Scribe-Cleave-Passivate (SCP) Slim Edge Technology for Silicon Sensors

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Acknowledgements:

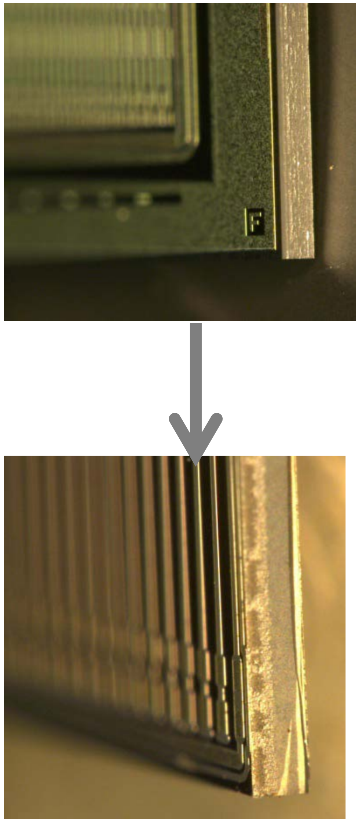
1) Technical Guidance and Support by
Marc Christophersen*, Bernard F. Phlips*
(*) Code 7654, U.S. Naval Research Laboratory

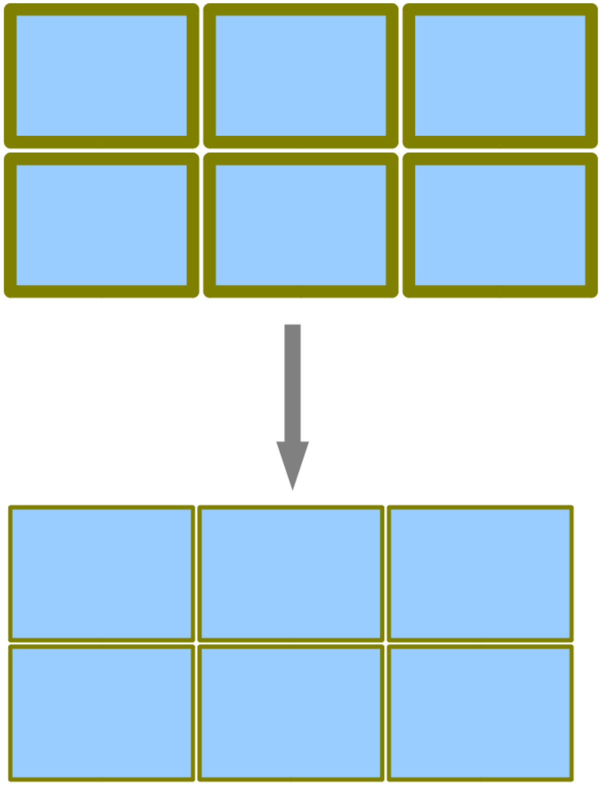
2) *Our numerous collaborators from ATLAS and RD50*

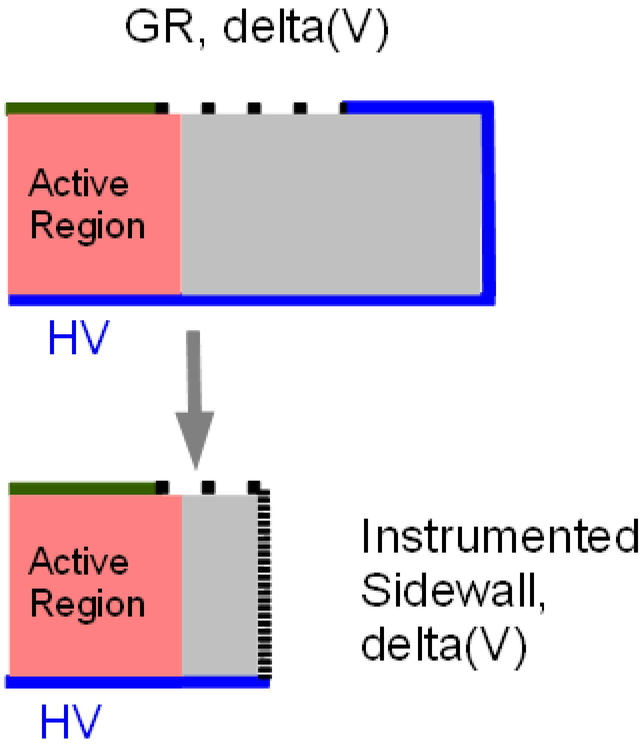
Slim Edges -- Motivation

<u>Basic Idea</u>: To minimize ~1 mm wide inactive peripheral region. This is relevant for “tiling” (as opposed to “shingling”) of large-area detector composed of small sensors.

