is good to 1kV
our spec: 500V

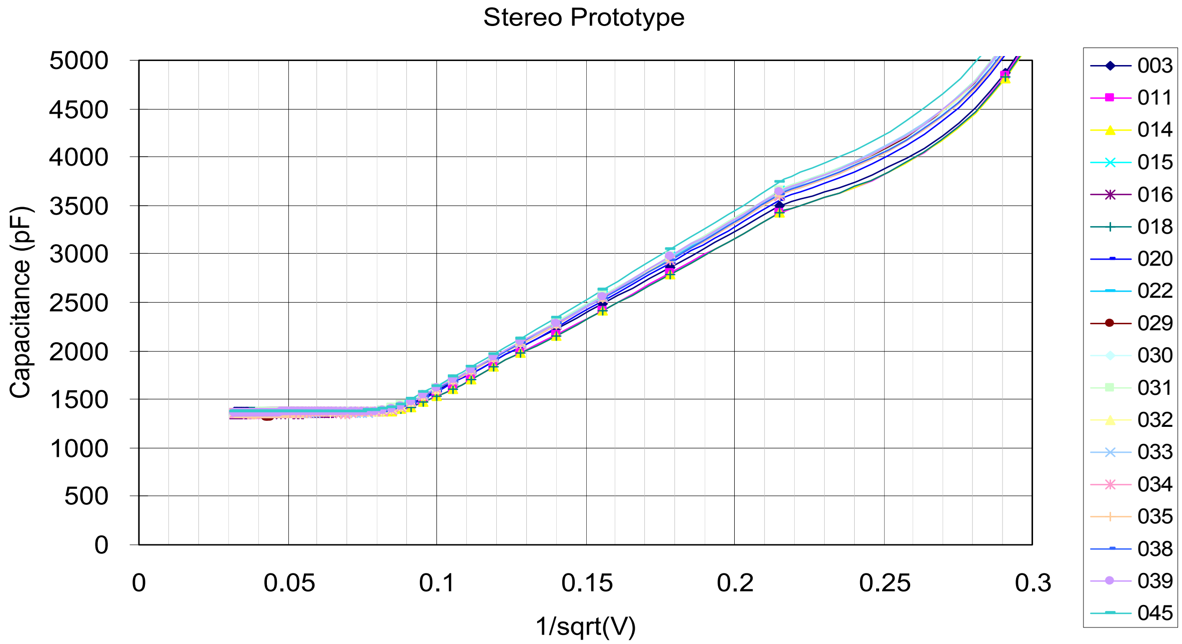
C-V curves

(axial)

f=400Hz



(stereo)



C-V curves

Full Depletion Voltage

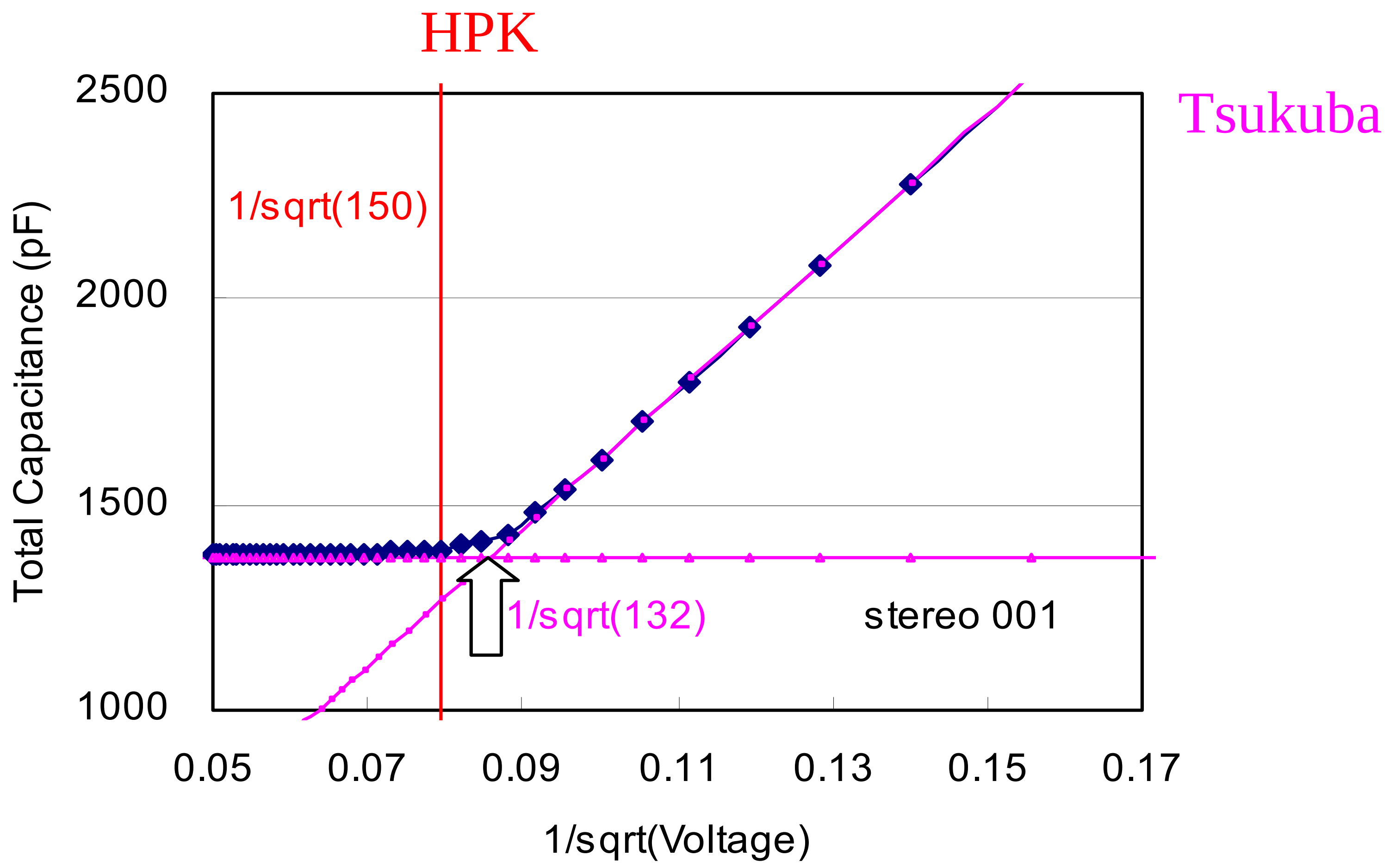


Fig. 3a C-V curve and evaluation of "the full depletion voltage". HPK determines (see text) it to be 150V, whereas we obtain 132V for this sensor, stereo #001.

HPK: lowest Vbias when $\Delta(1/C^2) < 0.02\ (1/C^2)$ @ Vstep=10V

Correlation of Full Depletion Voltages between HPK and Tsukuba

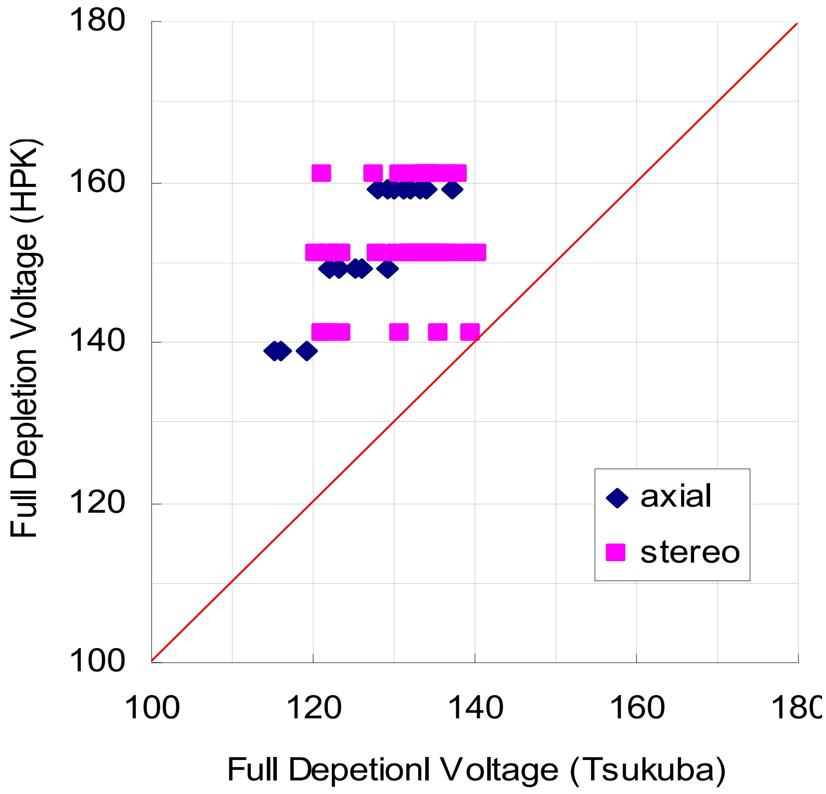


Fig. 3b Correlation of full depletion voltages defined by HPK and Tsukuba.

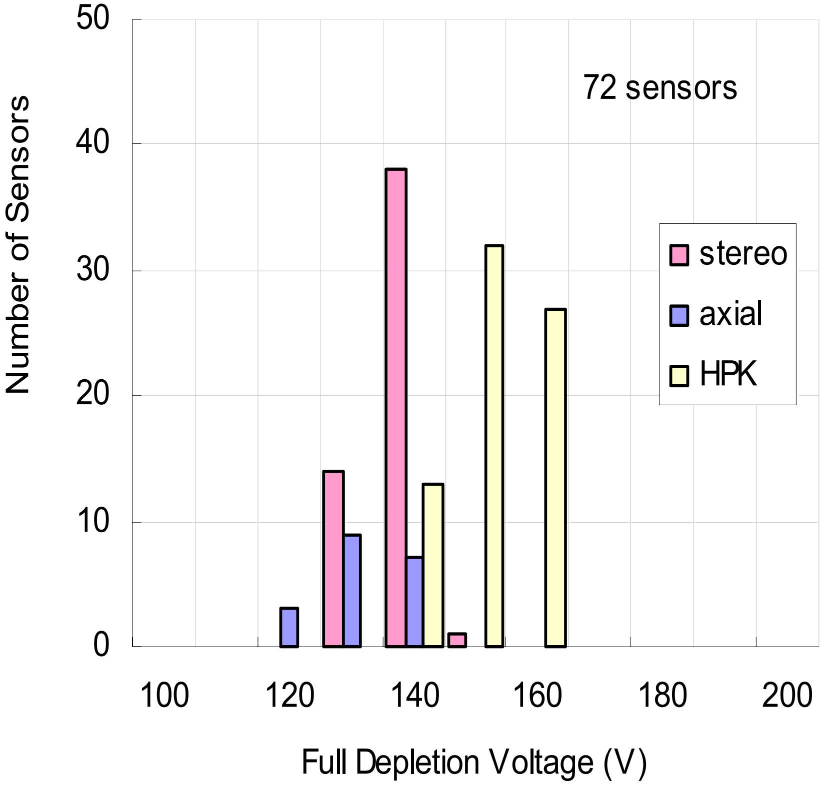


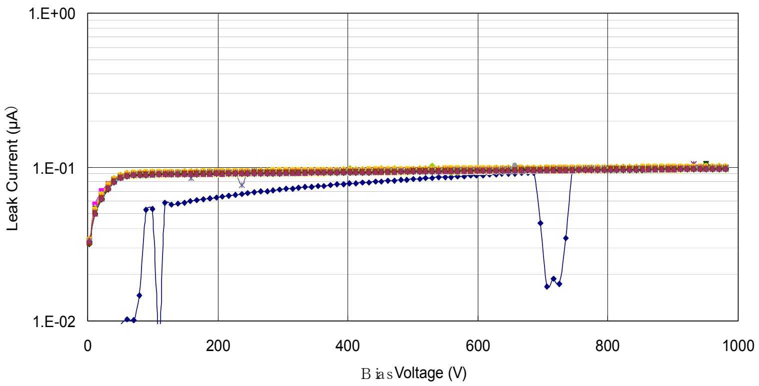
Fig. 3c Full depletion voltage distributions for axial and stereo sensors (Tsukuba) and for all (HPK).

good correlation, though HPK gives ~20V larger
our spec: 120V < Vdep < 250V

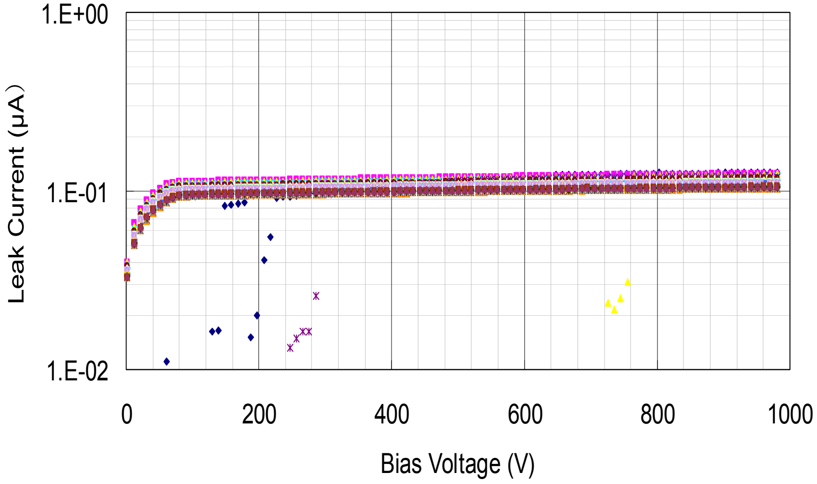
IV stability (axial)

good ones …

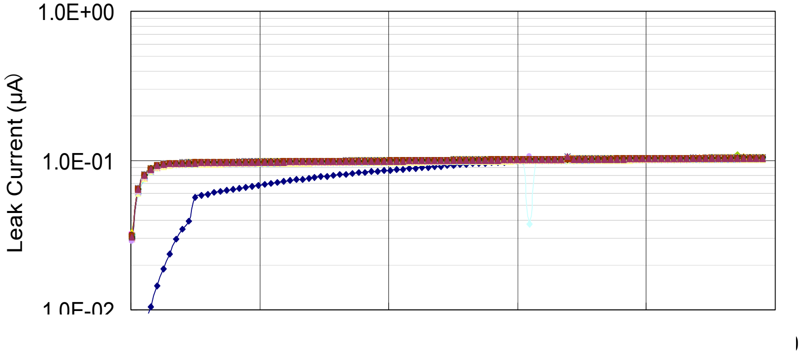
001 I-V stability



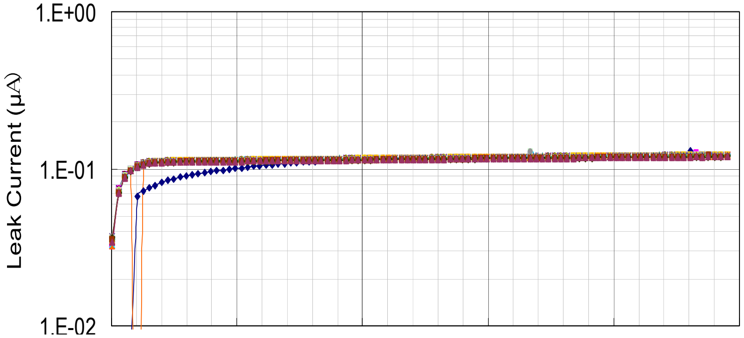
002 I-V stability



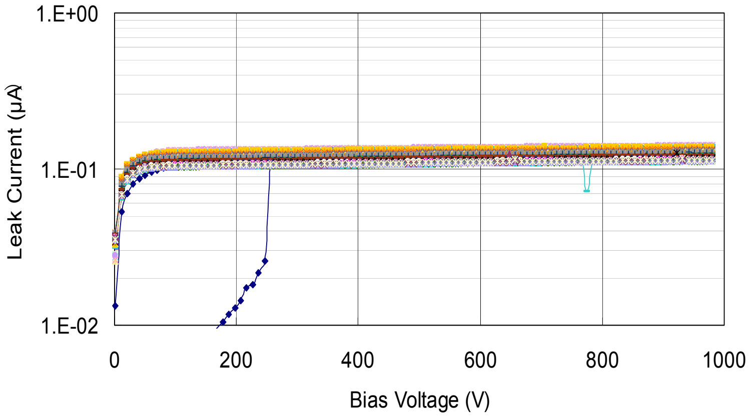
005 I-V stability



007 I-V stability

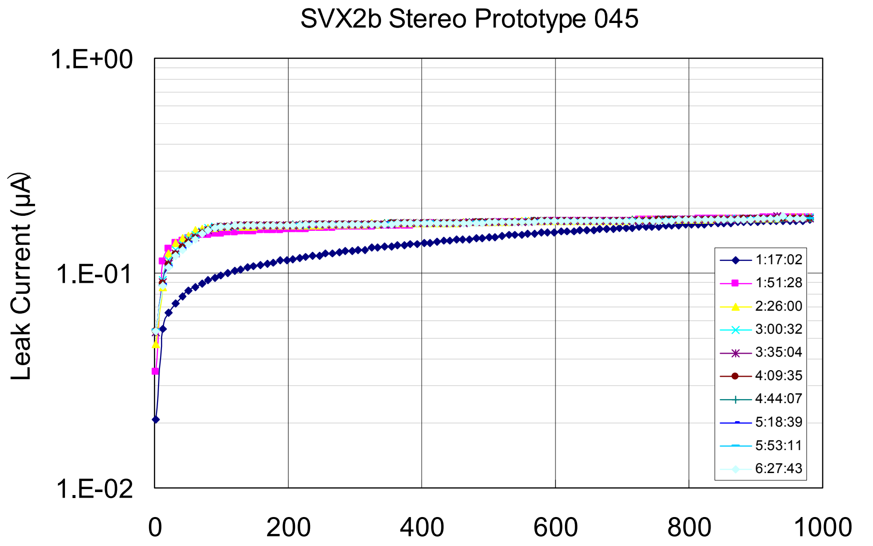


016 I-V stability

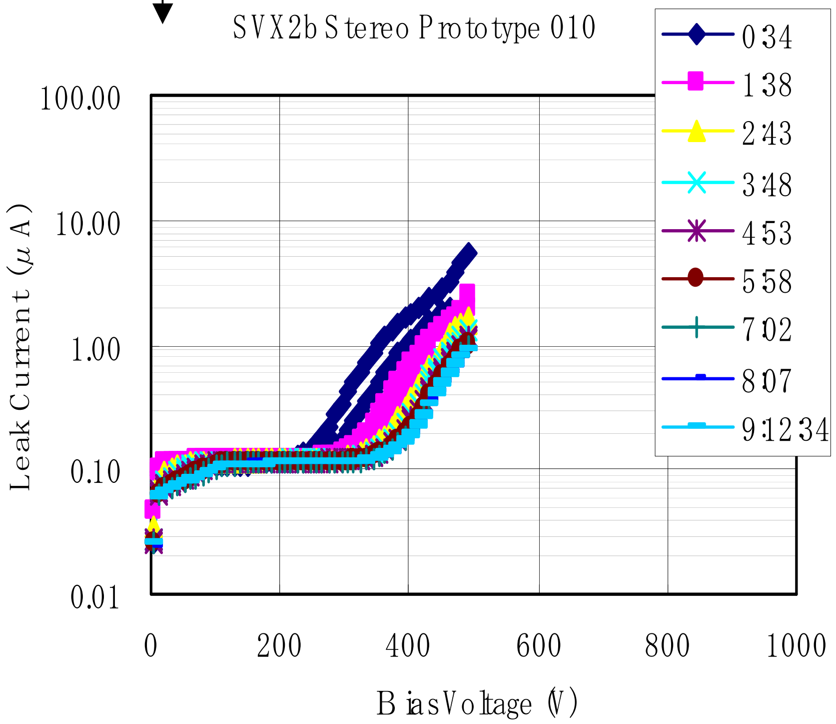


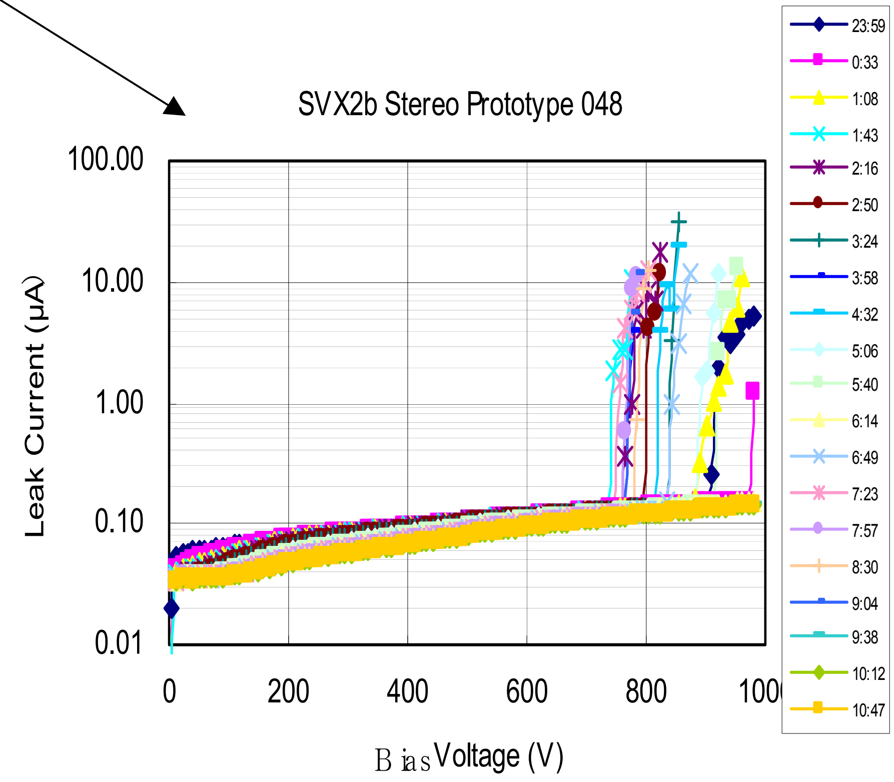
IV stability (stereo)

usual ones →

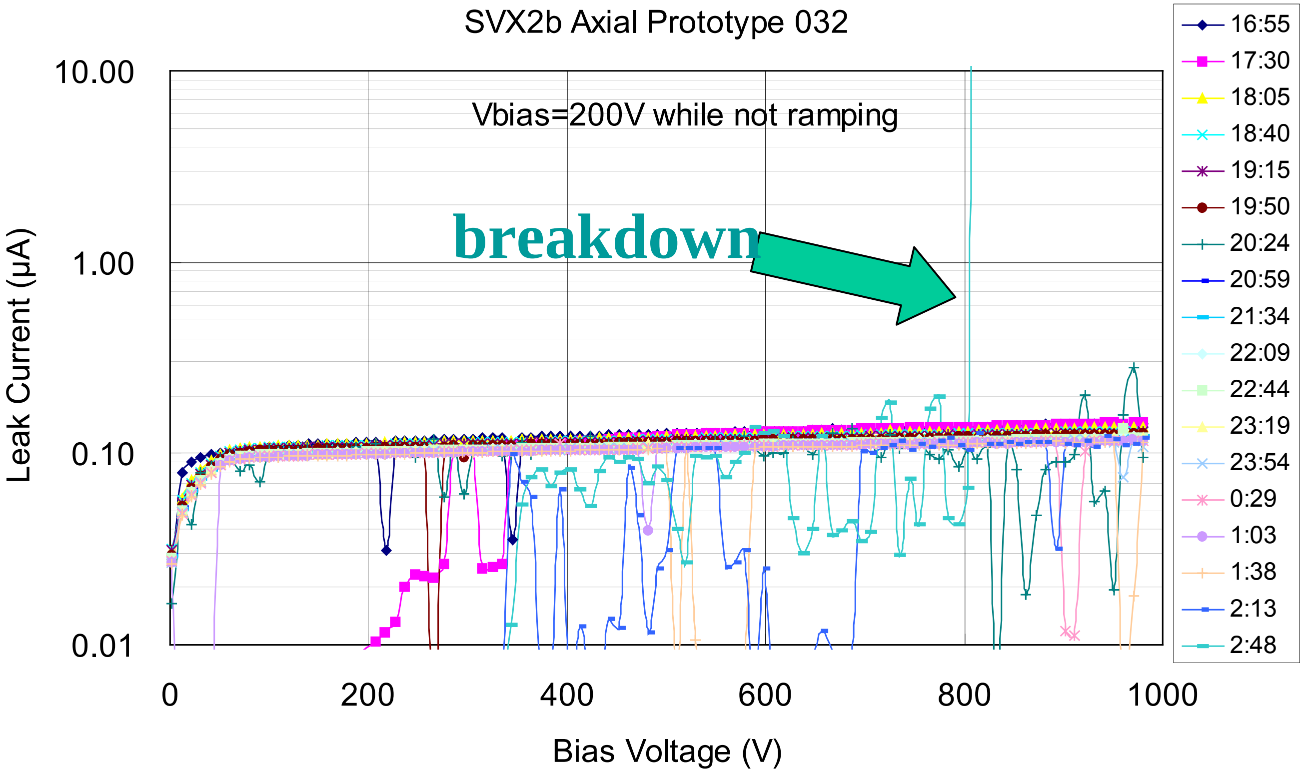


two sensors with micro-discharge





IV stability (bad axial)



A032 showed instability at later stages (~7hrs) breakdown at HV ramping (at 800V after 10hrs)

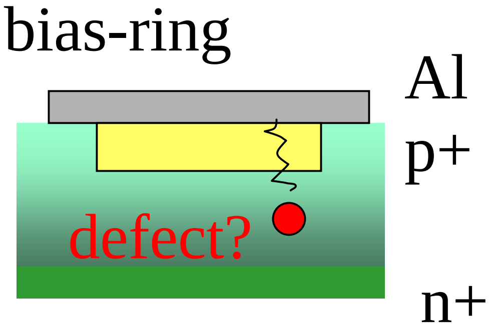
Out of 16 sensors, we found one bad sensor…

What went wrong with 032?