<u>Method</u>: To instrument the sidewall in a close proximity to active area, such that it’s <u>resistive</u>.



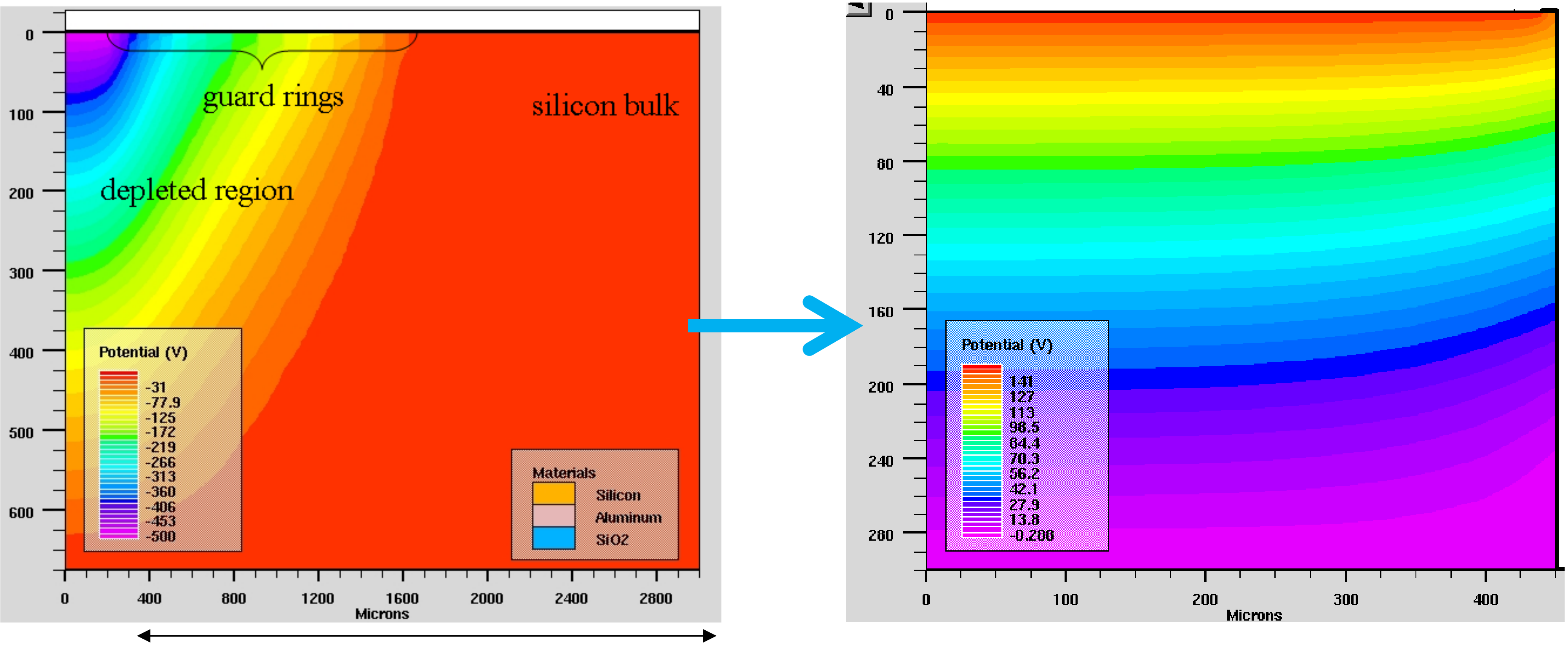




Slim Edges – Surface Quality

Conventional sensors have the bias voltage gradient in the guard rings region. To implement slim edges, we’d like to have the gradient on the sidewall => similar surface quality and passivation requirements.

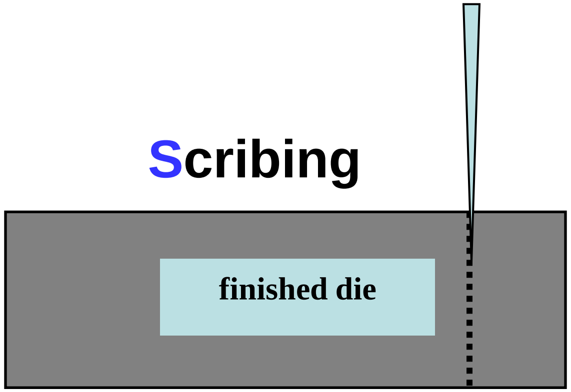
Surface imperfections lead to additional current consumption => IV test as a measure of performance.



inactive region

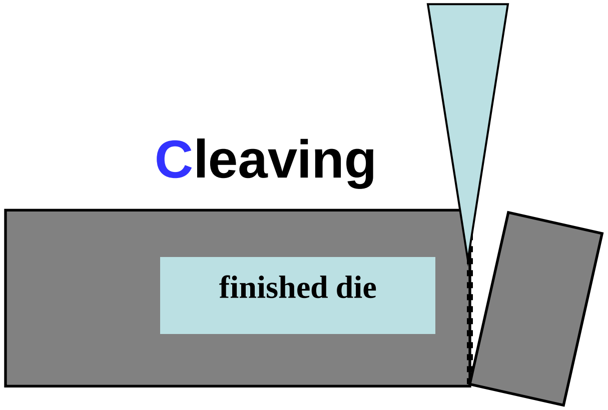
Method -- SCP Treatment

Scribing



- Diamond stylus
- Laser
- XeF_2 Etch
- DRIE Etch

Cleaving



- Tweezers (manual)
- Loomis Industries, LSD-100
- Dynatex, GTS-150

Passivation

Native Oxide
+ Radiation
or:

N-type	P-type
Native SiO_2 + UV light or high T PECVD SiO_2 PECVD Si_3N_4 ALD “nanostack” of SiO_2 and Al_2O_3	ALD of Al_2O_3

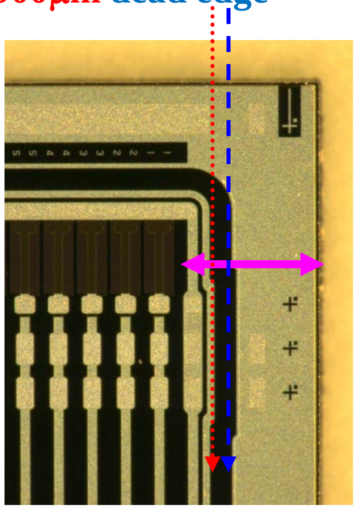
All Treatment is <u>post-processing & low-temp</u>
(Etch-scribing can be done during fabrication)

Basic requirement: 100 wafers (for rectangular side cleaving) with reasonably good alignment between sensor and lattice.