IR camera view:

clear trace of discharge

junction breakdown: no recovery

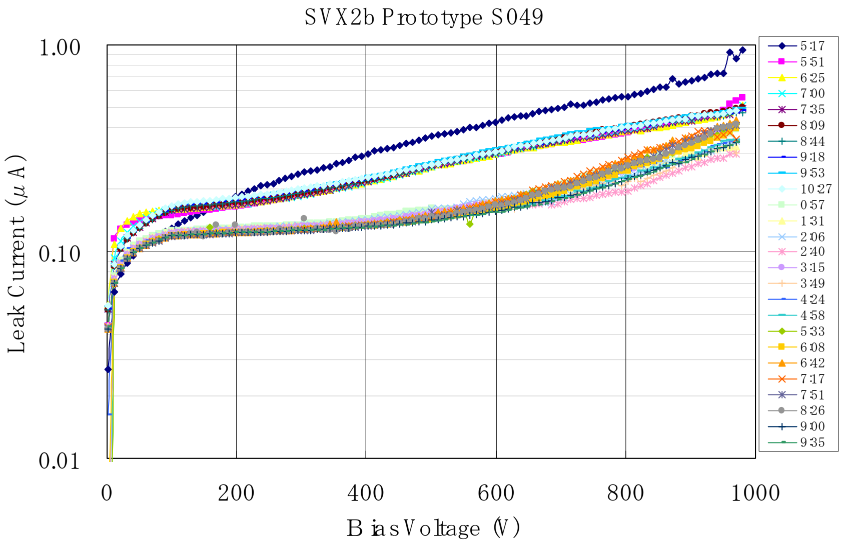


We must respect the spec (500V)!?

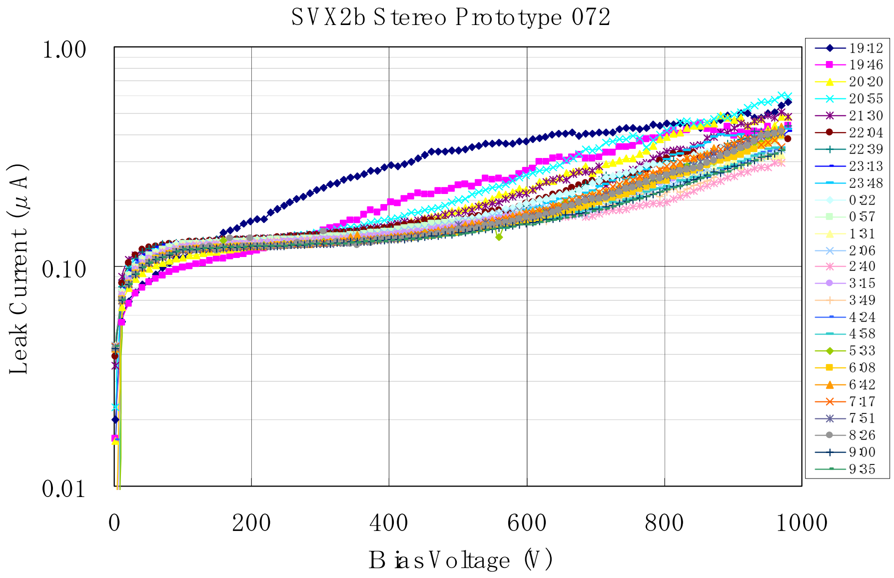
scratch degrades I-V stability?

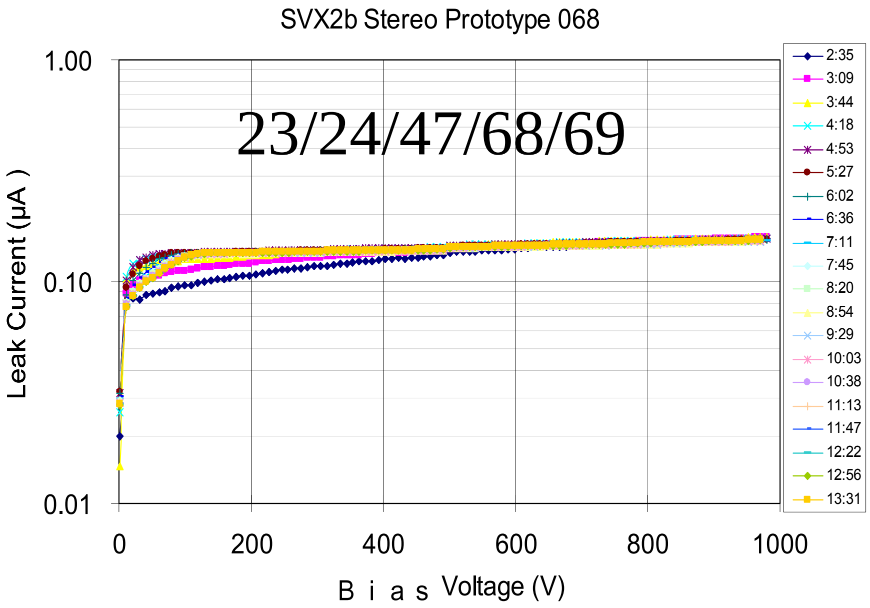
some of I-V curves are certainly worse for stereo…

class A



class Bs





23/24/47/68/69

DC scan

… only for leaky sensors

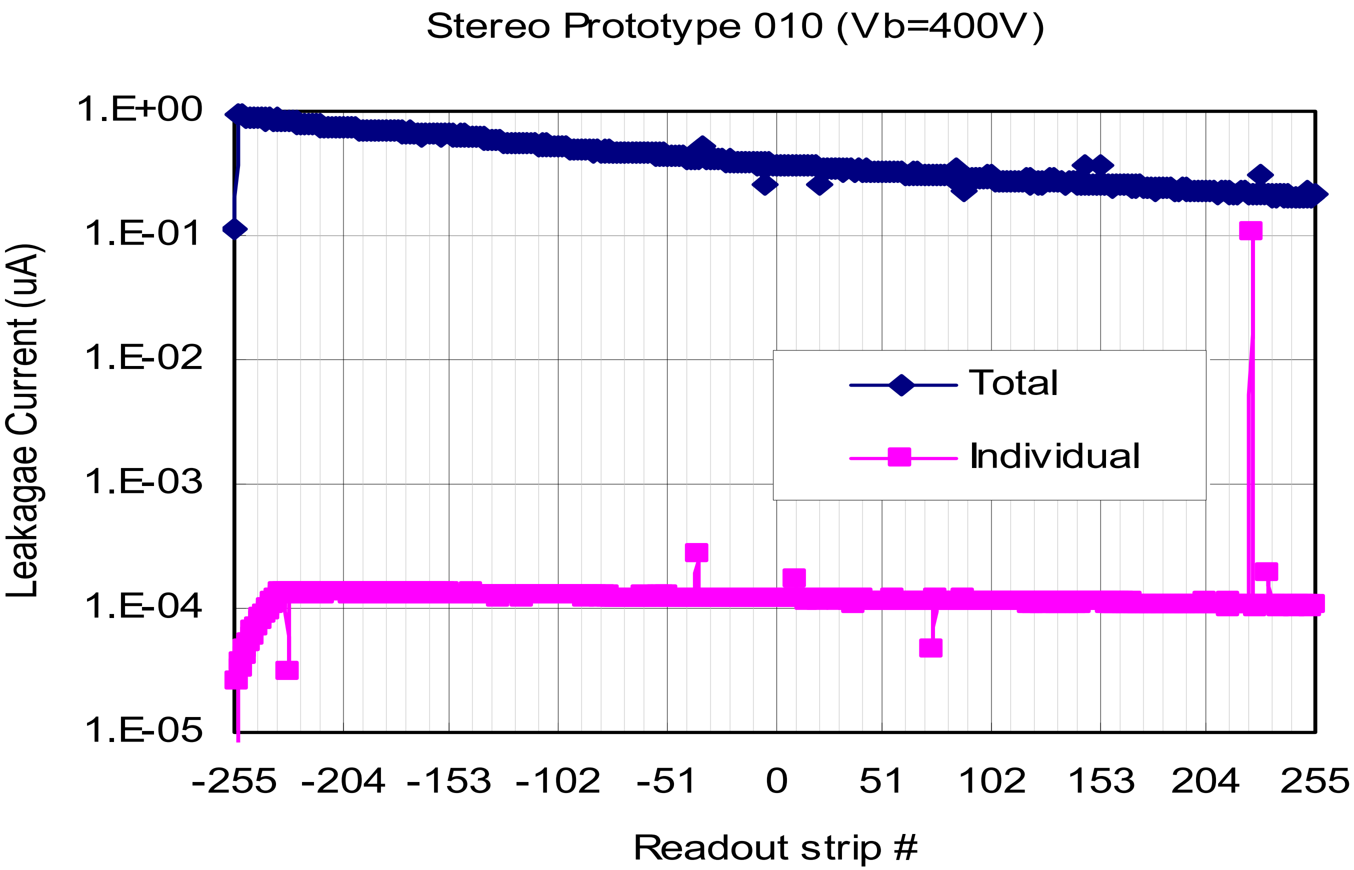


Fig. 5 DC scan (stereo #010) measured at 400V

RU225: HPK leaky

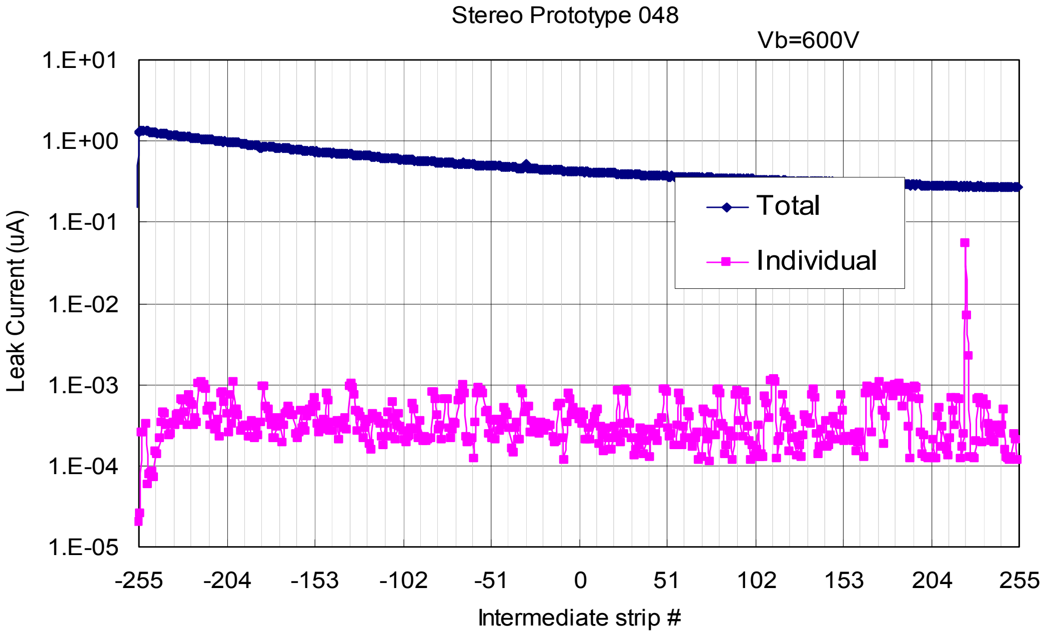
DC scan

No leaky strip reported by HPK

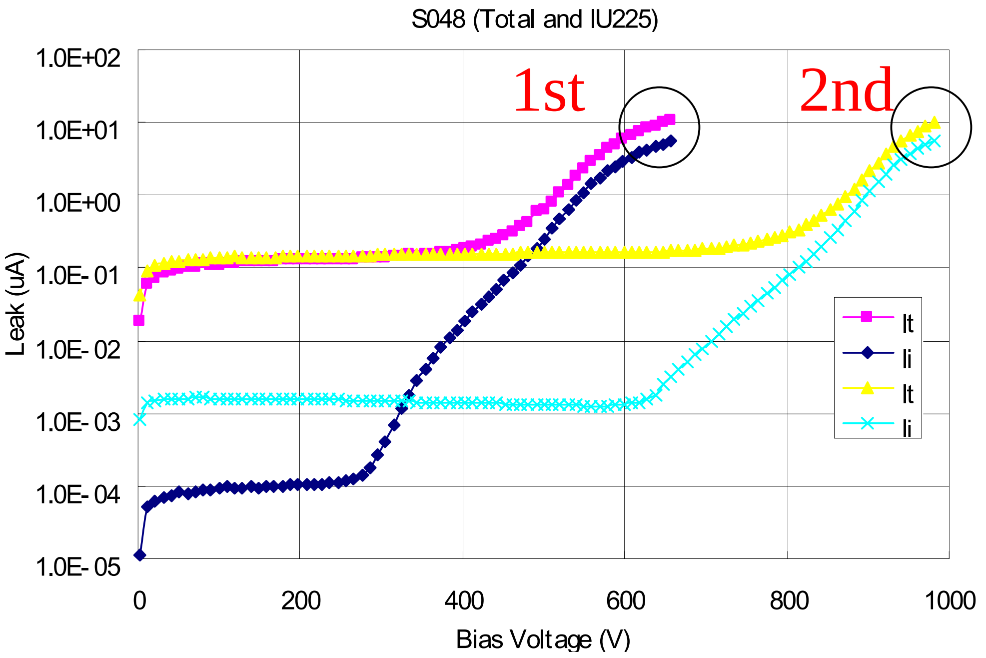
Intermediate strip scan

I-V curve for leaky strip

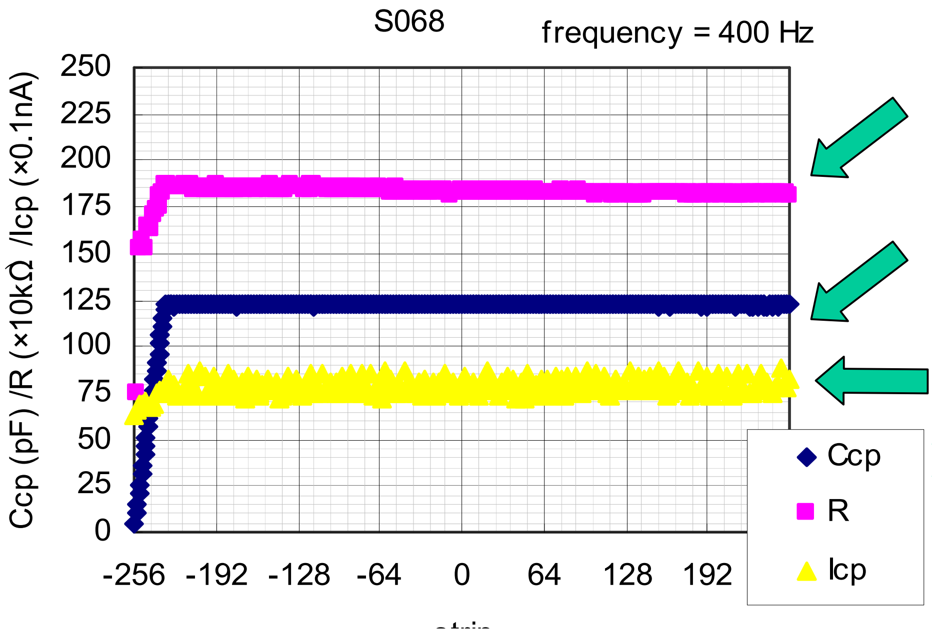
increase in total leakage current is fully explained by this single strip



IU225



AC scan



R~1.9MΩ

includes contribution of implant resistance in series (Rbias is 0.4MΩ smaller)

Ccp~120pF

Icp~7nA

leakage through relays (~0 if relays are not used)

~9µA if oxide punch-through

Fig. 4a Example of A(Strip number #068).

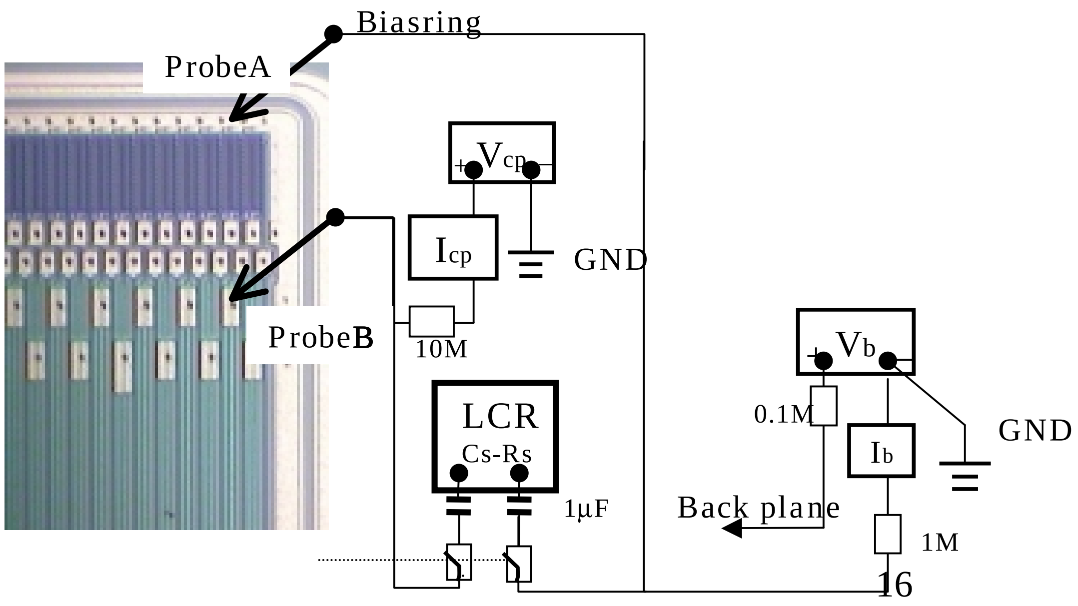


Figure 3: Setup for the full strip scan (AC scan)

Step:

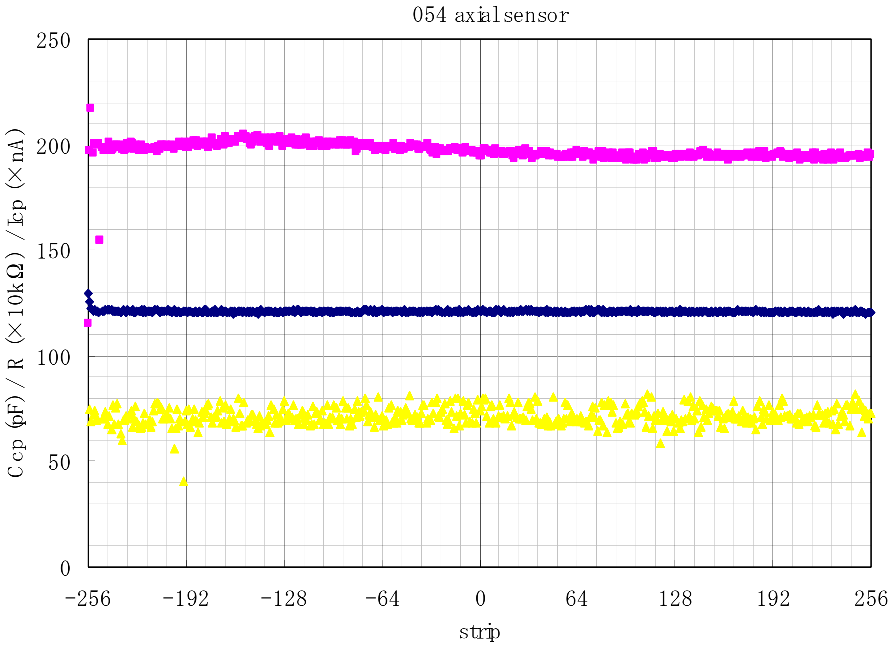
measure Ccp-R (relay-on)

apply 100V across Ccp for 1s

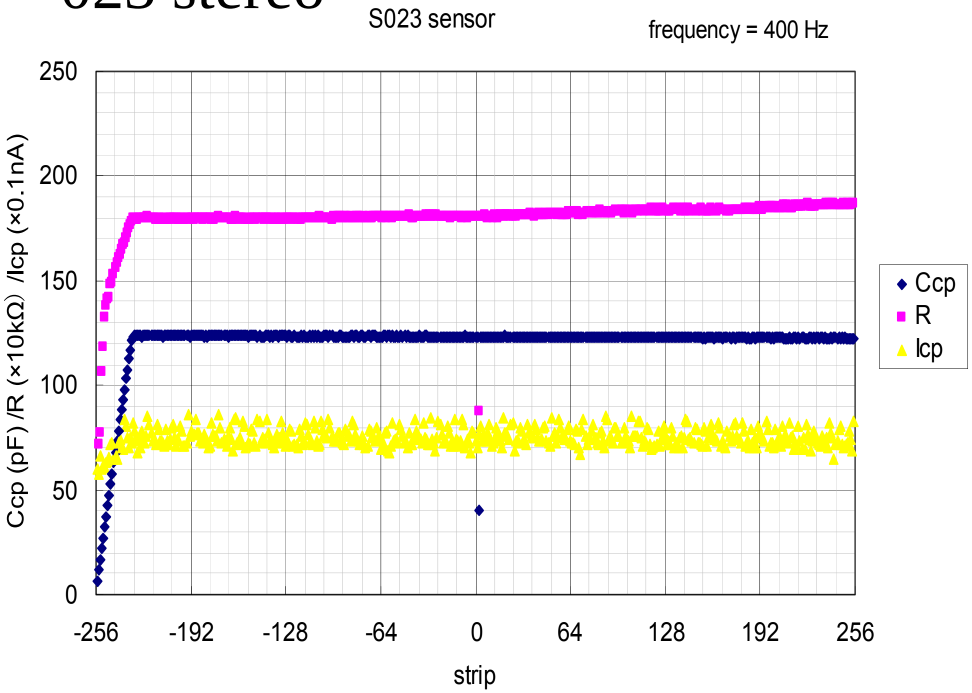
measure Icp (relay-off)

AC scan results (bad examples)

054 axial



023 stereo



RD256
RD249
RD248
RD244

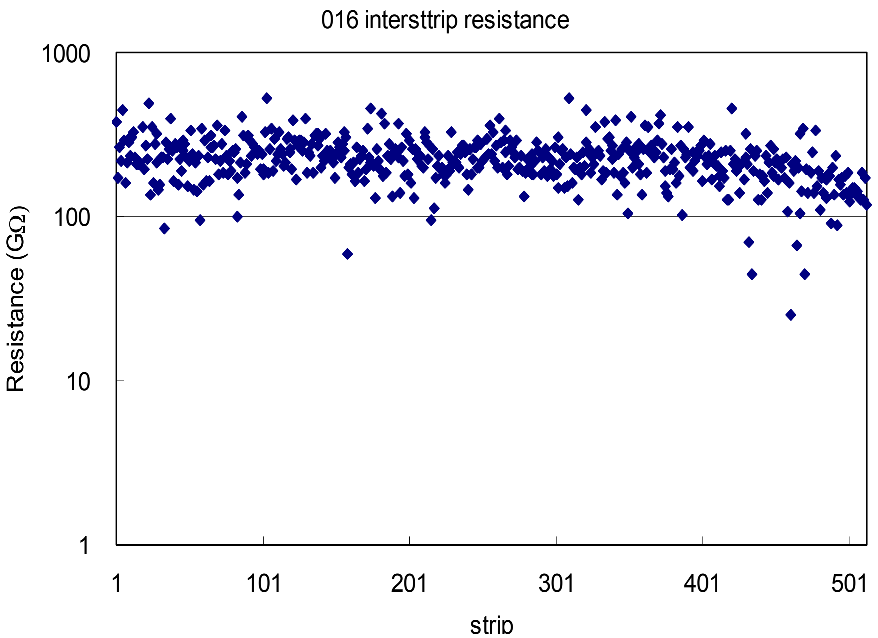
punch-through
Icp is large

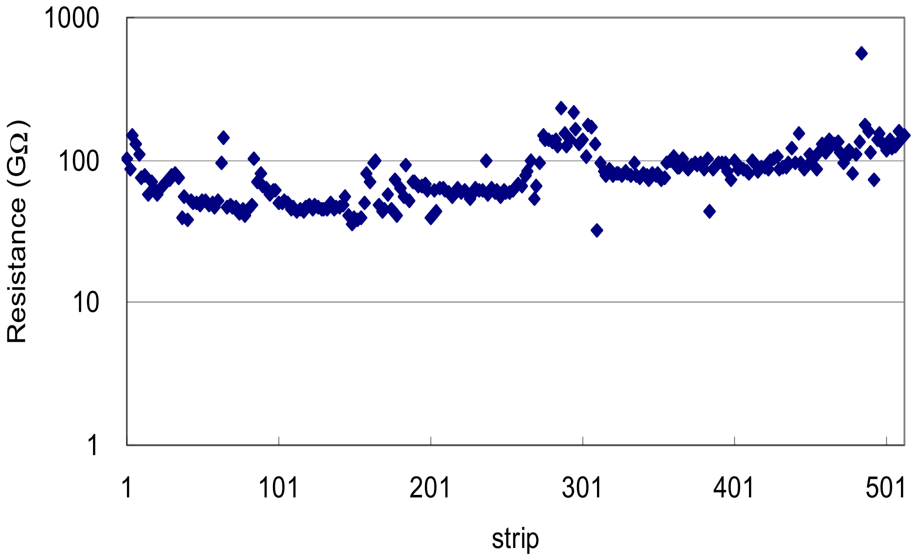
RU2 implant open
open is identified with microscope

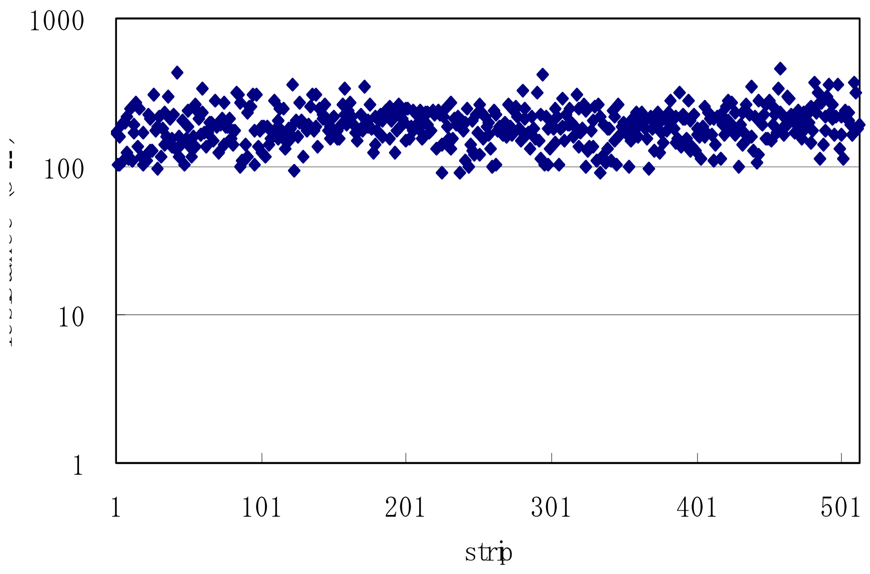
Interstrip Resistance

Distribution looks different, but all are >50GΩ

In addition to these scans, Rint is measured to identify strips with irregular result…

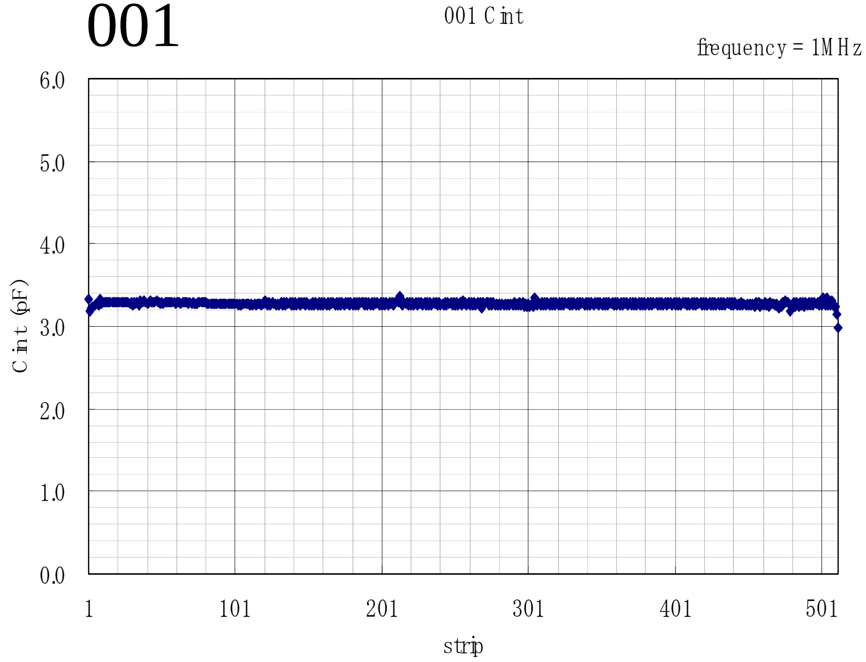




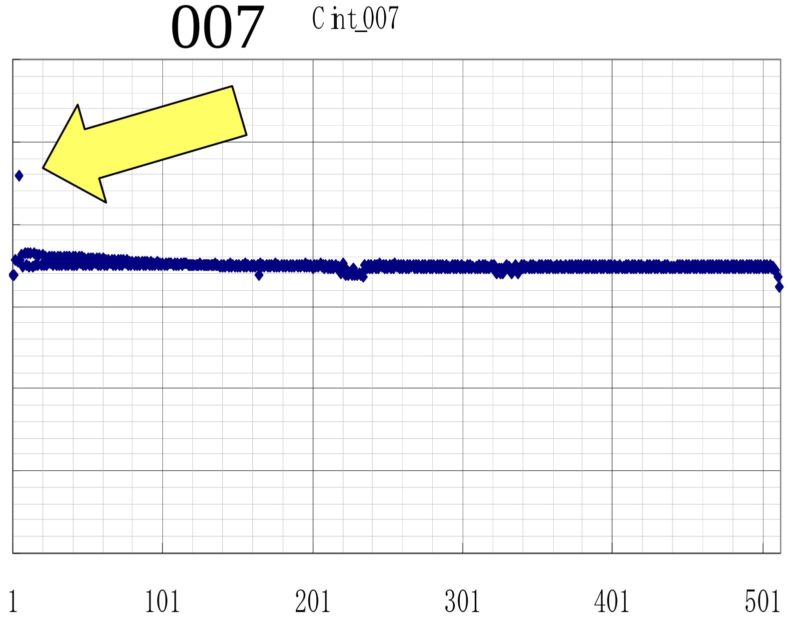


Interstrip Capacitance

001



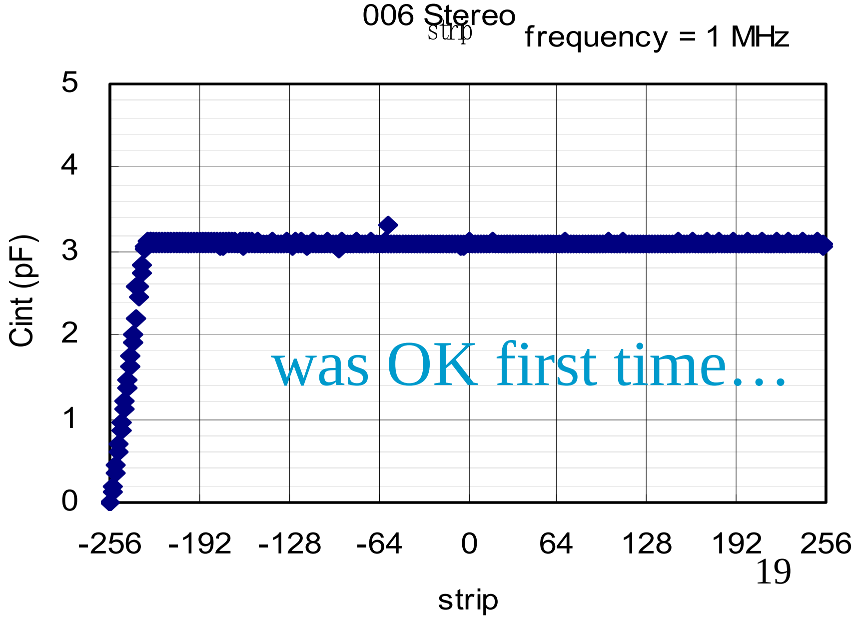
007



All looked similar except #007

Cint(R5-R6) is high …

R5 & R6 showed smaller R

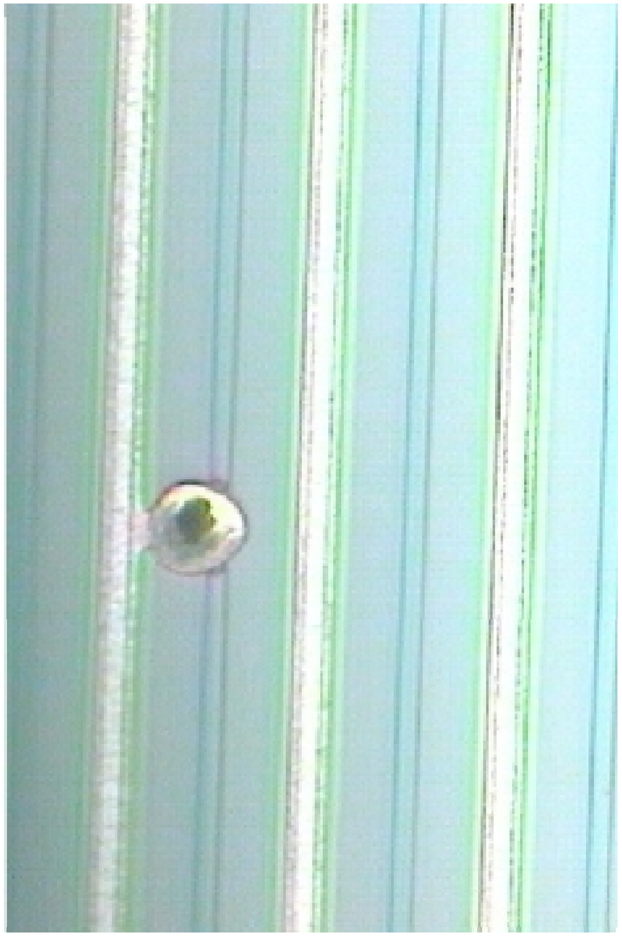


was OK first time…

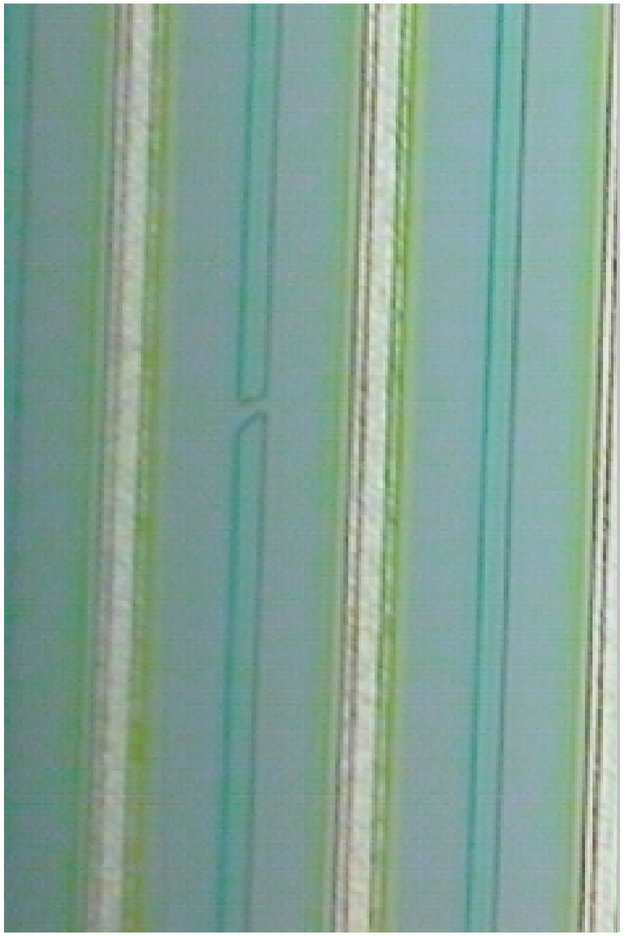
Fig. 7b Interstrip capacitance: Sensor 006 (Stereo) with an irregular value

Intermediate Implant Opens

Examples of Implant Opens

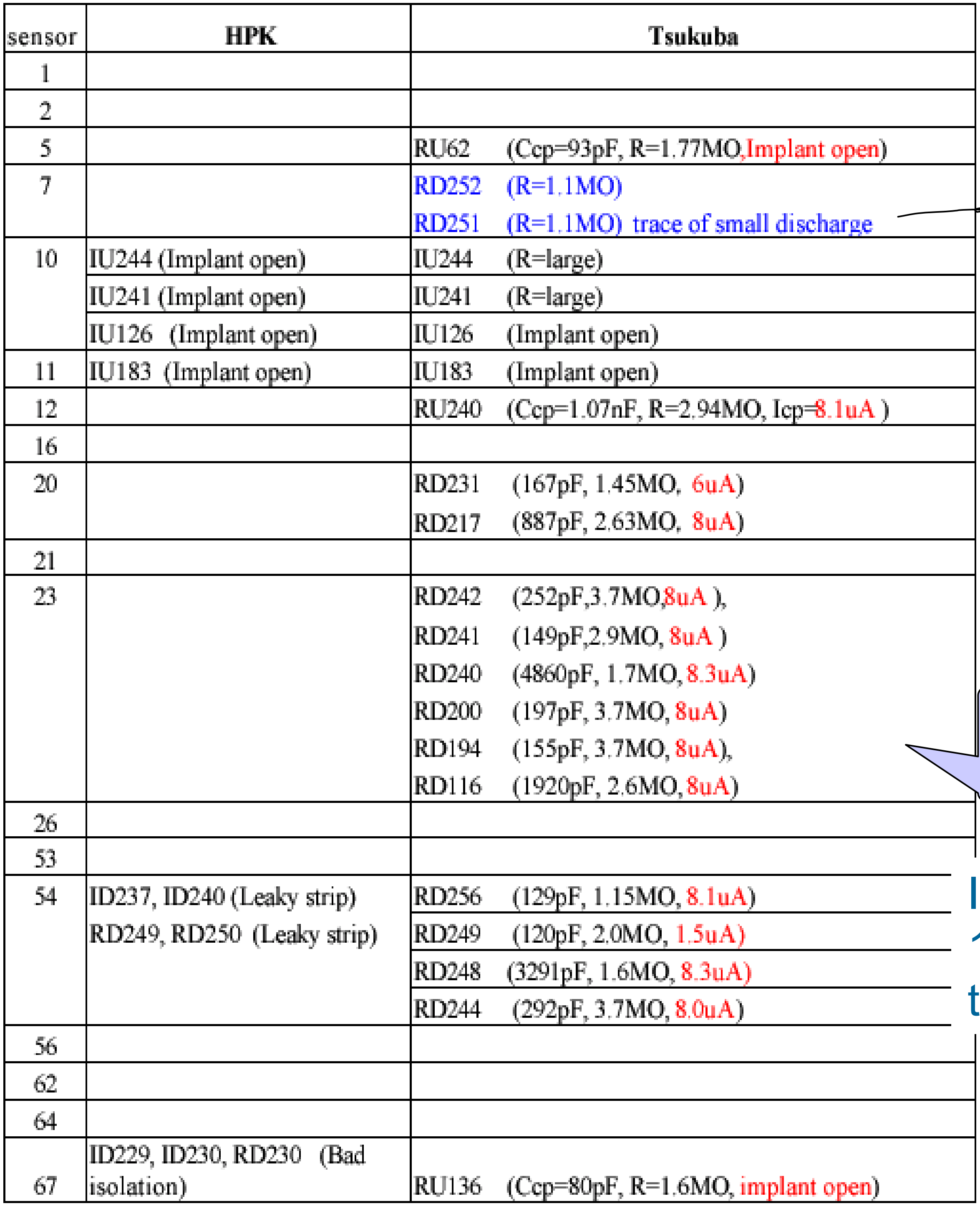


just one case



usual case

Dead Channels:axial summary



sensor	HPK	Tsukuba
1		
2		
5		RU62 (Ccp=93pF, R=1.77MO,Implant open)
7		RD252 (R=1.1MO) RD251 (R=1.1MO) trace of small discharge
10	IU244 (Implant open)	IU244 (R=large)
	IU241 (Implant open)	IU241 (R=large)
	IU126 (Implant open)	IU126 (Implant open)
11	IU183 (Implant open)	IU183 (Implant open)
12		RU240 (Ccp=1.07nF, R=2.94MO, Icp=8.1uA)
16		
20		RD231 (167pF, 1.45MO, 6uA) RD217 (887pF, 2.63MO, 8uA)
21		
23		RD242 (252pF,3.7MO,8uA), RD241 (149pF,2.9MO, 8uA) RD240 (4860pF, 1.7MO, 8.3uA) RD200 (197pF, 3.7MO, 8uA) RD194 (155pF, 3.7MO, 8uA), RD116 (1920pF, 2.6MO, 8uA)
26		
53		
54	ID237, ID240 (Leaky strip) RD249, RD250 (Leaky strip)	RD256 (129pF, 1.15MO, 8.1uA)
		RD249 (120pF, 2.0MO, 1.5uA)
		RD248 (3291pF, 1.6MO, 8.3uA)
		RD244 (292pF, 3.7MO, 8.0uA)
56		
62		
64		
67	ID229, ID230, RD230 (Bad isolation)	RU136 (Ccp=80pF, R=1.6MO, implant open)

small discharge

new & obvious

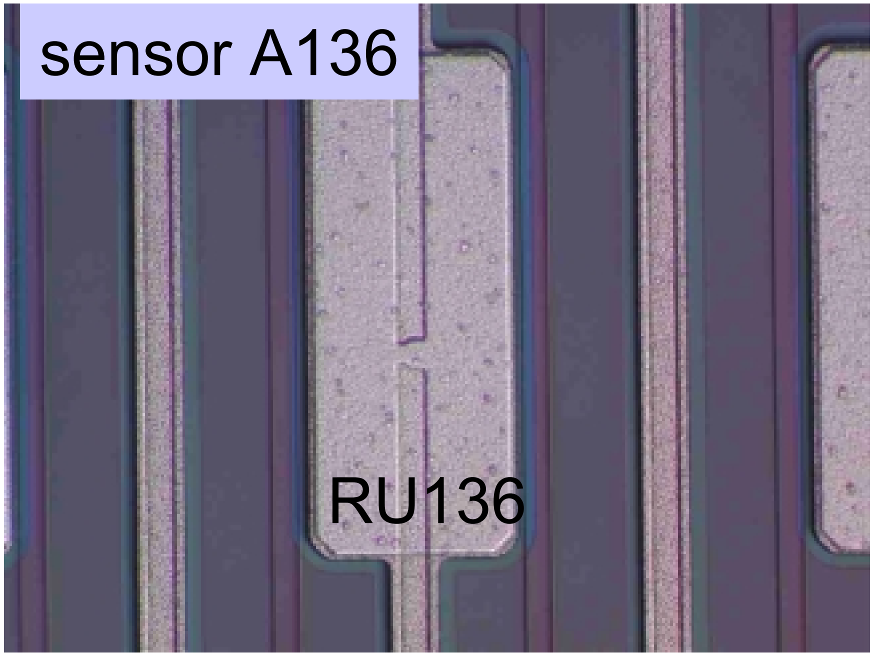
- open identified with microscope
- resistance of DC pad to B.R. large
- Icp consistent with punch-through

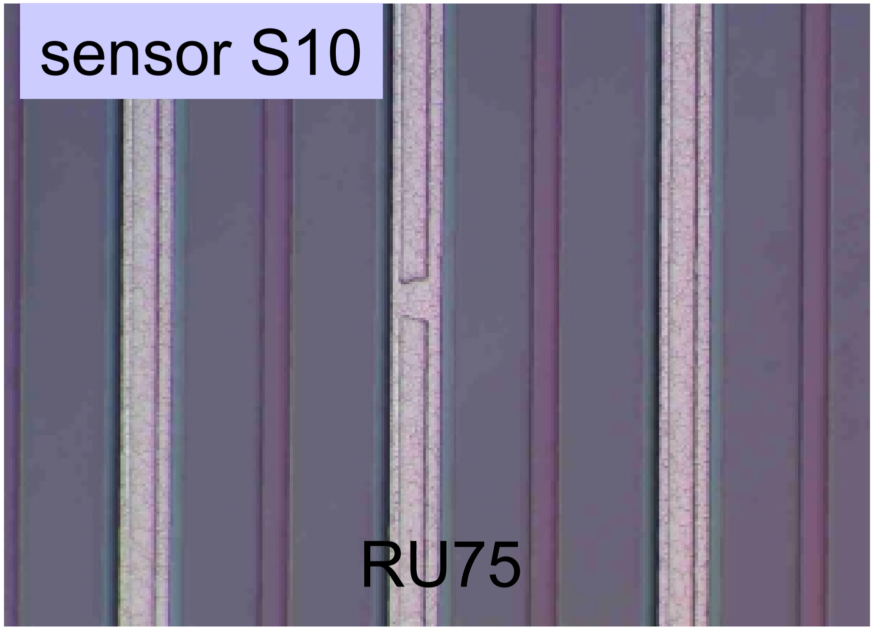
Too many punchthrugh created…?