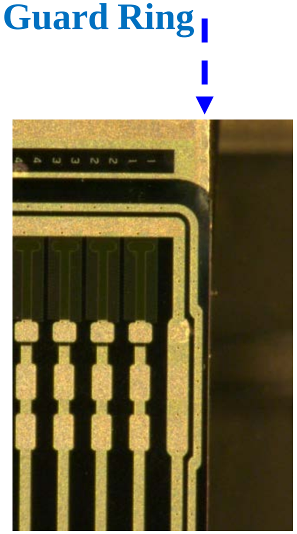
Examples with N-type Sensors

XeF2 scribing + Nitride PECVD

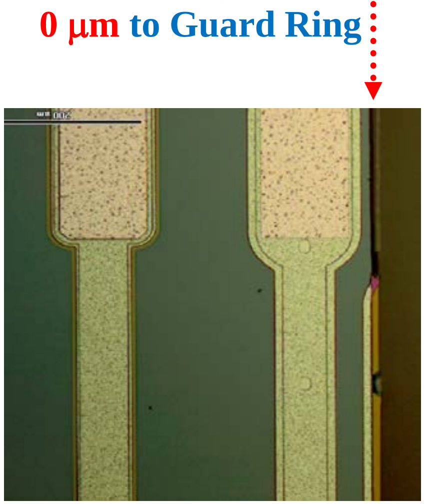
Si SSD with
900µm dead edge

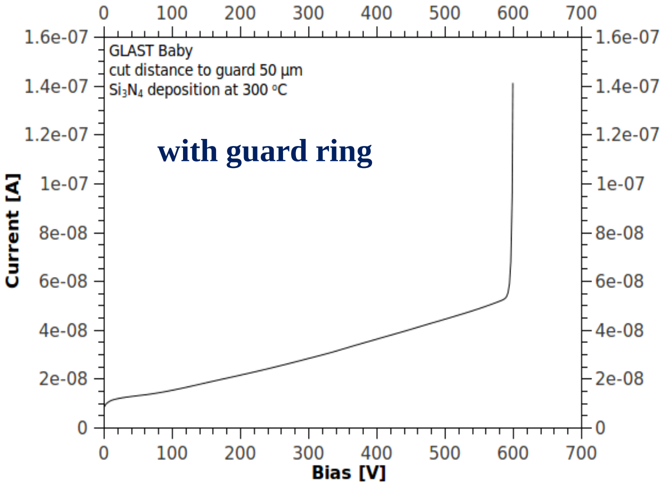


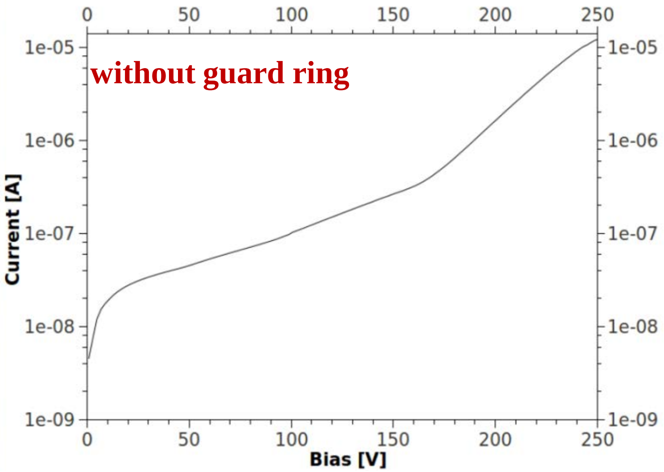
Cut within 50 µm
of Guard Ring



Guard Ring Cut (!)
0 µm to Guard Ring