Informed that HPK applied only 100V instead of 120V at punch through test!

new & obvious:

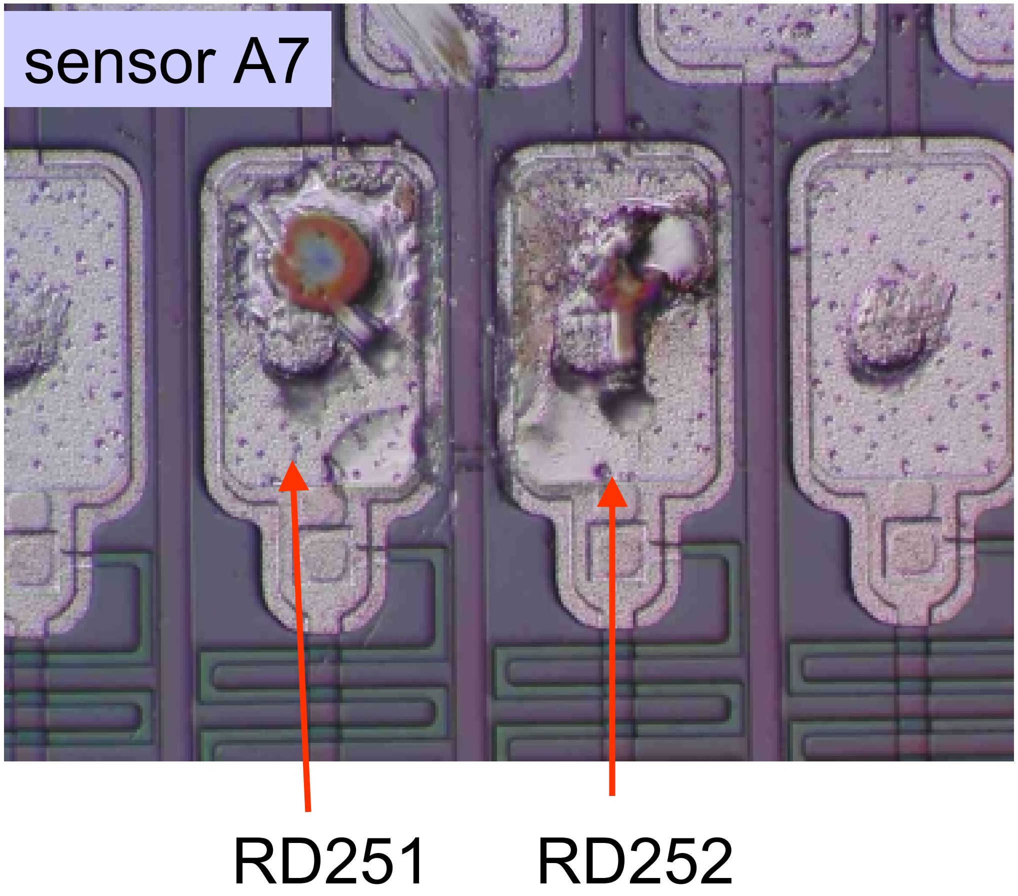
Readout implant opens





almost certainly new:

Discharge at probing!



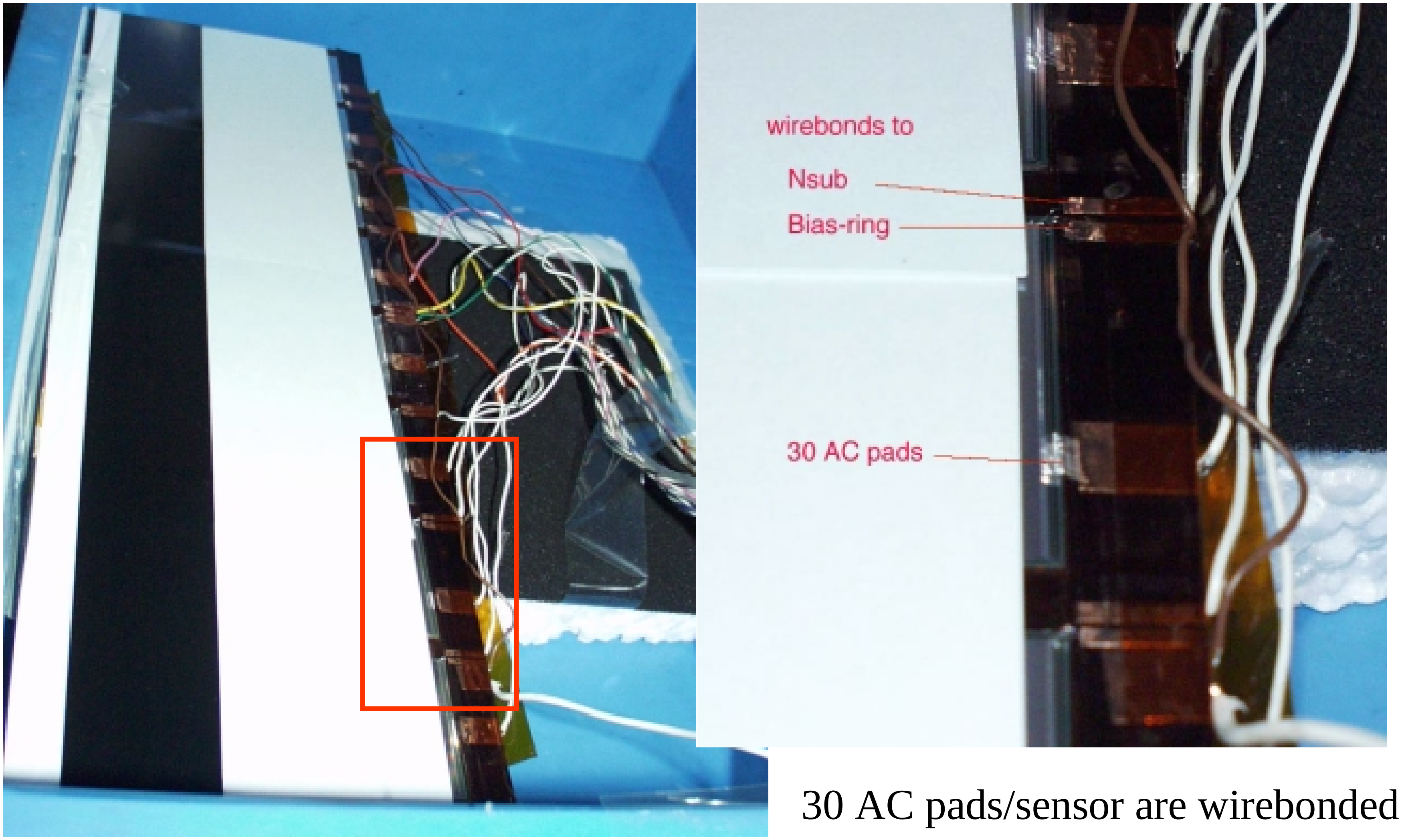
Dead Channels:stereo summary

ID	**HPK**	**Tsukuba**
6		
7	RU225 (Leaky)	
10		RU225 (leaky)
		RU75 (C=55,R=1.16; implant open)
23		RU2 (C=40,R=0.88; implant open)
24		
47	IU158 (Implant open)	IU158 (Implant open)
65	IU59 (Implant open)	IU59 (R=20M)
66	IU238 (Implant open)	IU238 (implant open)
68	IU21 (Implant open)	IU21 (implant open)
69		
13		RD83 (C=111, R=1.77)
46		
49	IU147 (Implant open)	IU147(R=large)
50		
53	ID7 (Implant open)	ID7 (implant open)
		RD24 (C=90,R=1.6, implant open)
57	ID62 (Implant open)	ID62 (implant open)
63	ID146 (Implant open)	ID146 (implant open)
25	ID230 (Implant open)	ID230 (implant open)

No new punch through since HPK applied 120V!

now at FNAL

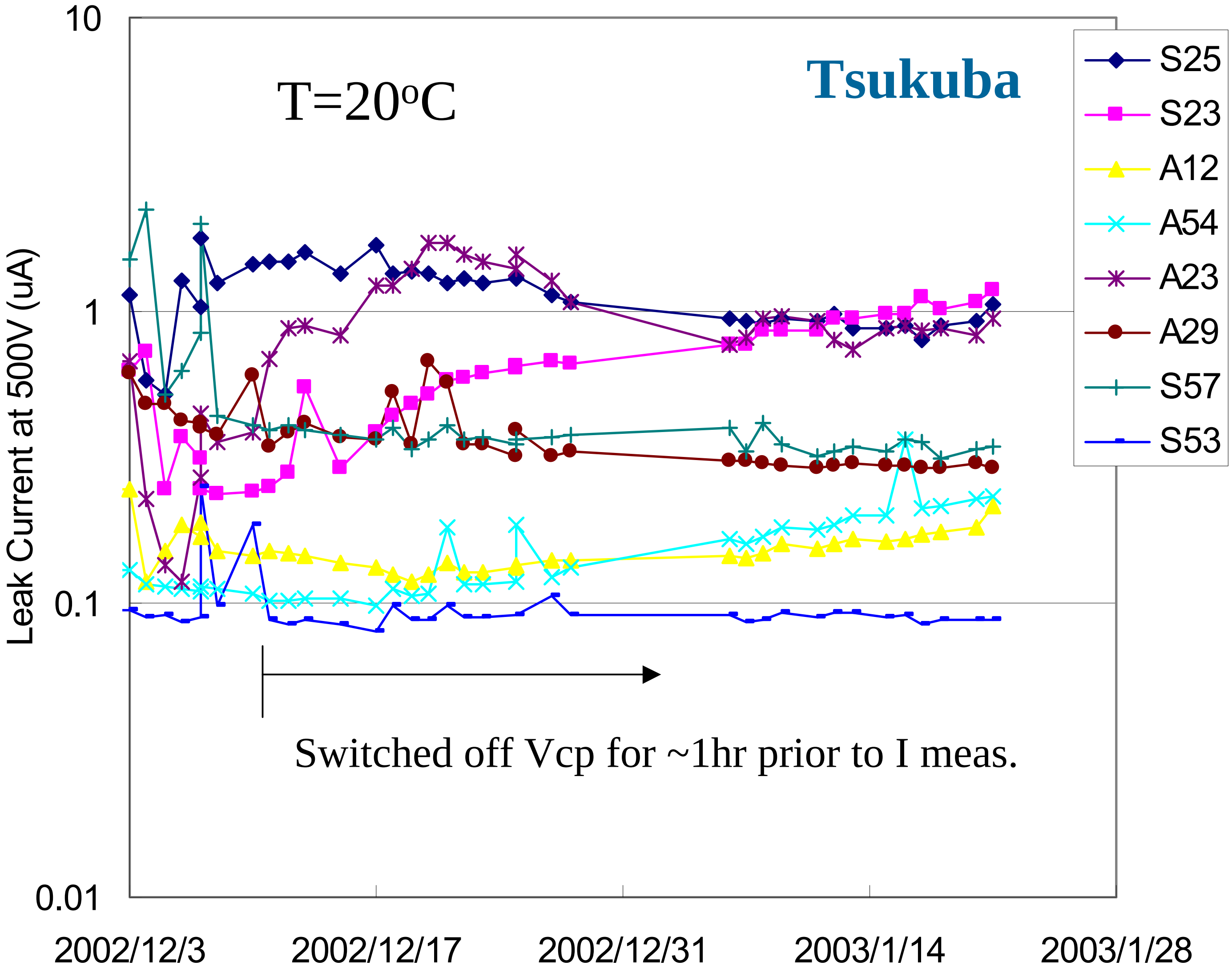
Long-term current stability



4 axial + 4 stereo sensors are placed
in an environmental chamber (20degC)

30 AC pads/sensor are wirebonded to
external V to test oxide punch-through
Vb=+500V
Vcp=+100V

Long-term stability test: status(1)



$T=20^{o}C$

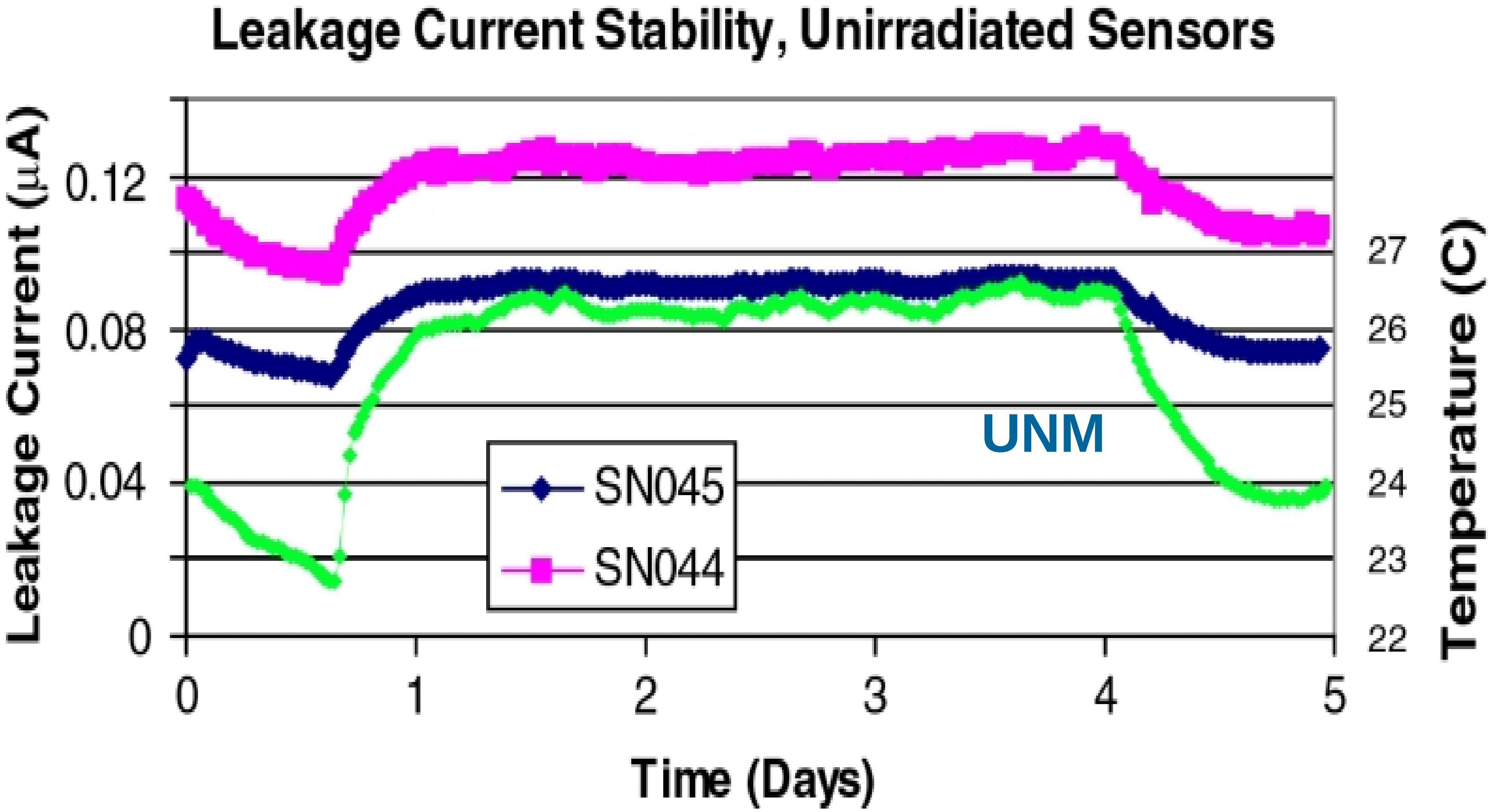
Tsukuba

Switched off Vcp for ~1hr prior to I meas.

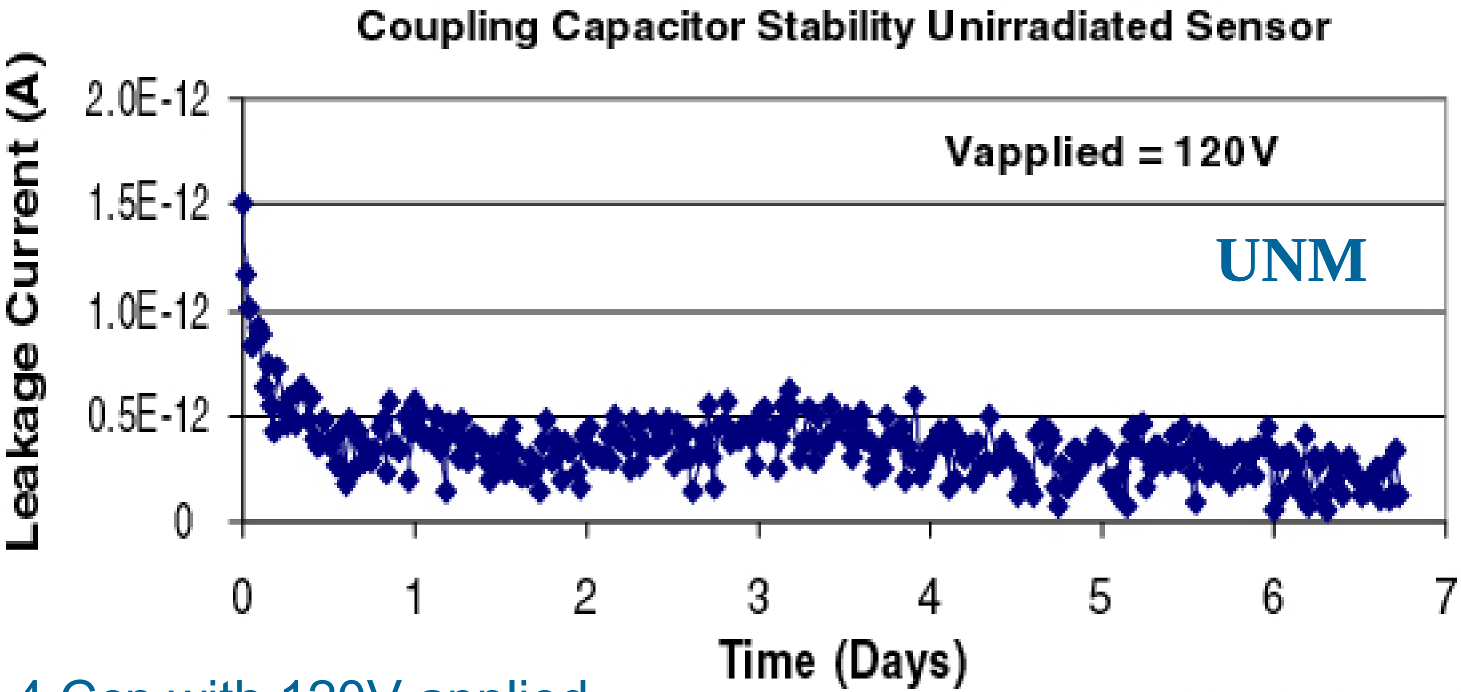
No breakdown sensors

One axial (A23) failed oxide stability, as HPK/tested at 100V only

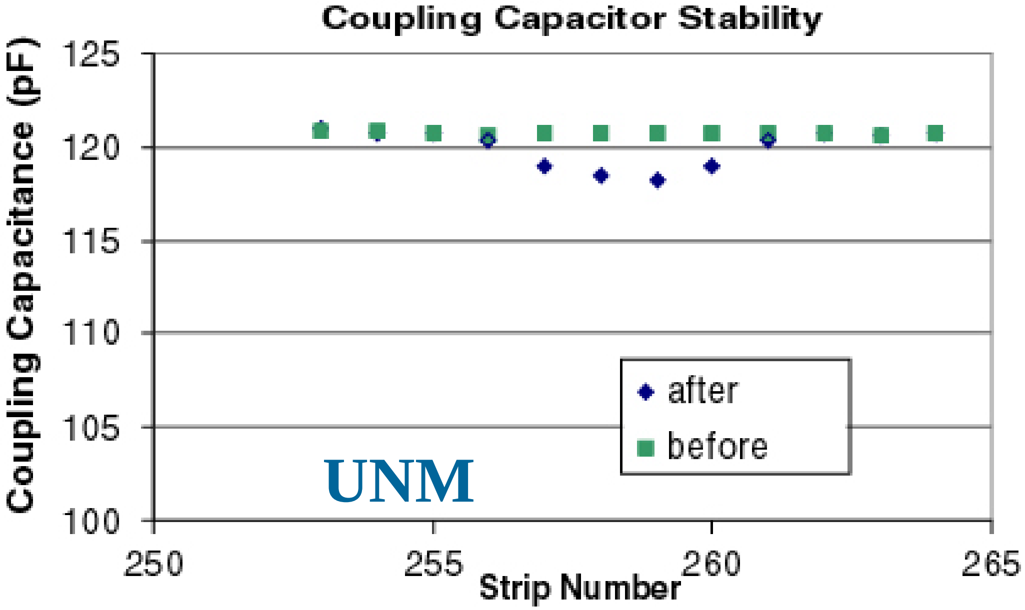
Long-term stability test: status(2)



Coupling capacitor at 120V



4 Ccp with 120V applied



Ccp dropped by 1.5% …

Limitations in HPK probing

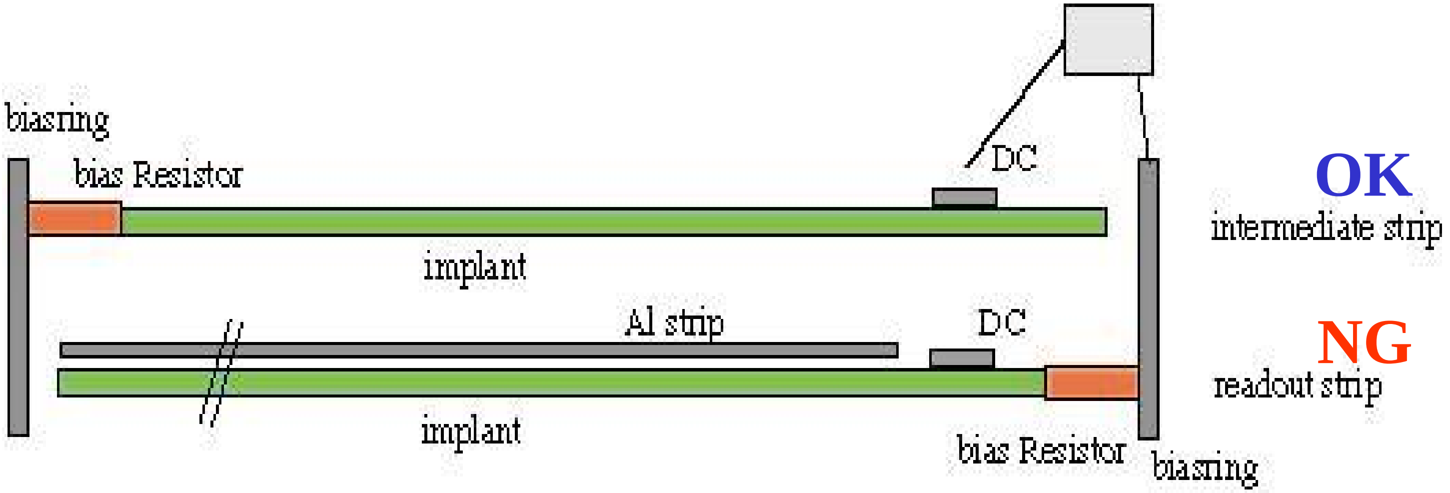


Fig. 9 Illustration of measurement configurations of readout and intermediate implant opens. strips .measurements.

HPK probing is not sensitive to detect Readout Implant Opens

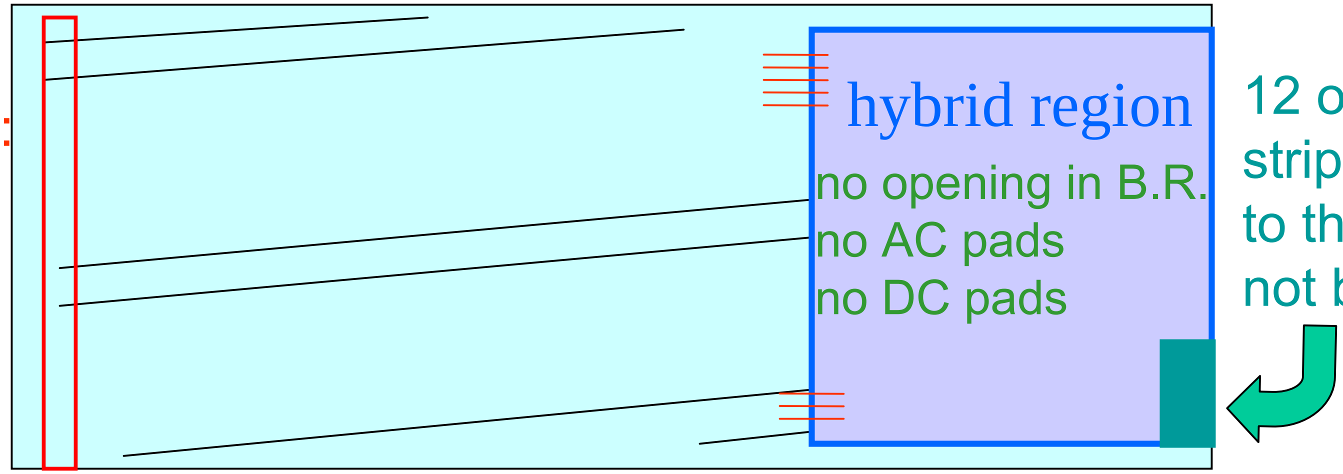
- DC scans at the poly-Si side

Tsukuba found 5 Readout Implant Opens, but none by HPK*

*HPK revisited their data, but no hint of irregularity found.
HPK tested the same sensor we tested, but failed to identify.

Also …

Limitation for stereo sensors



probe end:
511 pads

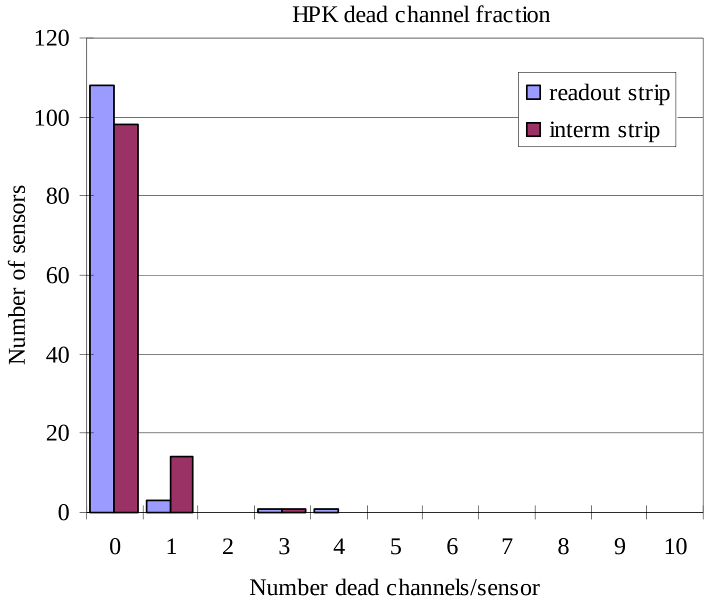
hybrid region

no opening in B.R.
no AC pads
no DC pads

12 or 19 short strips connected to this end can not be probed.

Our decision :

We accept un-probed short strips and un-detected implant opens, since the fraction of defect rate should be very small.



estimate from total number of defects, which is almost zero.

15 defects / 113 sensors
15 / 58k strips = 0.0026%

Post Irradiation Measurements

expected fluence at CDF: $(0.46 \pm 0.14) \times 10^{14}$ 1-MeV n/cm^2/fb^{-1} @L0

1.4×10^{14} n/cm^2 for 30 fb^{-1} @L0 (r=2.1 cm)

3 sensors irradiated to 1.4 x 10^{14} n/cm^2 …. Purdue
2 sensors irradiated to 0.7 x 10^{14} n/cm^2 …. UNM/Tsukuba

at MNRC Irradiation Facility at UC Davis

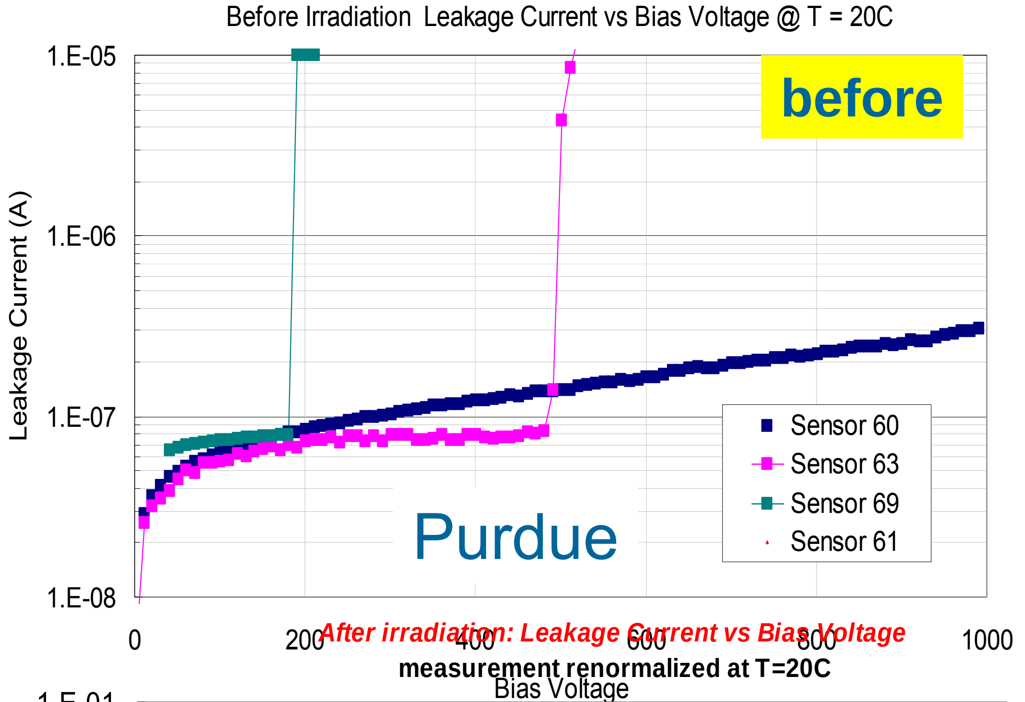
measured items:

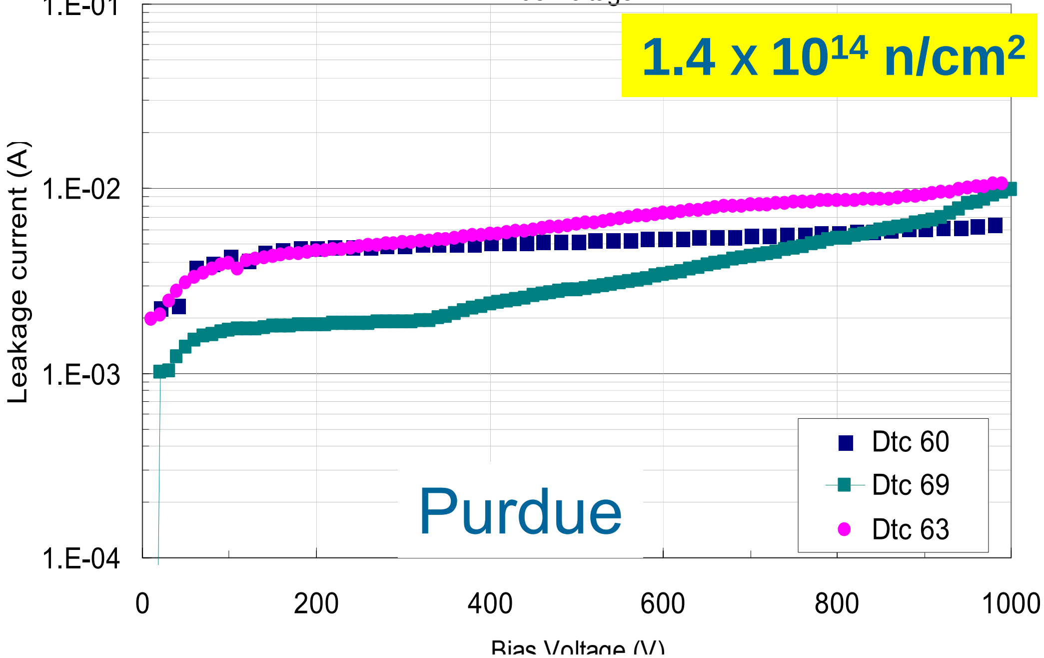
- **I-V Curve**
- **C-V Curve**
- **Interstrip Resistance**
- **Interstrip Capacitance**
- **Bias Resistance**
- **Coupling Capacitance**

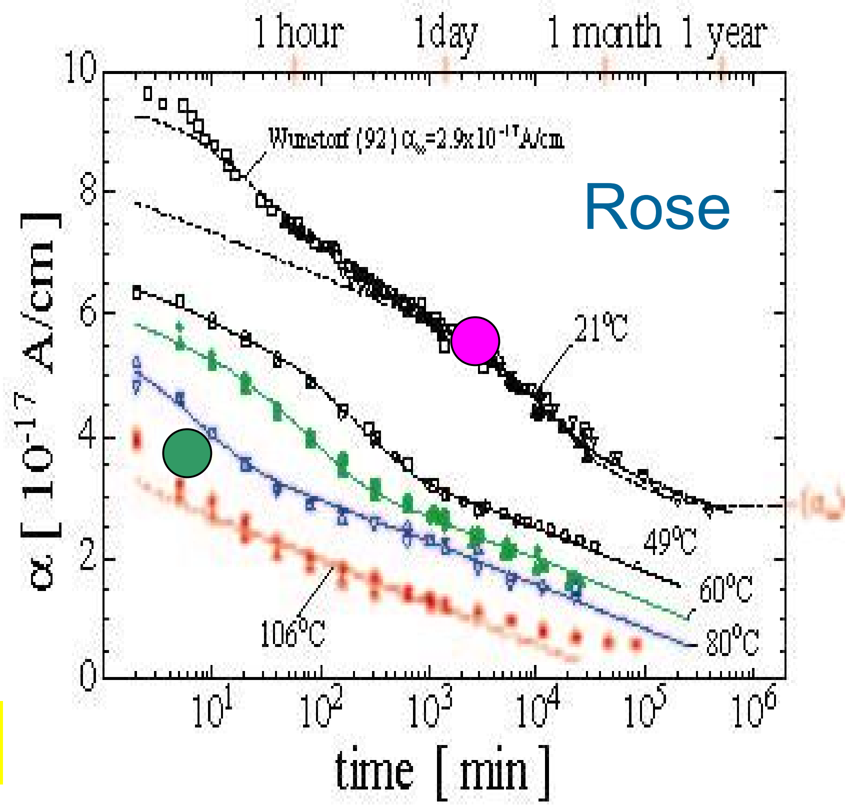
to see if any surprises …

in practice: not straightforward to characterize due to large leakage current…

I-V and Damage Constant (equiv. neutron fluence)


Before Irradiation Leakage Current vs Bias Voltage @ T = 20C

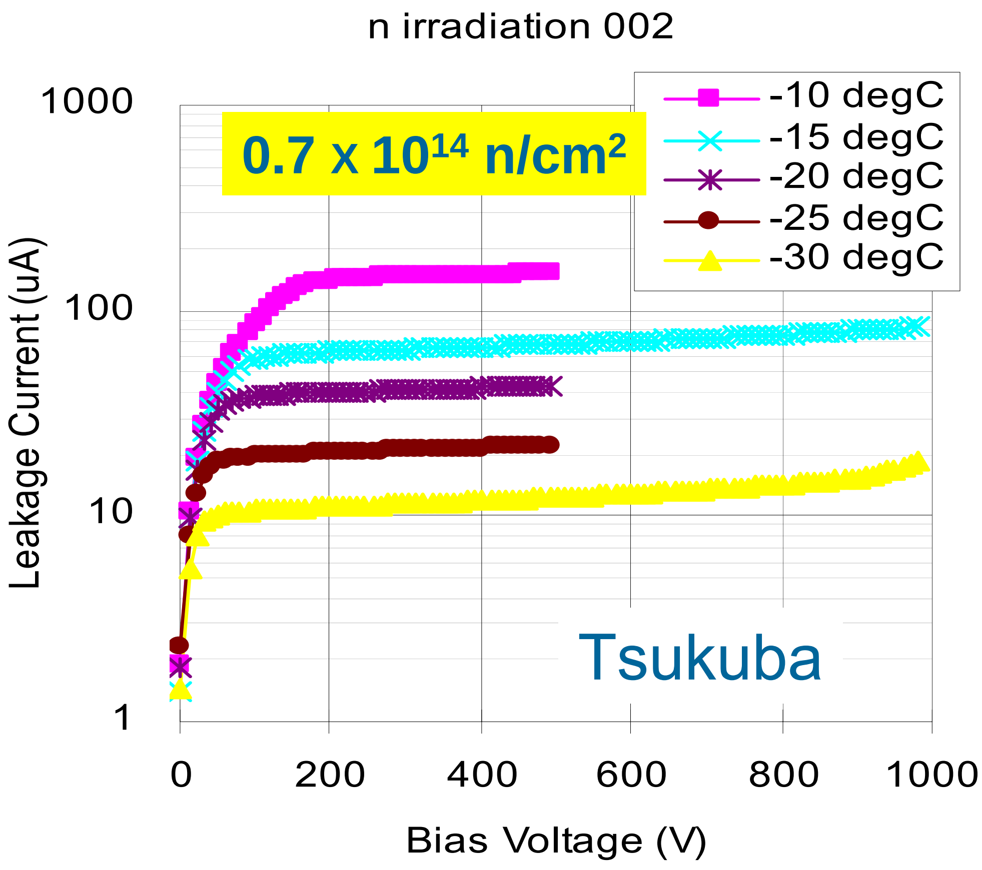

After irradiation: Leakage Current vs Bias Voltage
measurement renormalized at T=20C

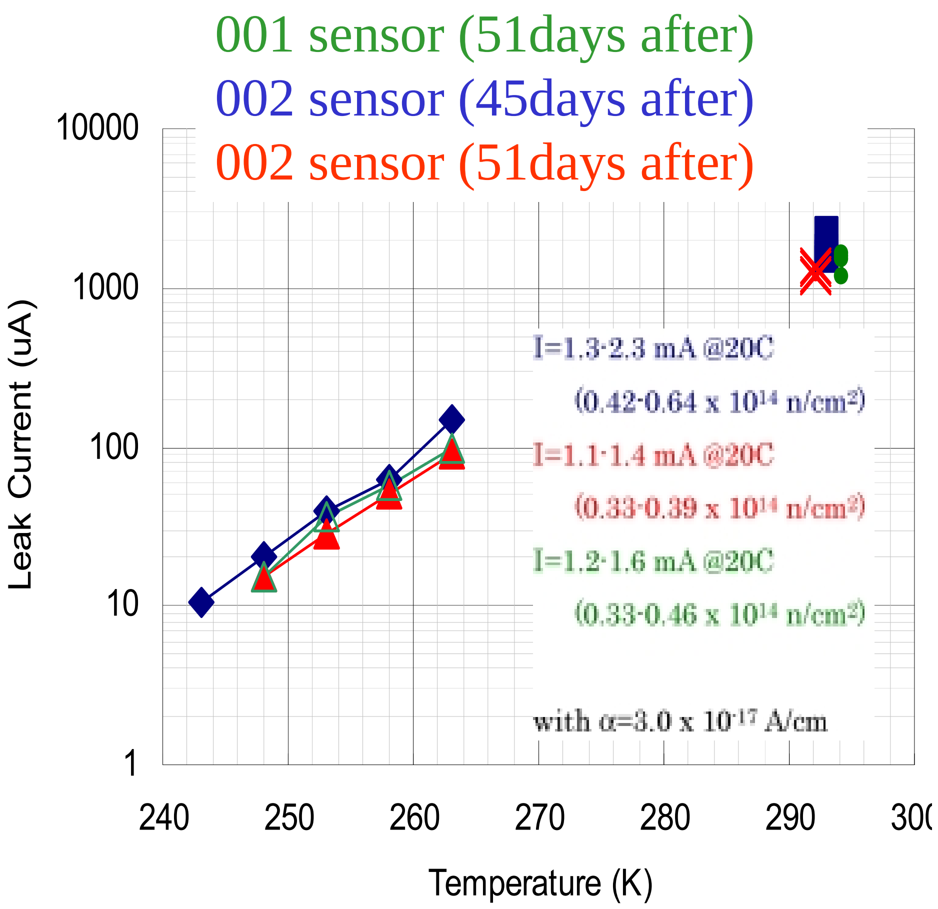


Sensor 69 experienced additional annealing

Using 4 x10^{-17} A/cm,
ϕ ~ **1.1 x 10^{14}** n/cm^2

I-V and Damage Constant (equiv. neutron fluence)