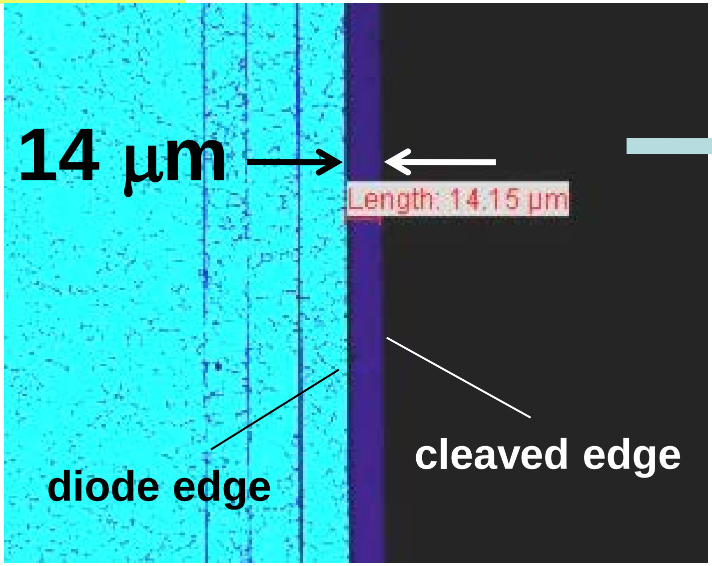


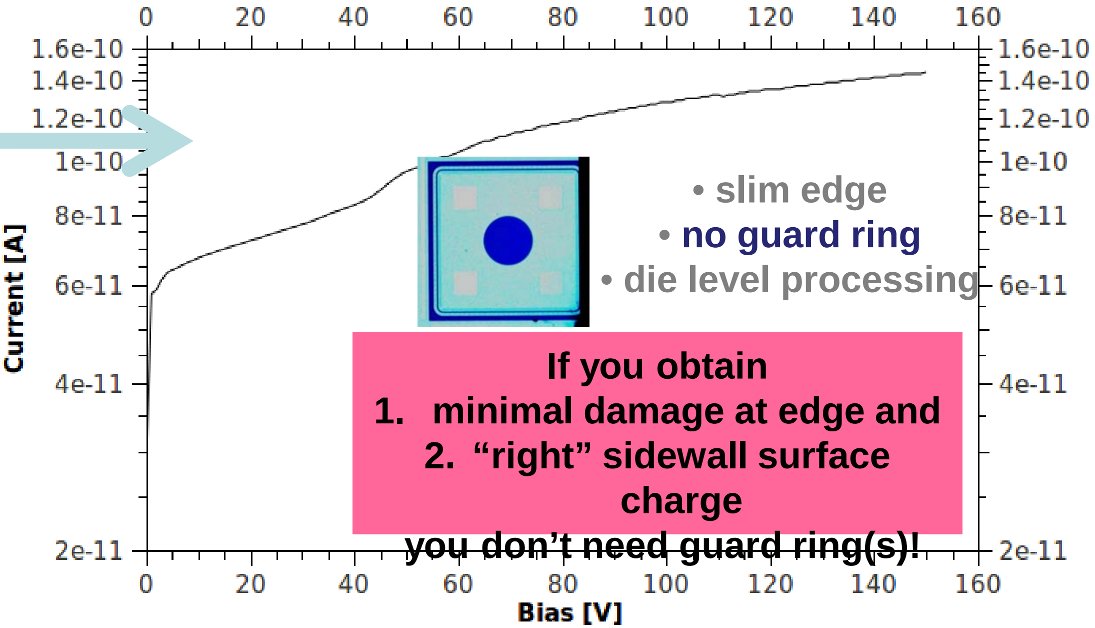




Examples with P-type Sensors

Device A



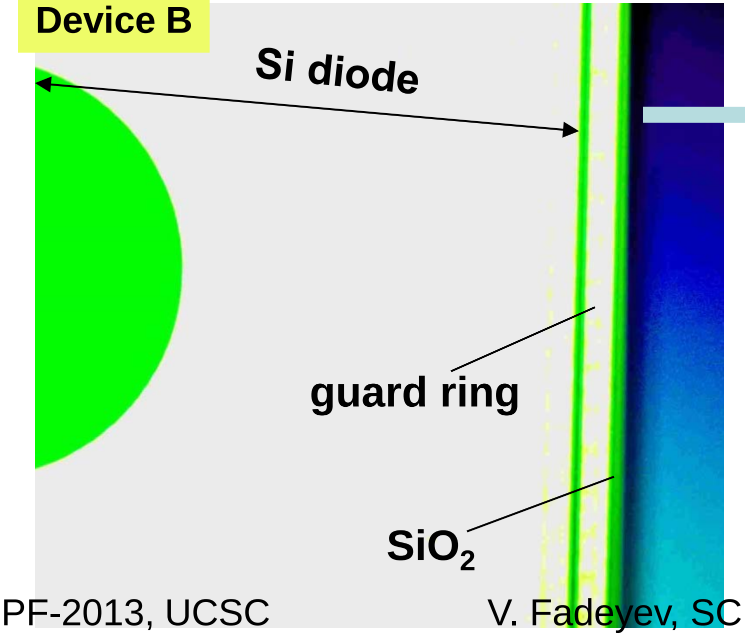


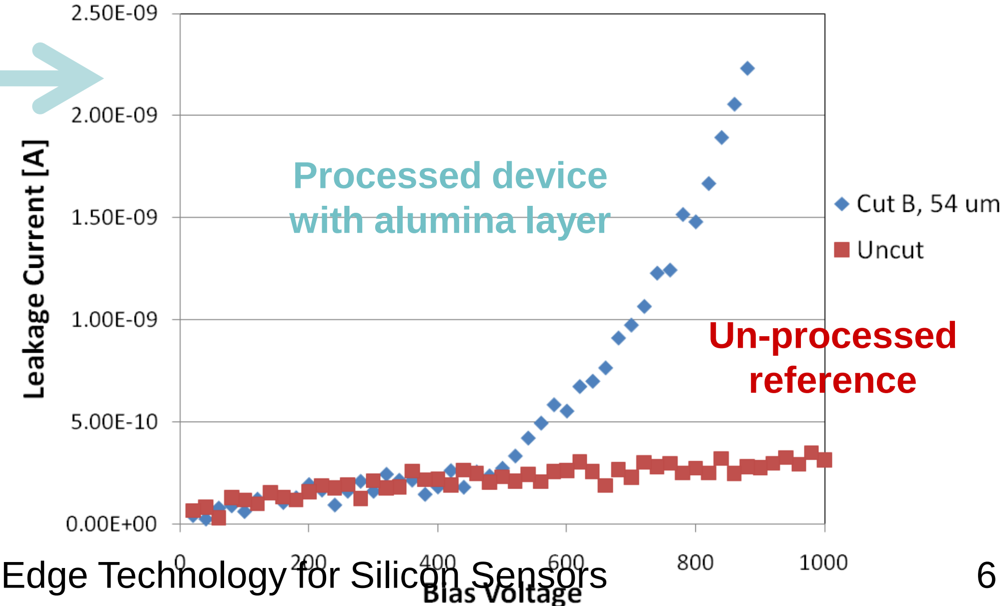
- slim edge
- **no guard ring**
- die level processing

If you obtain
1. **minimal damage at edge and**
2. **"right" sidewall surface charge**

you don't need guard ring(s)!

Device B





Processed device with alumina layer

Un-processed reference

SCP: RD 50 (*) Common Project

* CERN-based collaboration for radiation hardness studies of silicon sensors.

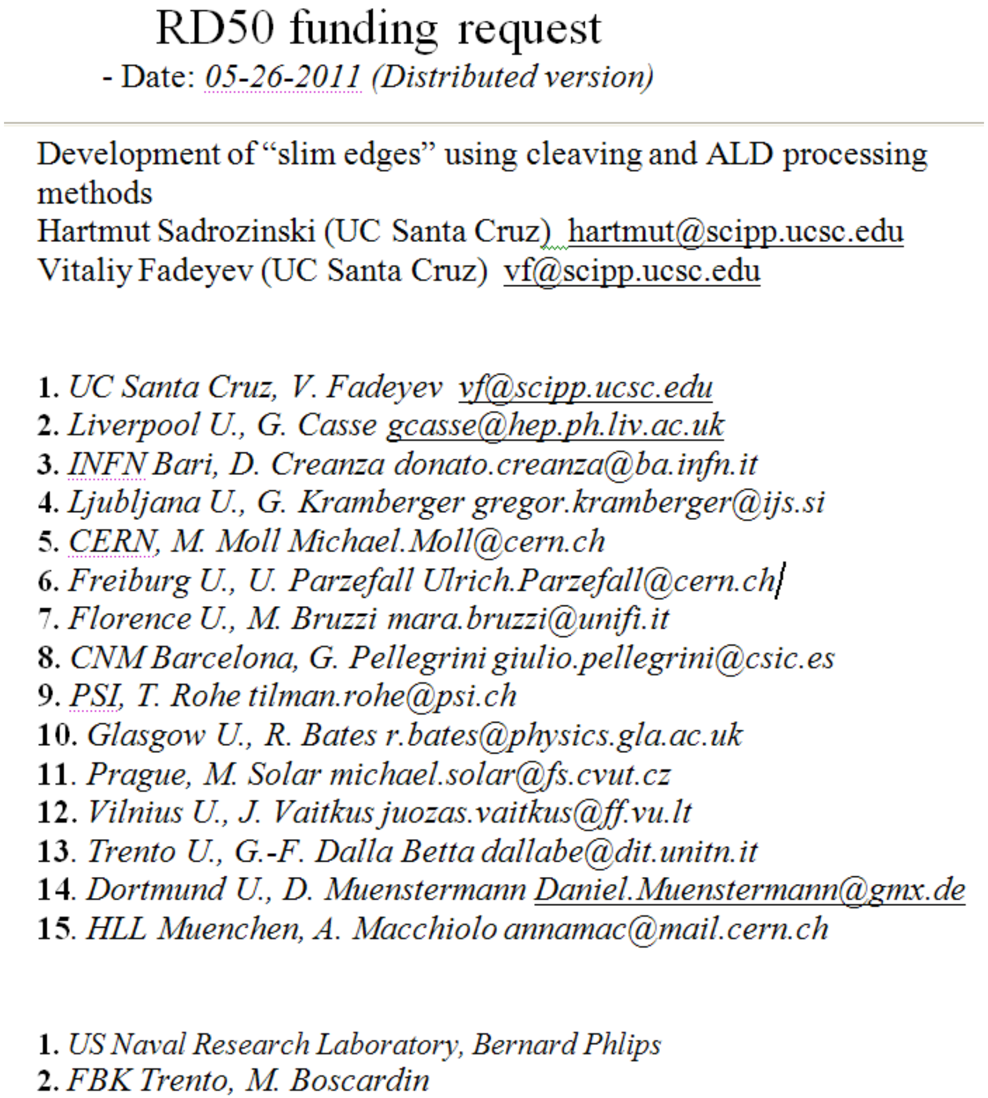
The initial trials started within the framework of ATLAS Planar Pixel Collaboration.