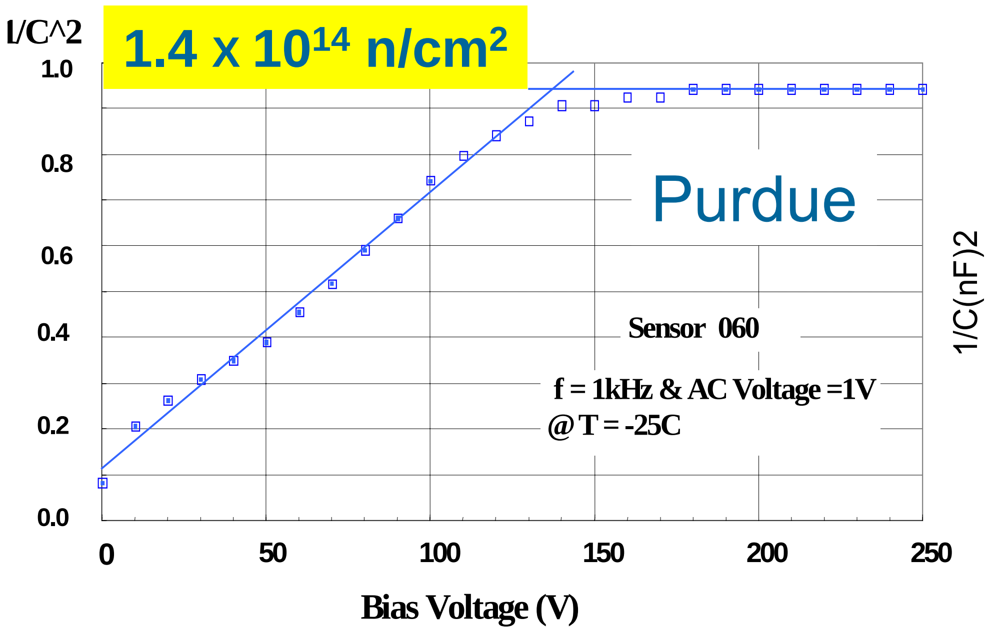


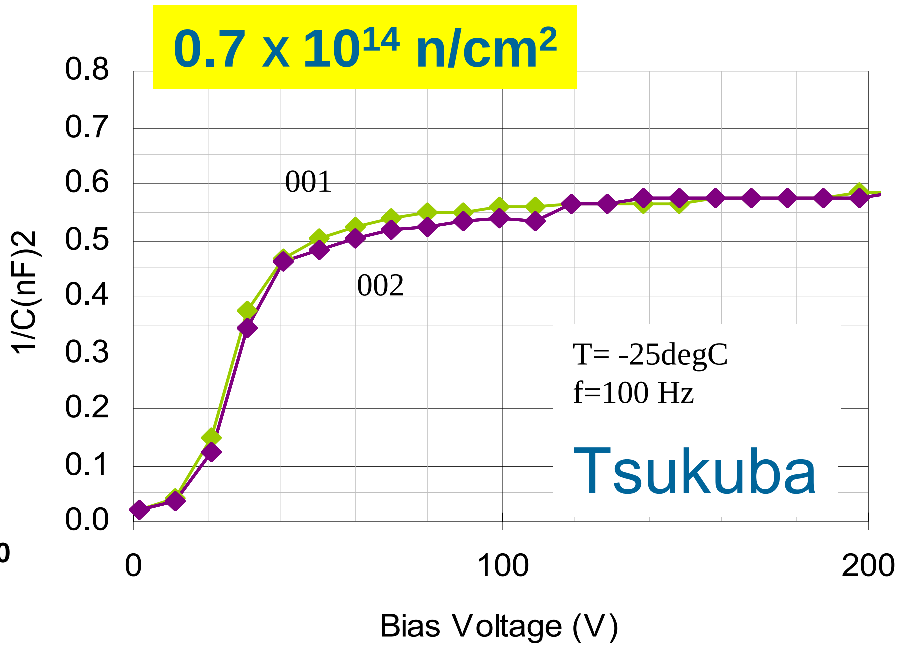
Using 3×10^{-17} A/cm,

$\phi = (0.33\text{-}0.64)\mathrm{X}10^{14}$ n/cm^2

- No unexpected I-V characteristics
- Damage as expected

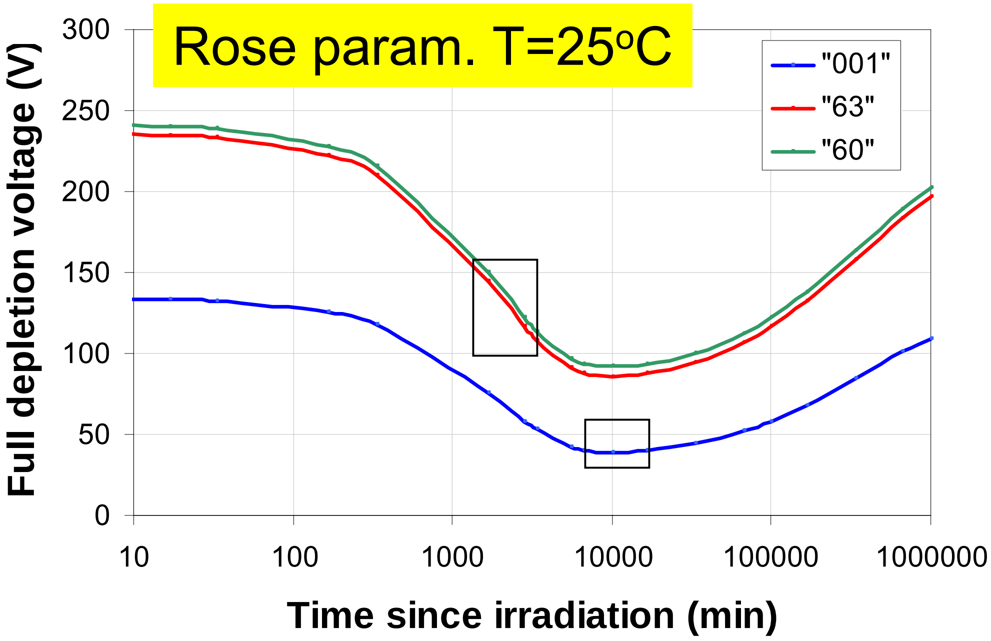
C-V and Full Depletion Voltage





Sensor 060: 128V
Sensor 063: 130V

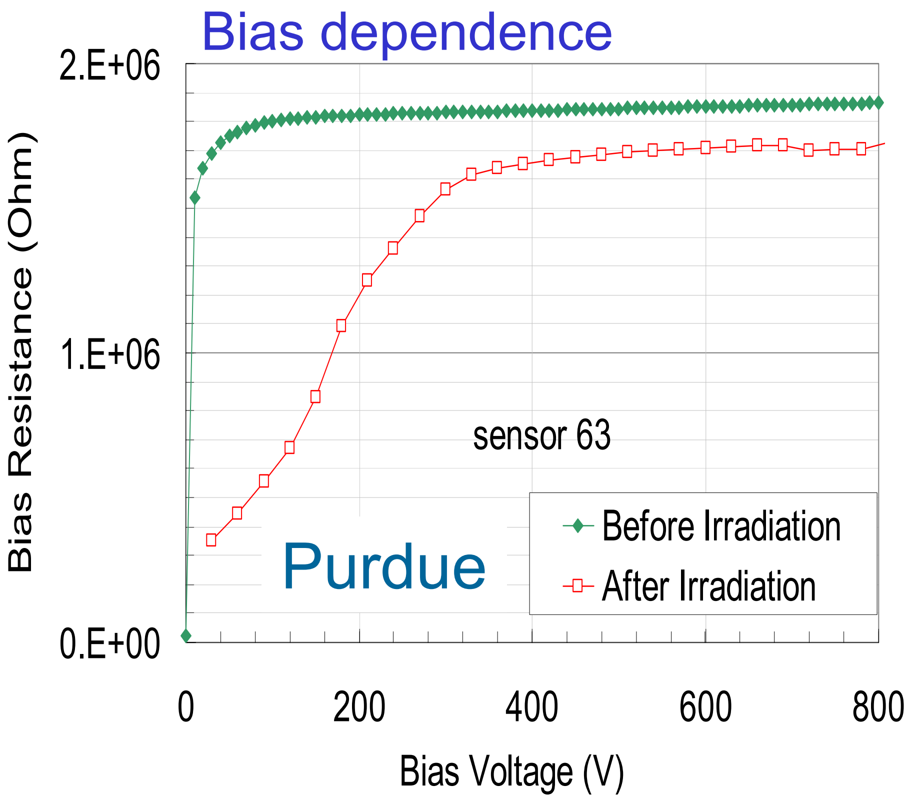
Sensor 01&02: ~50V

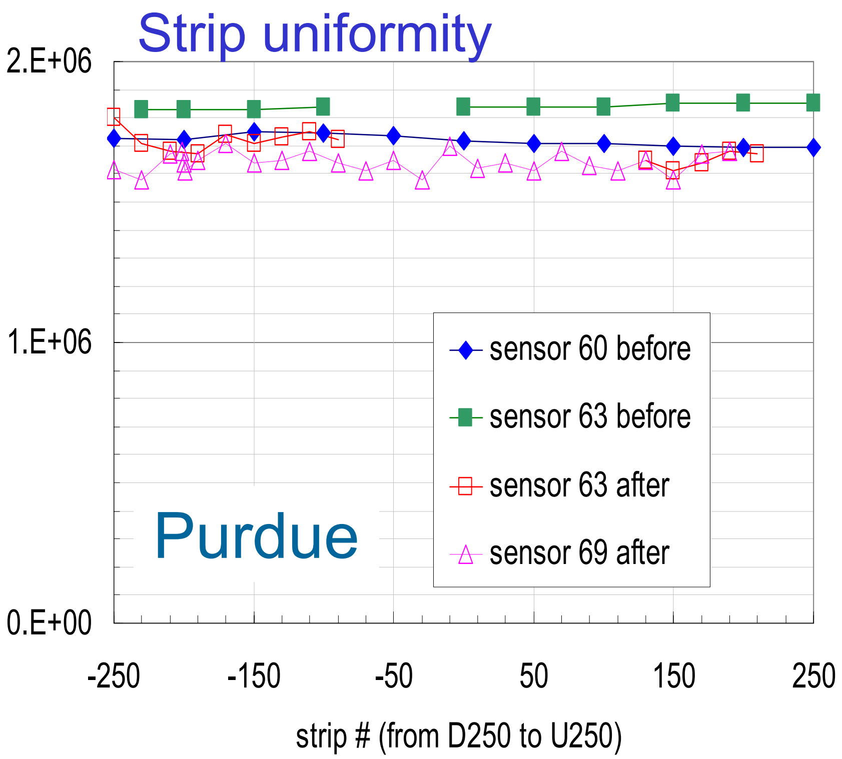


Results not inconsistent with Rose prediction

Poly-silicon Resistance

1.4×10^{14} n/cm^2





"Resistance" reaches the asymptotic value above ~350V *

"Resistance" is smaller after irradiation

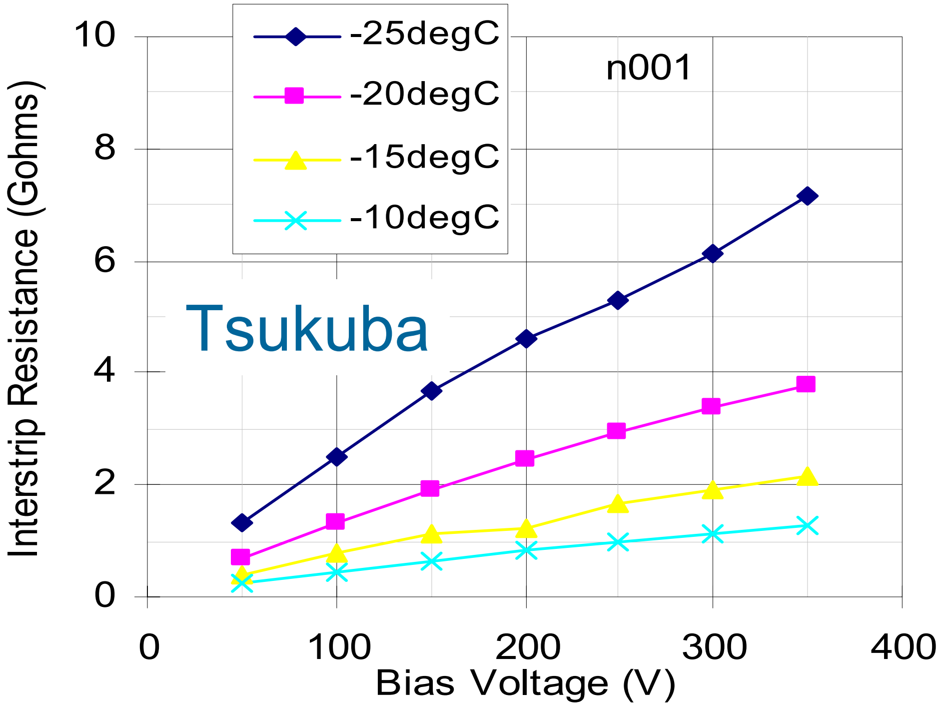
Intrinsic R is not degraded, but we see effects from surface charge

* substantially larger than V_{FD} (~130V)

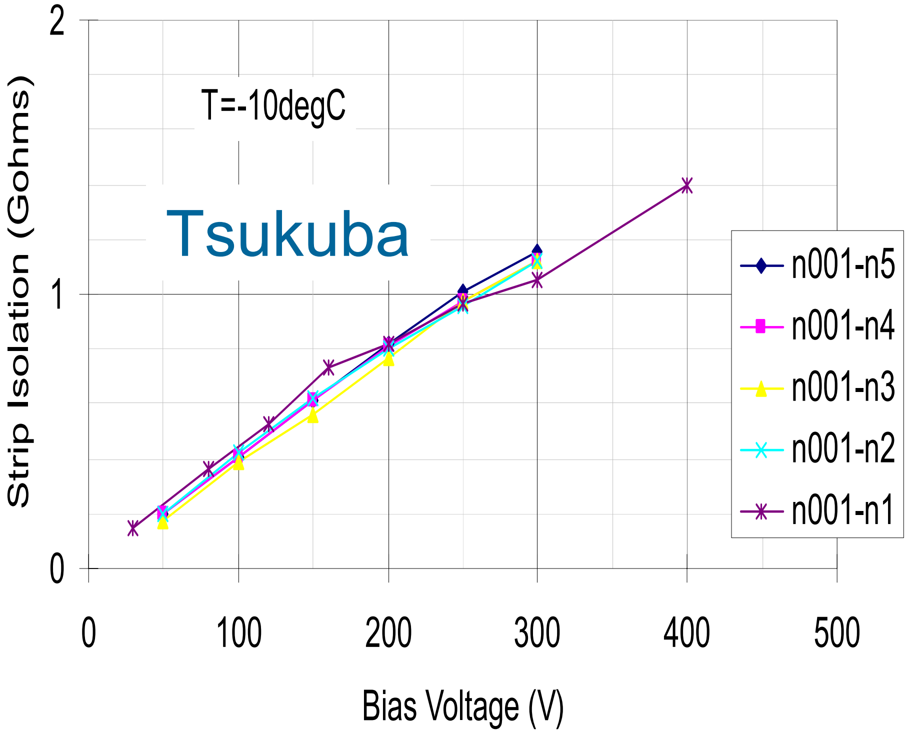
Interstrip Resistance

0.7 x 10^{14} n/cm^2

temperature dependence:



strip uniformity@ -10^{o}C:

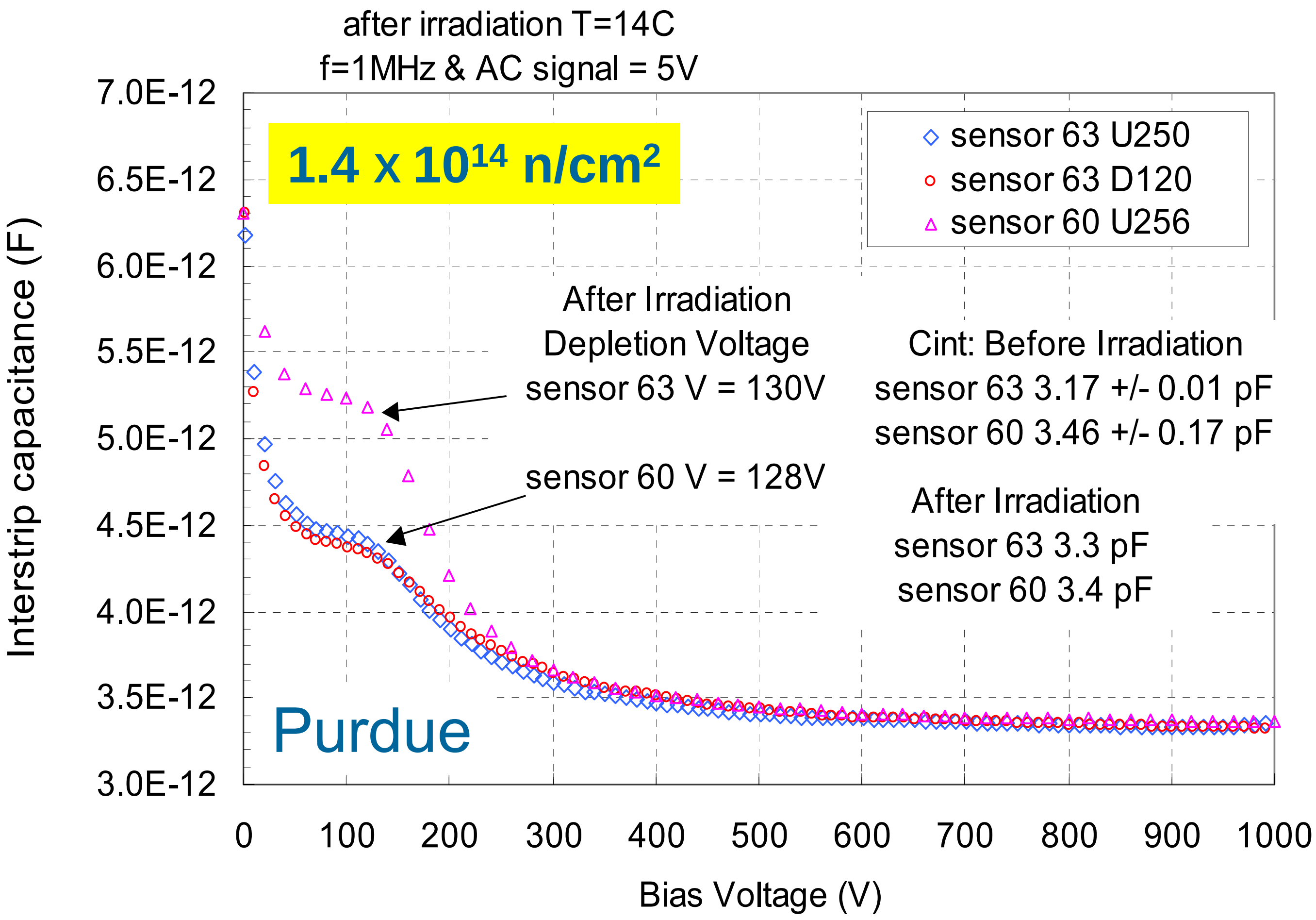


Strong temperature dependence due to surface charge

Bias be >250V* at –10^{o}C for R>1GΩ

* substantially larger than V_{FD} (~50V)

Interstrip Capacitance (I)



Shoulders corresponding to the measured full depletion voltage

Asymptotic Cint consistent with pre-irradiation values

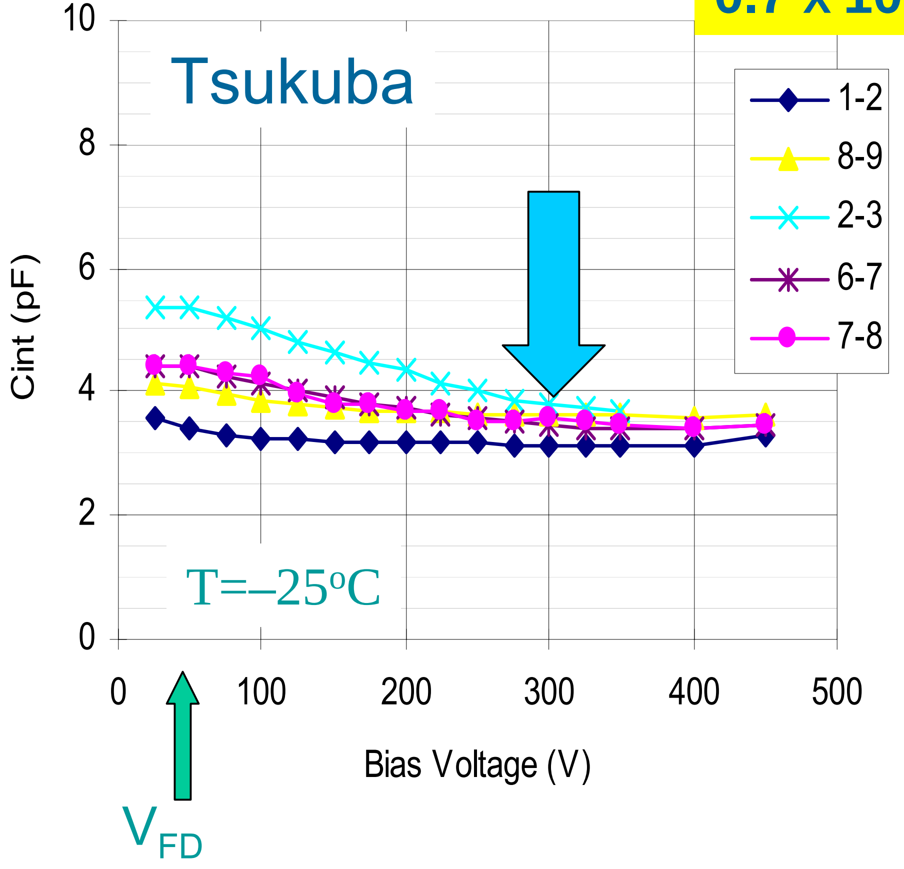
Cint decreases slowly above V_{FD}

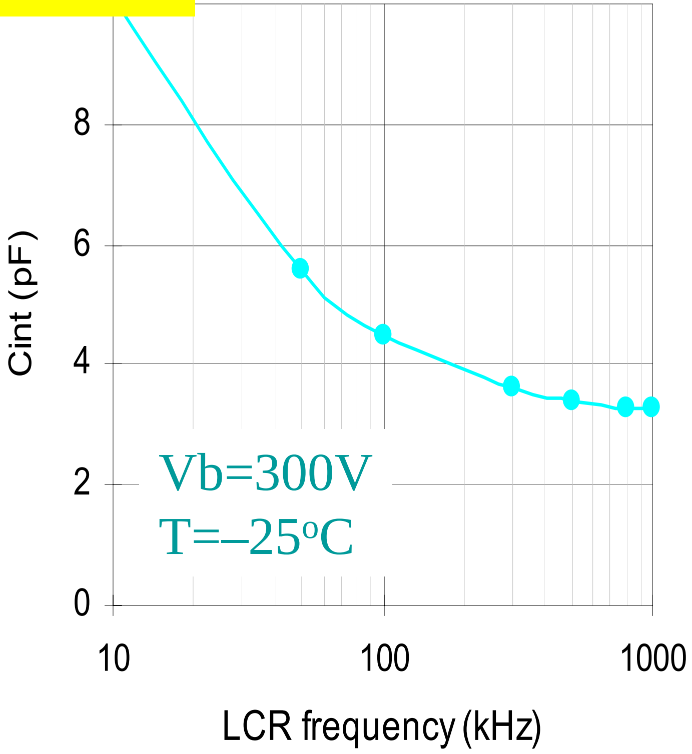
Interstrip Capacitance (II)

strip uniformity@ -25°C:

0.7 x 10^{14} n/cm^2

freq depend. at 300V

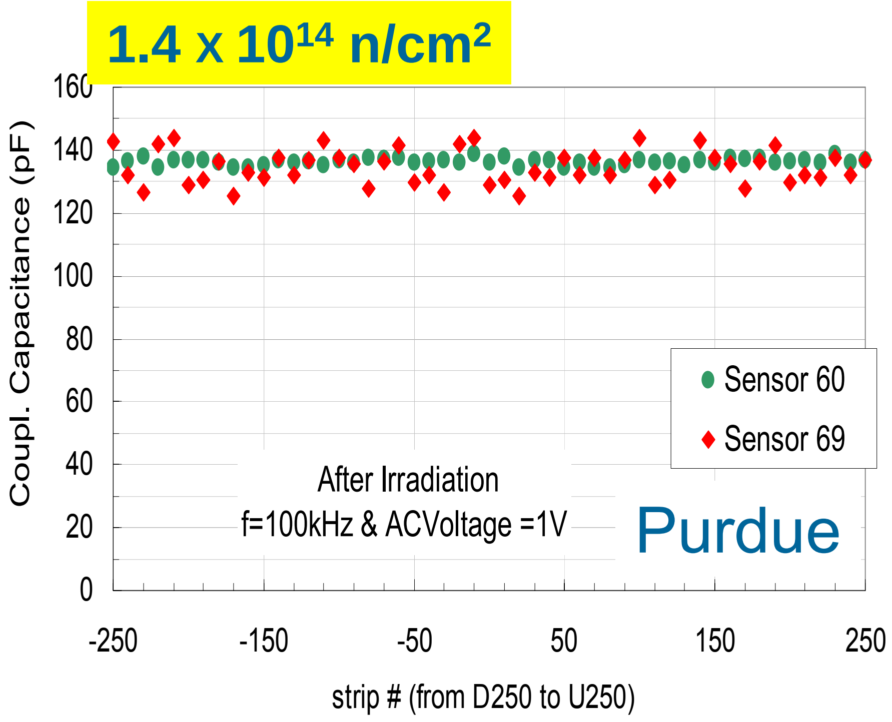




LCR freq (1MHz) may be not high enough …?

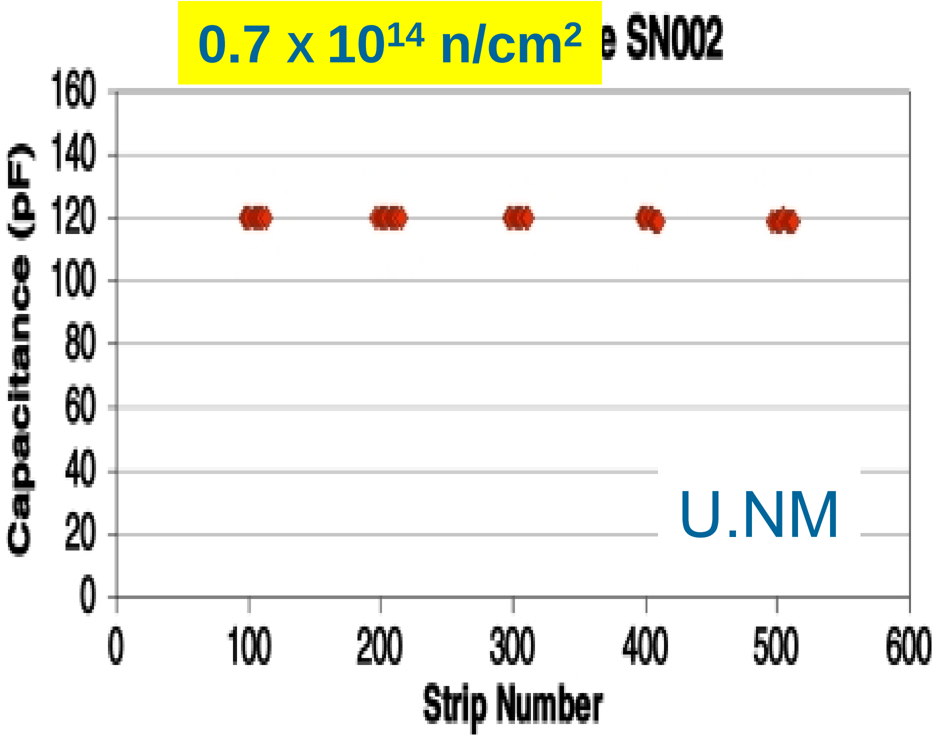
Require a bias substantially larger than V_{FD} to reach the asymptotic values

Coupling Capacitance



1.4 x 10^{14} n/cm^2

Purdue



0.7 x 10^{14} n/cm^2

U.NM

Coupling Capacitors are OK!

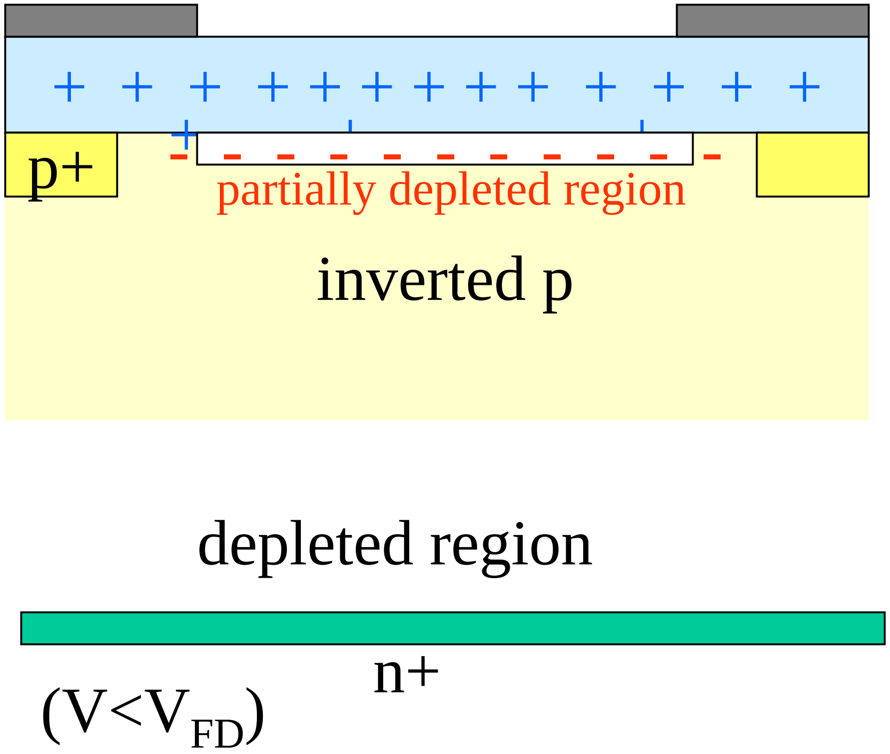
A Consideration …

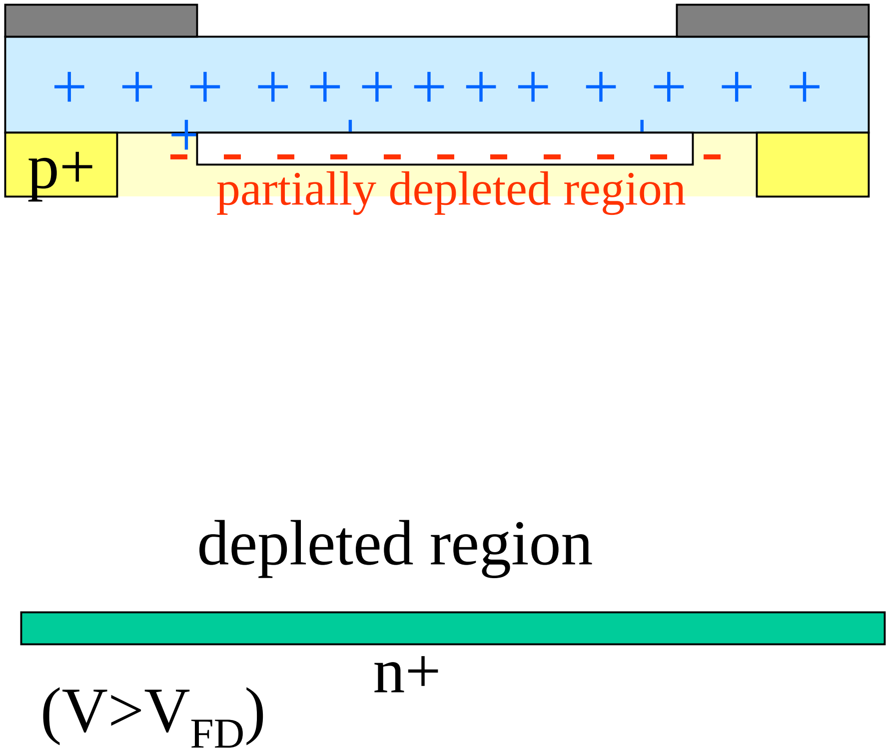
For V< V_{FD}:

Moderate isolation is achieved

Cint is not very large

V>> V_{FD} is required to
isolate strips
minimize Cint

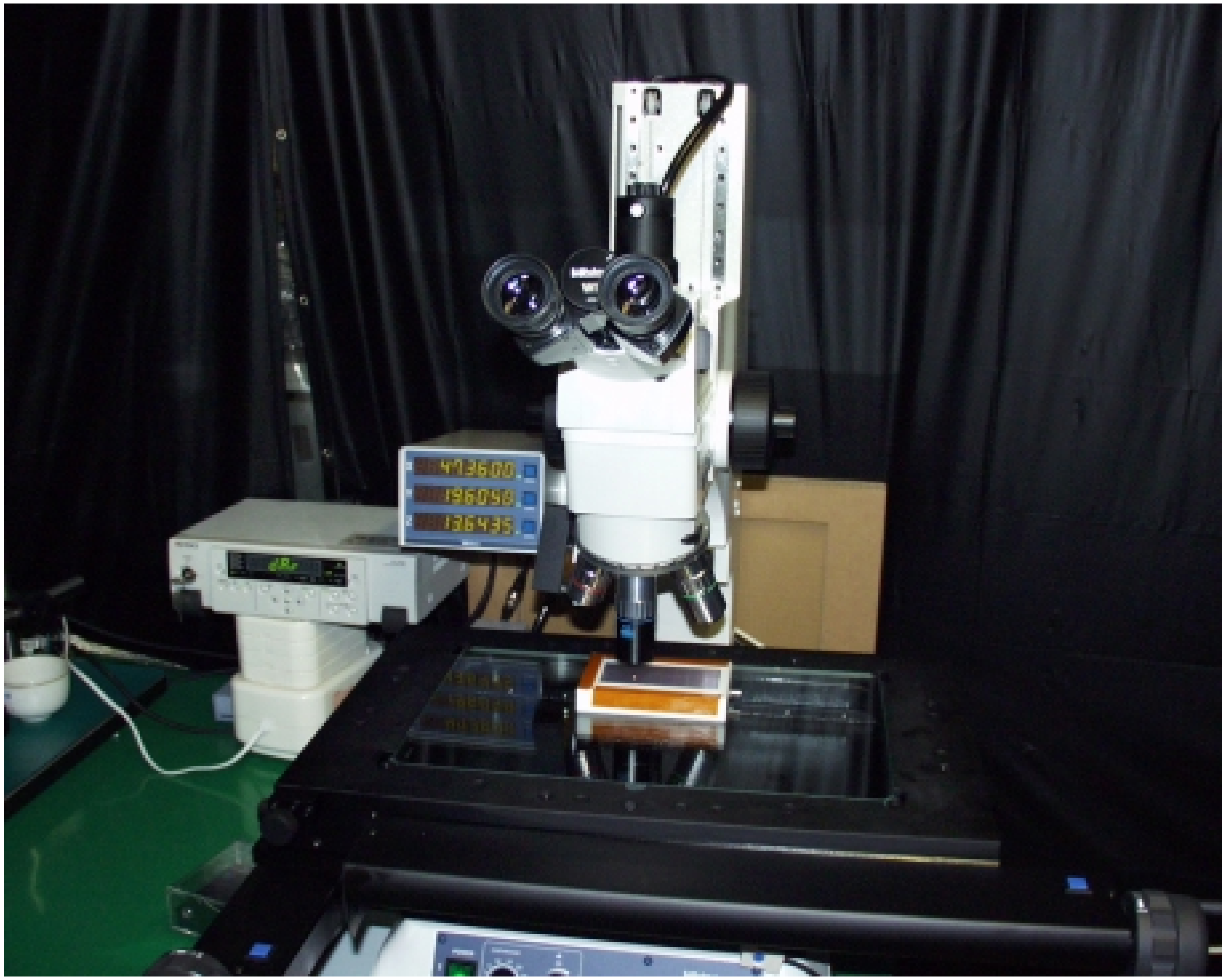




Mechanical Precisions

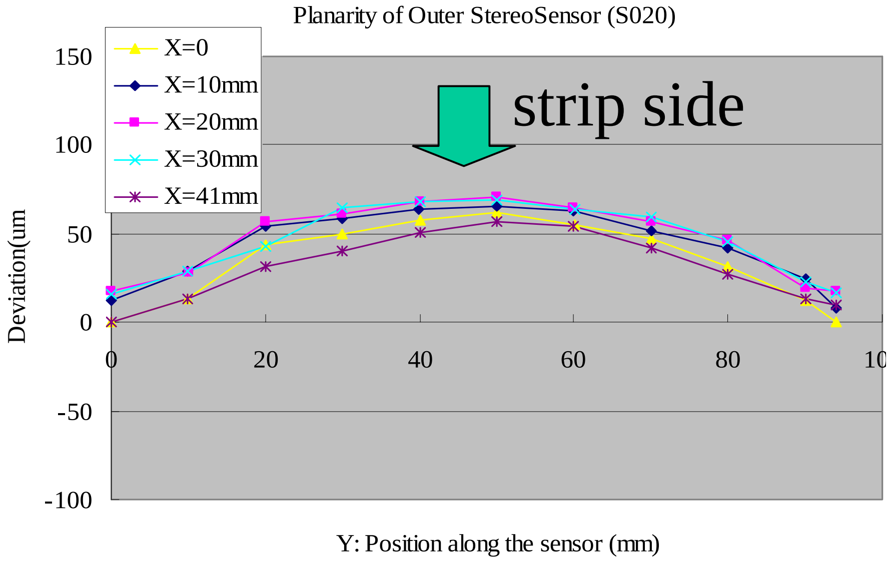
Measuring Microscope : Mitutoyo MF-UA

typ 1-2 um in XY
typ 3 um in Z



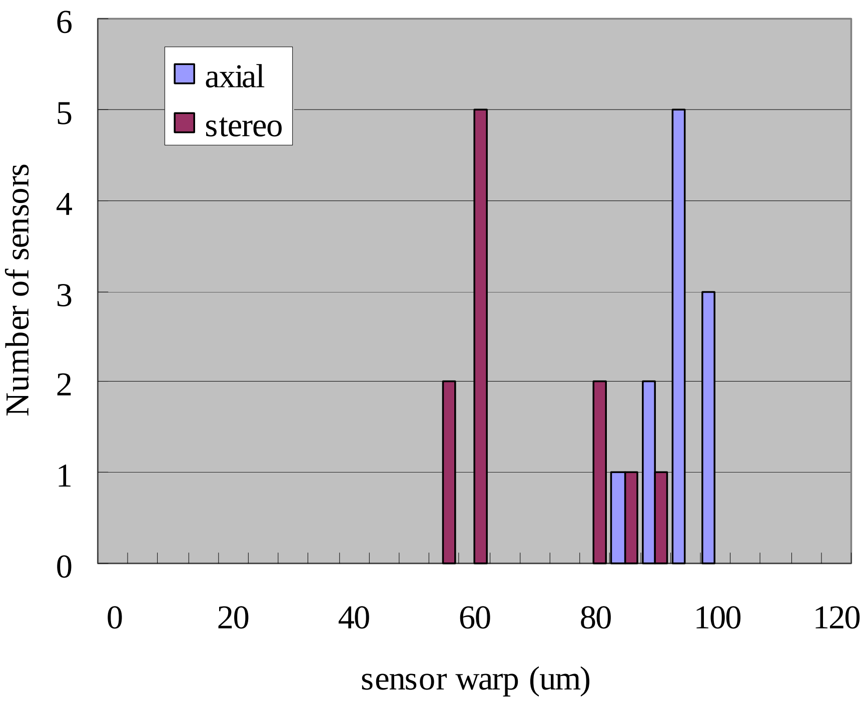
- Wafer thickness
- Edge cut precision
- Sensor warp

Sensor Planarity

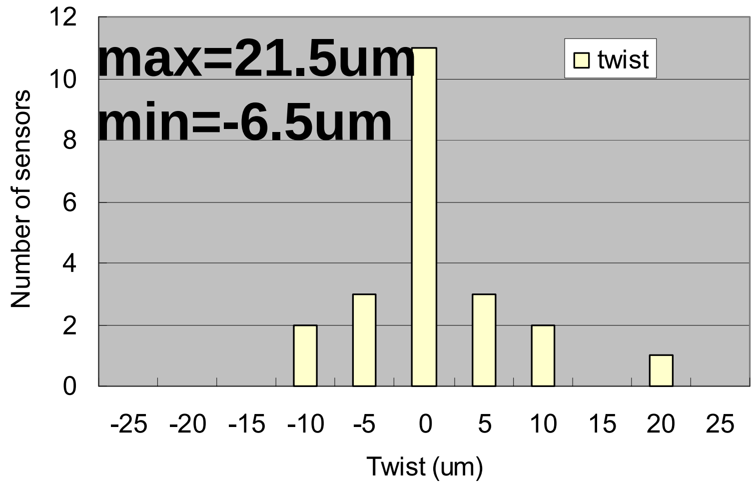


(single side) sensors are bowed due to CTE difference

typical profile

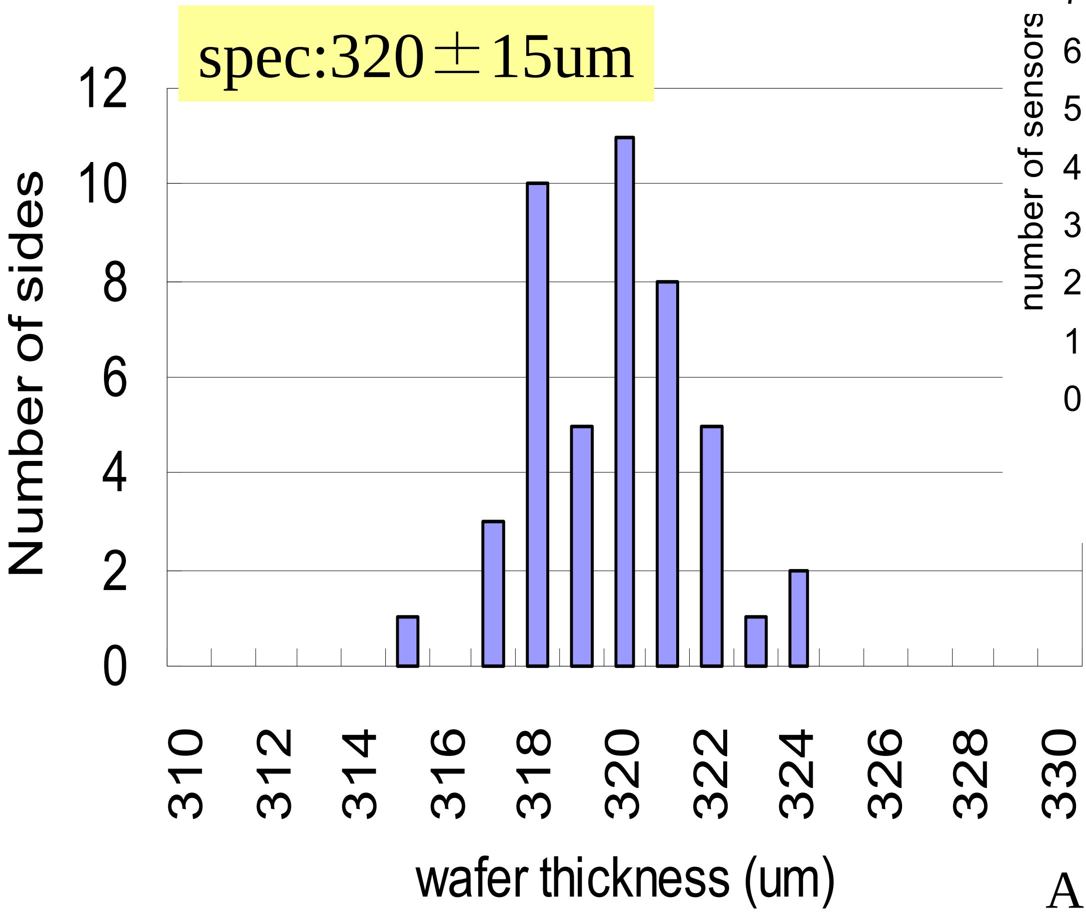


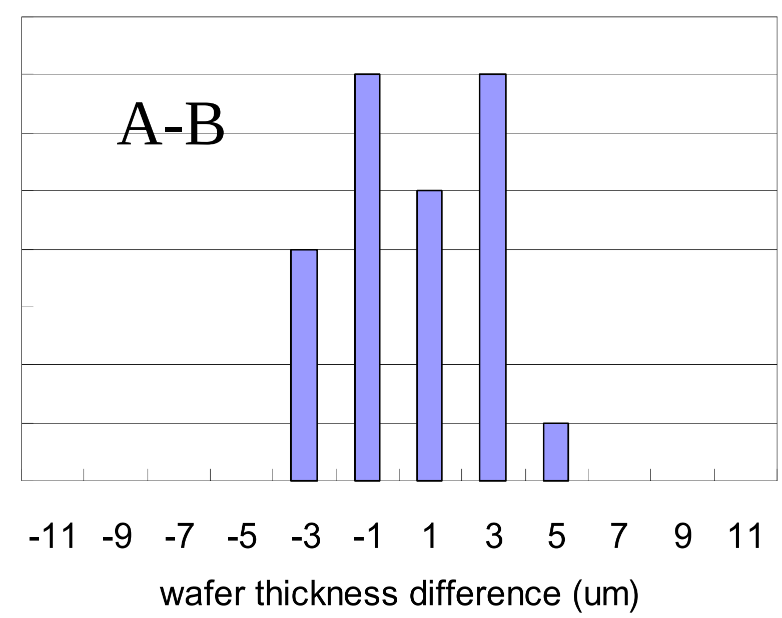
height at the center wrt fiducials at 4 corners

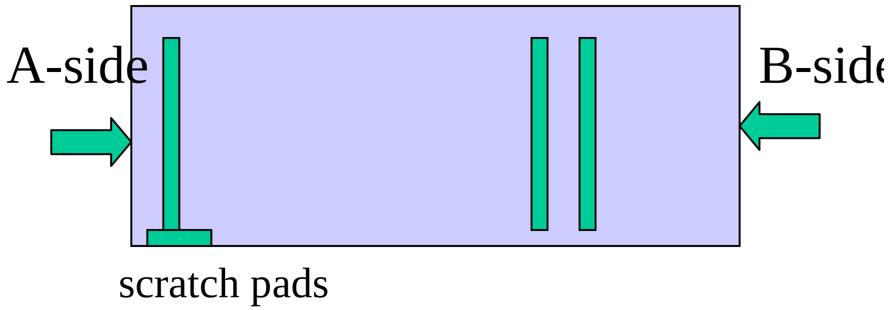


deviation of 4th fiducial wrt others

Wafer thickness

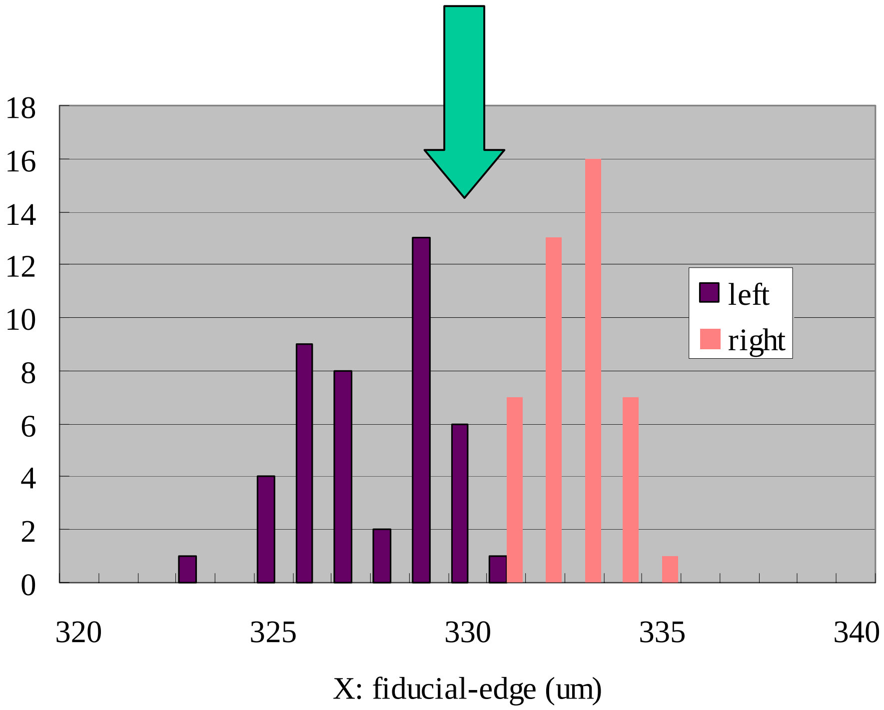


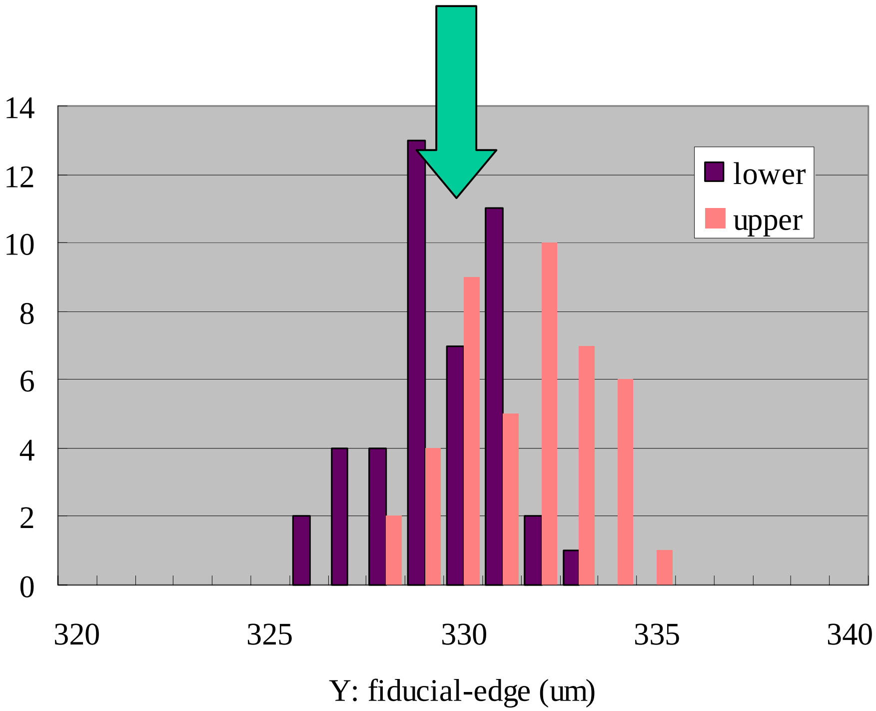




Edge cut precision

nominal = 330 um





edge cutting is precise to 5 um…

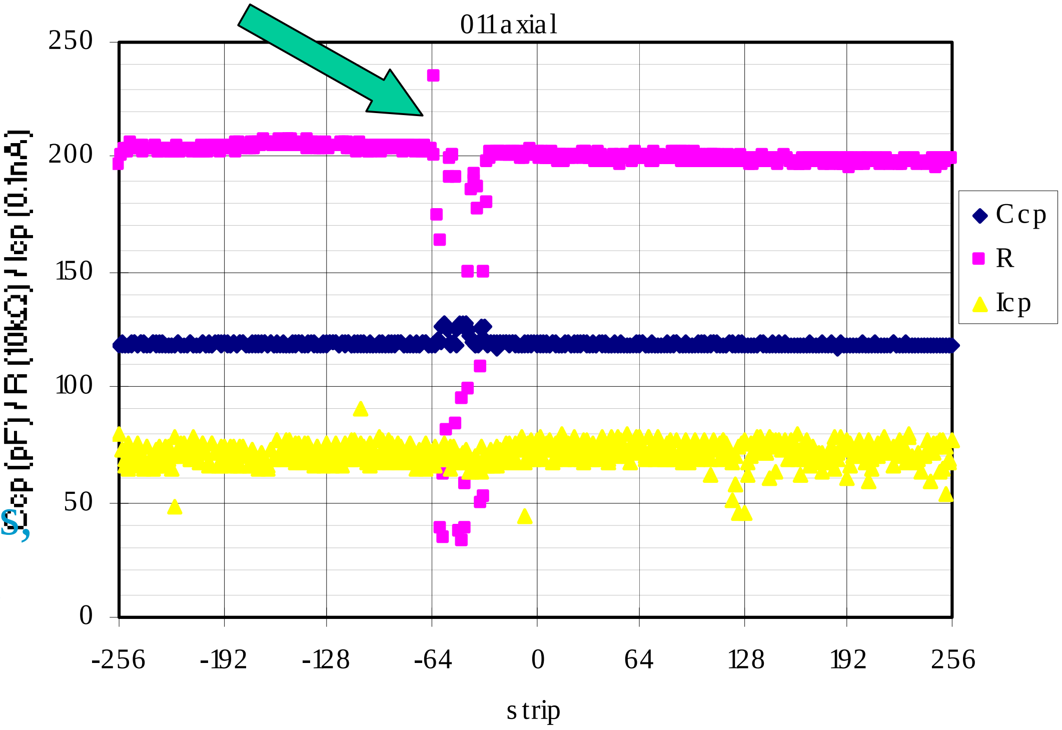
Charge-Up Issue

In early stage, we often got bad distributions (R/Ccp e.g.)

Rint, Cint are also affected

symptom: isolation degrad.