Last summer, the scribe-cleave-passivate (SCP) technology of fabricating slim edge sensors has been approved as RD50 project.

The participating institutions are interested in p- and n-type and 3D sensors.

We are currently actively working with CNM Barcelona, FBK Trento, MPI Muenchen, UNFN Bari, Ljubljana U., Glasgow U., and TU Dortmund on SCP application to their devices

Note that the methods developed are rather generic, applicable to a wide variety of Si devices.



RD50 funding request

\- Date: *05-26-2011 (Distributed version)*

Development of "slim edges" using cleaving and ALD processing methods

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2. *FBK Trento, M. Boscardin*

RD50 Activity Matrix

Institute	Contact Person	Sensors	Status
CNM Barcelona	G. Pellegrini	3D diodes, strips, pixels	2nd round of tests (FEI3 and FEI4 pixel)
FBK Trento	G.-F. Dalla Betta	3D diodes, strips	2nd round of tests ongoing
MPI Muenchen	A. Macchiolo	P-type planar pixels	P-type strip devices sent; in progress
UNFN Bari	D. Creanza	N-type “SMART” detectors	First processed devices sent for evaluation; in progress
Ljubljana U.	G. Kramberger	P- and N- type	Devices sent; used in laser TCT studies of the field profile
Glasgow U.	R. Bates	P- and N- type	Sensors with SCP used in a precision X-ray scan of charge collection efficiency
TU Dortmund	T. Wittig	IBL-style n-on-n sensors	Initial tests done, Iterations with IBL sensors
Vilnius U.	J. Vaitkus	P- and N-type for passivation quality studies.	P- and N-type diodes sent; irradiated p-type strip devices to be sent.

Ongoing Activities within RD50 Collaboration

Current Efforts

We had a lot of technical development, with different fabrication options explored. For details, see recent publications:

- **M. Christophersen et al., "Alumina and Silicon Oxide/Nitride Sidewall Passivation for P- and N-Type Sensors", NIM A 699 (2013) 14**
- **M. Christophersen et al, “The effect of different dicing methods on the leakage currents of n-type silicon diodes and strip sensors”, Solid-State Electronics 81 (2013) 8.**
- **M. Christophersen et al, “Scribing-Cleaving-Passivation for High Energy Physics Silicon Sensors”, Proceedings of Science, accepted for publication.**
- **V. Fadeyev et al, “Scribe-cleave-passivate (SCP) slim edge technology for silicon sensors”, NIM A (2013) – in press. DOI: http://dx.doi.org/10.1016/j.nima.2013.03.046**