From the location and size of bad strips, we suspected vacuum tweezers caused charge-up on sensor surface



After eliminating use of tweezers, only a few “charge-up” channels much less frequently

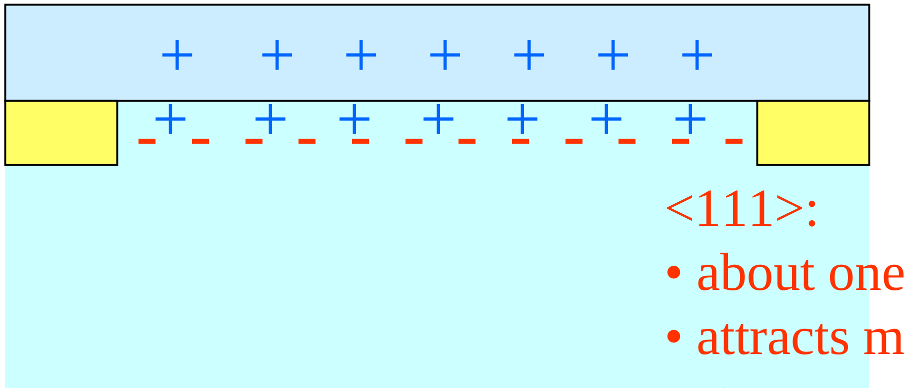
This could be due to probe tips not properly discharged

After 3 months, it became hard to reproduce charge-up…

anyway… Charge-up disappear if the sensor is back in envelope

Charge Up – its mechanism

<100> is easier than <111> to charge up
due to lower transition potential for inversion layer creation

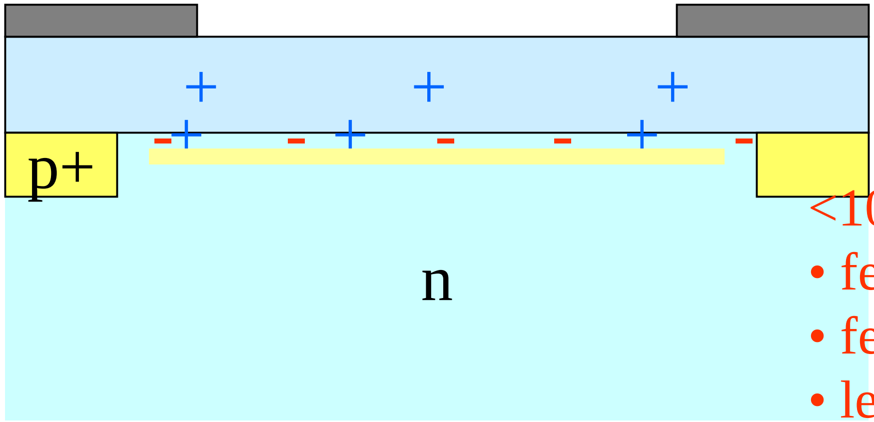


fixed oxide charges in SiO_2

Si-SiO_2 interface

<111>:

- about one order abundant positive charges
- attracts more electrons, which isolate P+ implants
- stronger against external effects



<100>:

- fewer positive charges
- fewer electrons attracted
- less robust against external effects

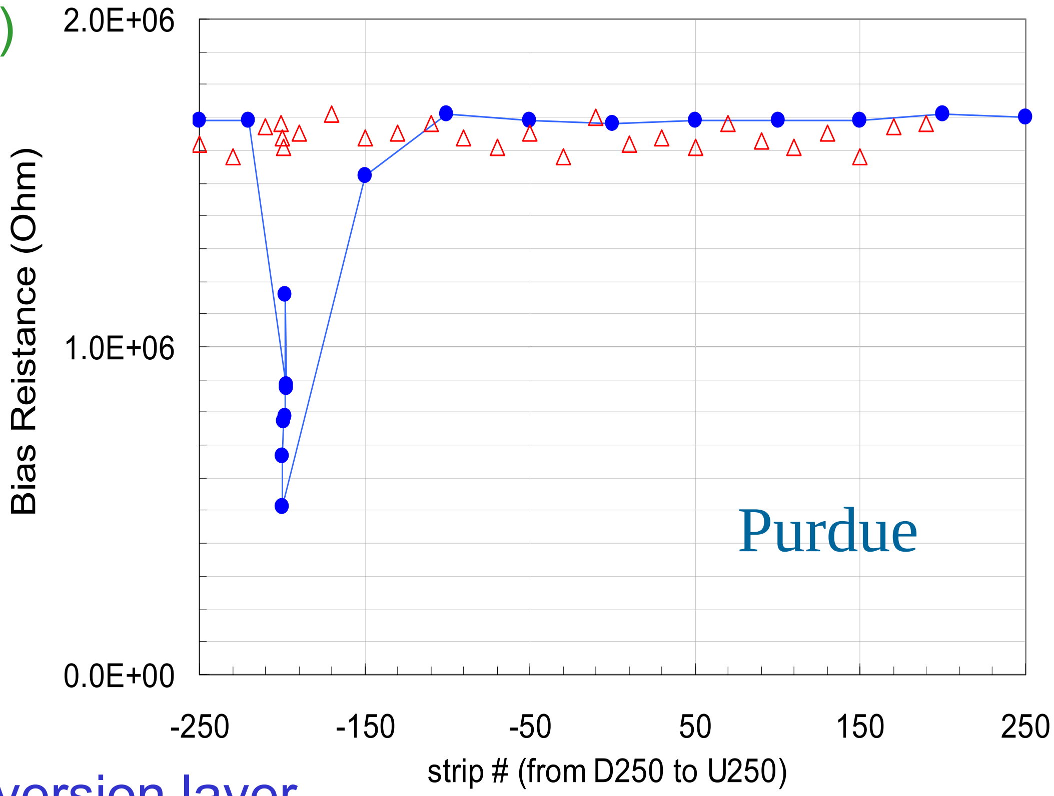
may create P layer = inversion layer

Charge Up – recovery

Inversion layer should disappear by radiation

accumulation of positive charges in oxide layer, which attract more electrons (> extra holes in inversion layer)

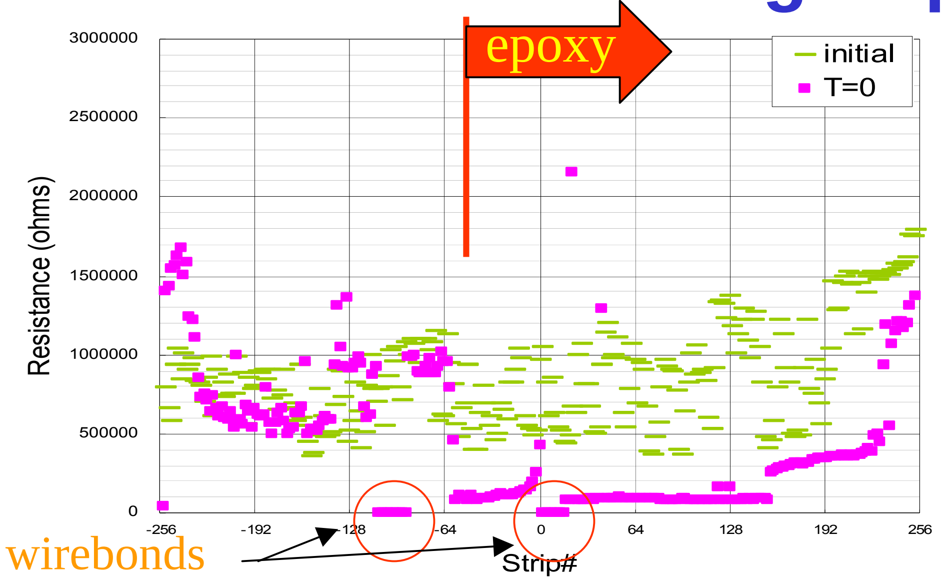
Strips with small R recovered after n irradiation

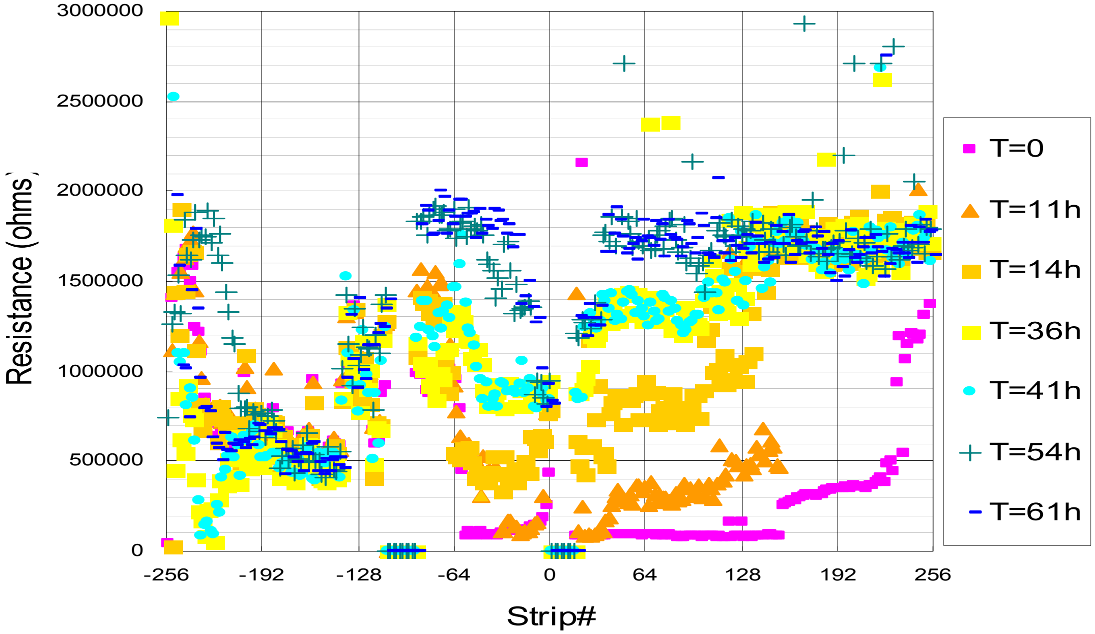


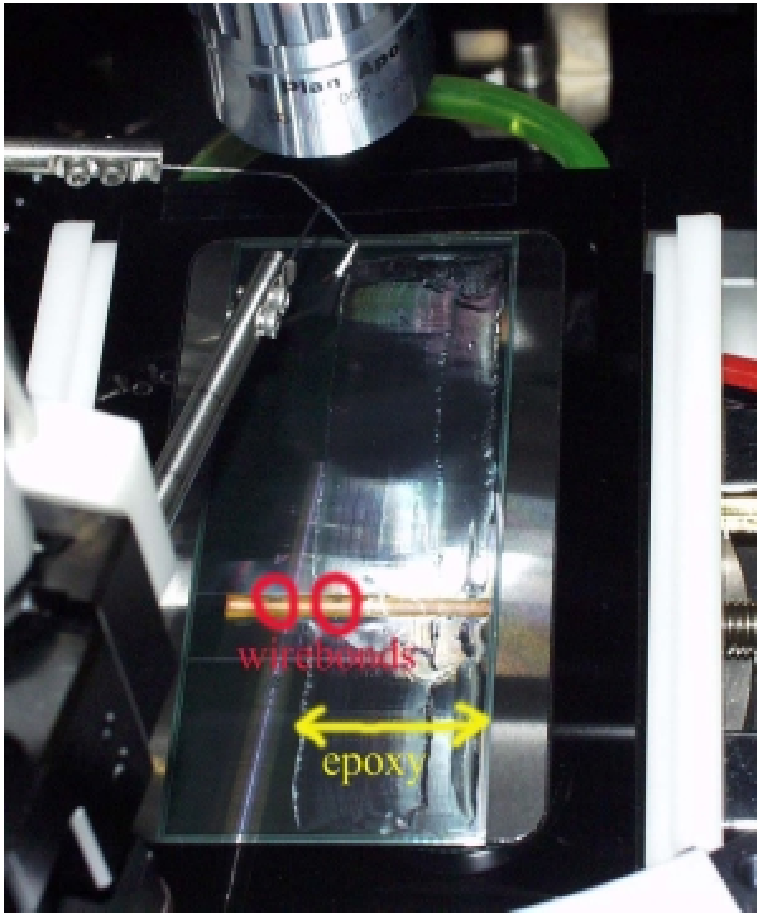
Surface charges responsible for inversion layer creation should be taken away if there is a route

- Al strips are wire-bonded
- substantial surface current

Charge Up – recovery







a sample heavily charged up
apply epoxy (Araldite 2011)
some Al strips wire-bonded

(1) recovery around bonded strips
(2) no recovery in isolated area for 61h

Charge-Up Recovery (w/ UV)

Bias is kept on at 200V

UV on (Ib~175uA)

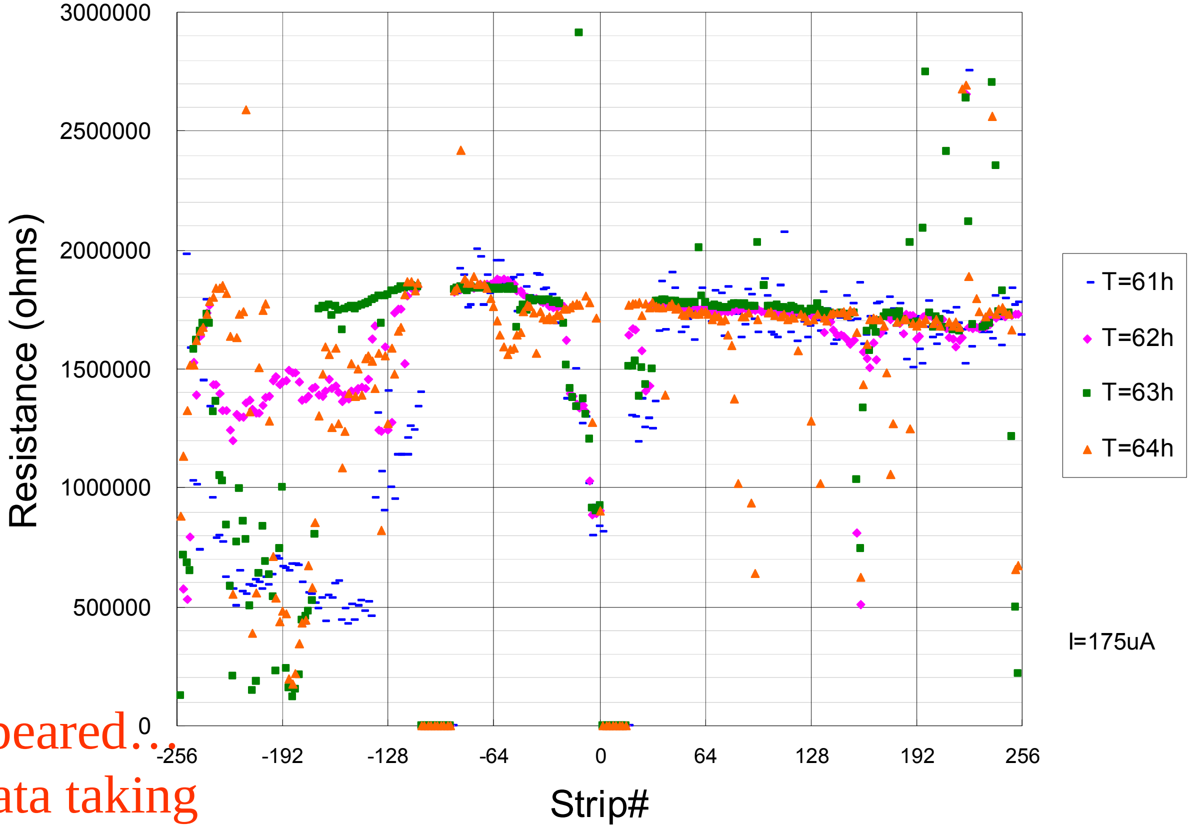
substantial recovery in the region close to wire-bonds (see the time constant)

Unfortunately but…

- probes wiped prior to T=63h measurement
- sensor taken off the stage !

UV lamp ON

please ignore isolated points (bad contact)



charge-up disappeared..

we terminated data taking

Lessons:

- wire-bonds remove surface charge
- surface charge in isolated area could remain at least for days
- UV enhances charge removal
- avoid use of tweezers unless it is proven not to charge-up

Summary of Prototype Characteristics

Electrical characteristics are OK

- Leakage current is small (~0.1uA) and IV good to 1000V
- Dead channel fraction is small
- Defects reported by HPK are all identified
- 5 new readout implant opens are found
- 1 new un-identified defect

limitation of the
HPK test system

Mechanical precisions are OK

Post-irradiation characteristics are OK

- Reasonable full depletion voltages of irradiated samples
- Degradations in Isolation, Cint,… due to surface charge
  as expected
  requires additional bias to recover them

Charge-up: understood & manageable

Important that our QA is sensitive to detect charge-up when it happens

Quality Assurance Procedure

CDF note 6283

Jan.25, 2003 v1

Silicon Sensor Quality Assurance for the CDF Run2b Silicon Detector

N. Bacchetta[1], G. Bolla[4], D. Bortoletto[4], A. Canepa[4], B. Flaugher[1], K. Hara[6], D-H. Kim[5],
S. Kim[6], M. Hoeferkamp[3], D. Pellett[2], A. Roy[4], S. Seidel[3], Y. Takei[6], I. Yu[5]

[1]Fermilab, Batavia, Illinois, USA
[2]University of California, Davis, California, USA
[3]University of New Mexico, Albuquerque, New Mexico, USA
[4]Purdue University, West Lafayette, Indiana, USA
[5]CDF-Korean Group (Syungpook U, Sungkyunkwan U)
[6]University of Tsukuba, Tsukuba, Ibaraki, Japan

Abstract

This documents describes in detail the quality assurance (QA) program for the CDF Run2b silicon sensors. The scope of the QA program, the responsibilities of the participating institutions and the measurement procedures are defined.

Production Schedule: HPK Proposal

6“ line is shared with other commercial products

HPK enhances those production till June 2003

HEP production is postponed/slowed down:

CMS ↘ GLAST → (ATLAS → 4”)

HPK Proposal for CDF order:

	03/06	07	08	09	10	11	12	04/01	02	
axial	135	135	270	270	270	210	275	135	+	= 1700+
stereo	0	0	125	125	0	125	125	190	+	= 690+

Outer axial: 1656

Outer stereo: 648

L0 axial: 144

+ spare: ~20%

QA program: guideline

Clear definition of QA program is essential to achieve effective/efficient QA among several institutions involved.

HPK: lot basis data: R_poly, R_implant

for each sensor: I-V up to 1000V
full depletion voltage (C-V)
visual inspection

for each strip: strip integrity (AC scan/DC scan)

- Ccp
- Al open
- Al bridge
- Isolation (~R_poly)
- implant open (interm.)
- leaky

Institutions:

intensive probing ~ intensive damaging …

do minimum required: I-V and visual inspection

intensive probing on sensors with irregular I-V
with visual problems
with many defect strips

check HPK's QA

Organization

Procurement and Testing Institutes

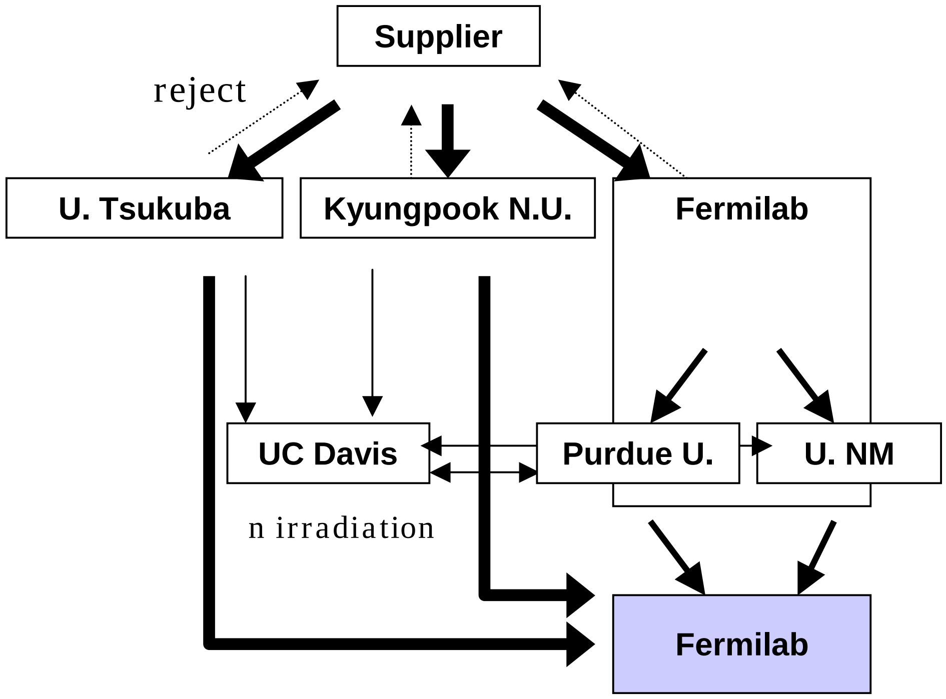
- University of Tsukuba, Japan. Local coordinator: K. Hara
- Kyunpook National University, Korea. Local coordinator: D-H. Kim

Procurement Institute

- Fermilab, Batavia, USA. Local coordinator: N. Bacchetta

Testing Institutes

- University of New Mexico: S. Seidel
- Purdue University: D. Bortoletto
- University of California, Davis: D. Pellett



Supplier
manufacture QA
QA datasheet

Procurement Institutes
Sensor registration
Visual inspection, I-V
QA on sub-sample, or
coordinate sub-sample tests
at Testing Institutes

Testing Institutes
QA on sub-sample

Fermilab, assembly center
visual inspection, I-V

QA program - summary

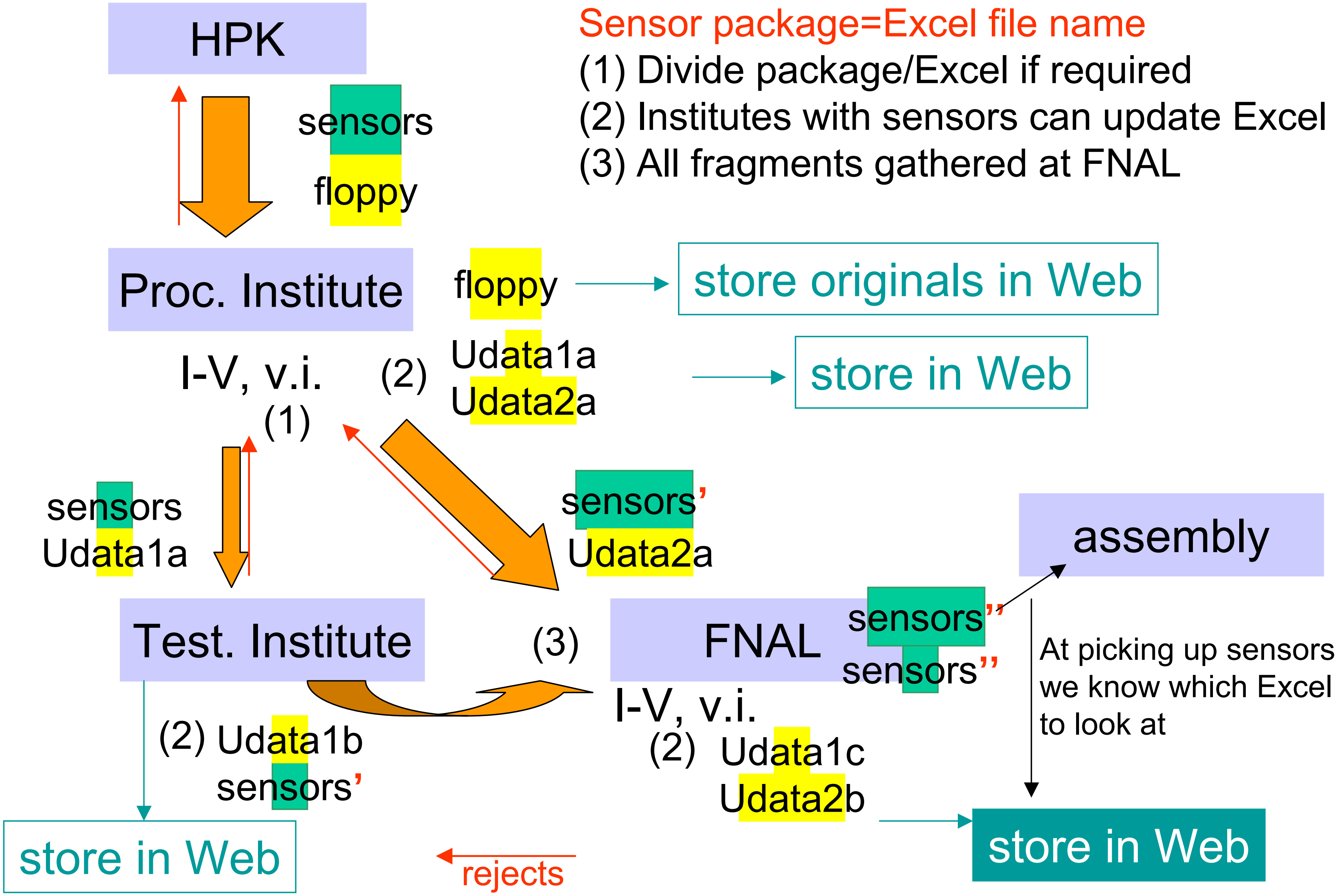
QA item	QA done by	sampling (production)	Comments	Excel book page
(1) Initial registration	Procur. Inst.	100%		Page-1
(2) Visual Inspection	Procur. Inst.	100%		Page-2
(3) I-V	Procur. Inst.	100%		Page-3
(4) IV-stability	Testing Inst.	30% (5%*)	Sensor subsets	Page-4
(5) AC-scan	Testing Inst.	30% (5% *)	Sensor subsets	Page-5
(6) C-V	Testing Inst.	30% (5% *)	Sensor subsets	Page-6
(7) Mechanical Tests	Testing Inst.	10% (5% *)	Sensor subsets	Page-7
(8) DC-scan	Testing Inst.	10% (5%*)	Diagnostic+subsets	
(9) Poly-Si resistor	Testing Inst.	10% (5% *)	Diagnostic+subsets	
(10) Interstrip Cap.	Testing Inst.	10% (5% *)	Diagnostic+subsets	
(11) Interstrip Res.	Testing Inst.	10% (5% *)	Diagnostic+subsets	
(12) n irradiation	Testing Inst.	3-4 / 2 mon		
(F) IV and Vis. Inspct	Fermilab	100%		Page-1

(2)/(3) will be merged to (F), once quality sensor production is established

*or at least one sensor per batch

Do (9) frequently if it is easier for detecting charge-up

Excel based Database



Sensor package=Excel file name

(1) Divide package/Excel if required

(2) Institutes with sensors can update Excel

(3) All fragments gathered at FNAL

At picking up sensors, we know which Excel to look at