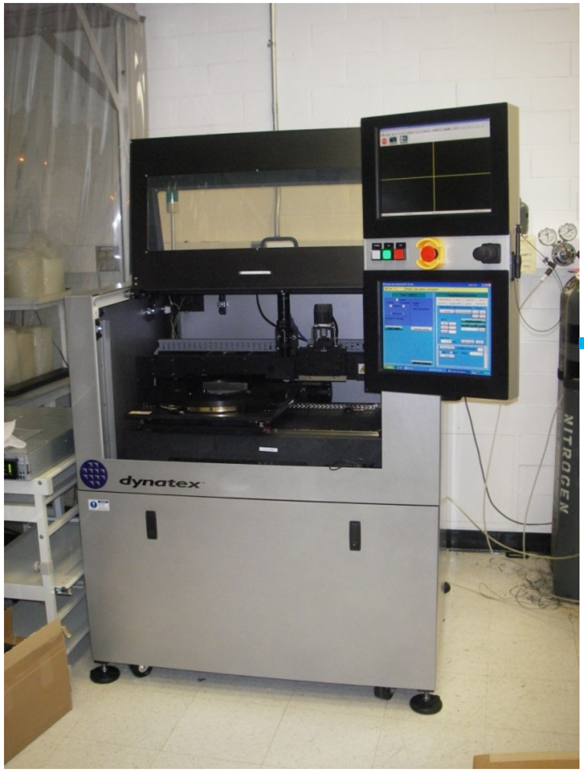
Recent work is focused on:

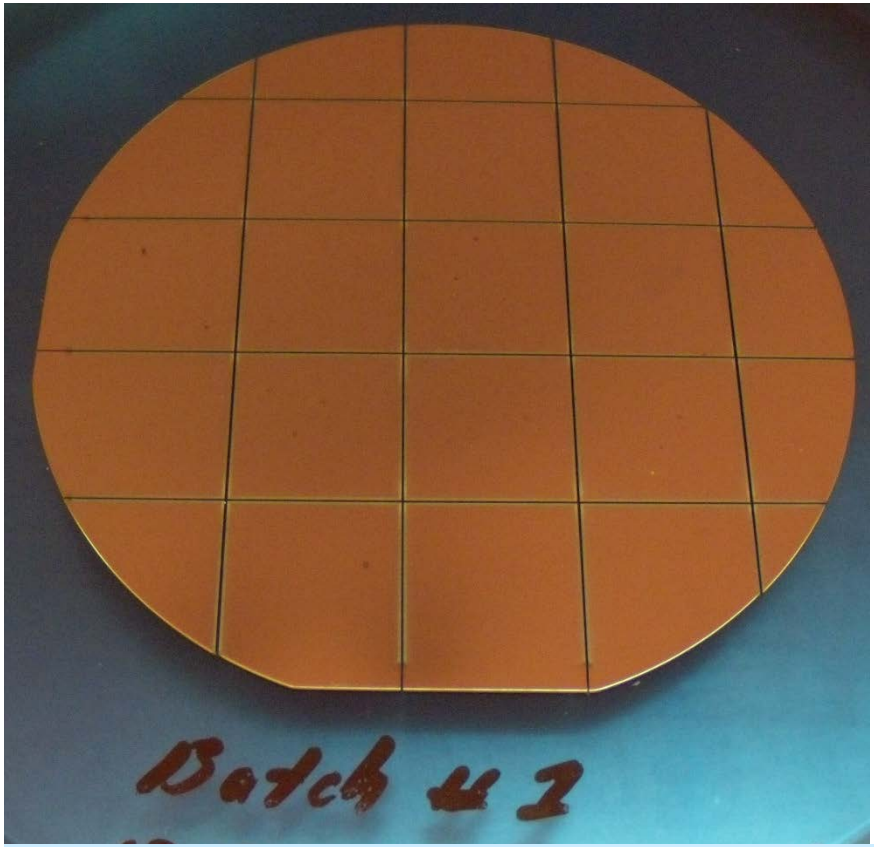
- Technical development:
  - Wafer-level processing
- Device performance:
  - CCE near the edge
  - Radiation hardness

Wafer-based Processing

A lot of processing steps are easily amenable to automation due to processing technology/machines. A key manual step we used so far is cleaving. It was done manually, with 2 tweezers.

In parallel with making and evaluating test samples, we explored machine-based cleaving options for mass-production.





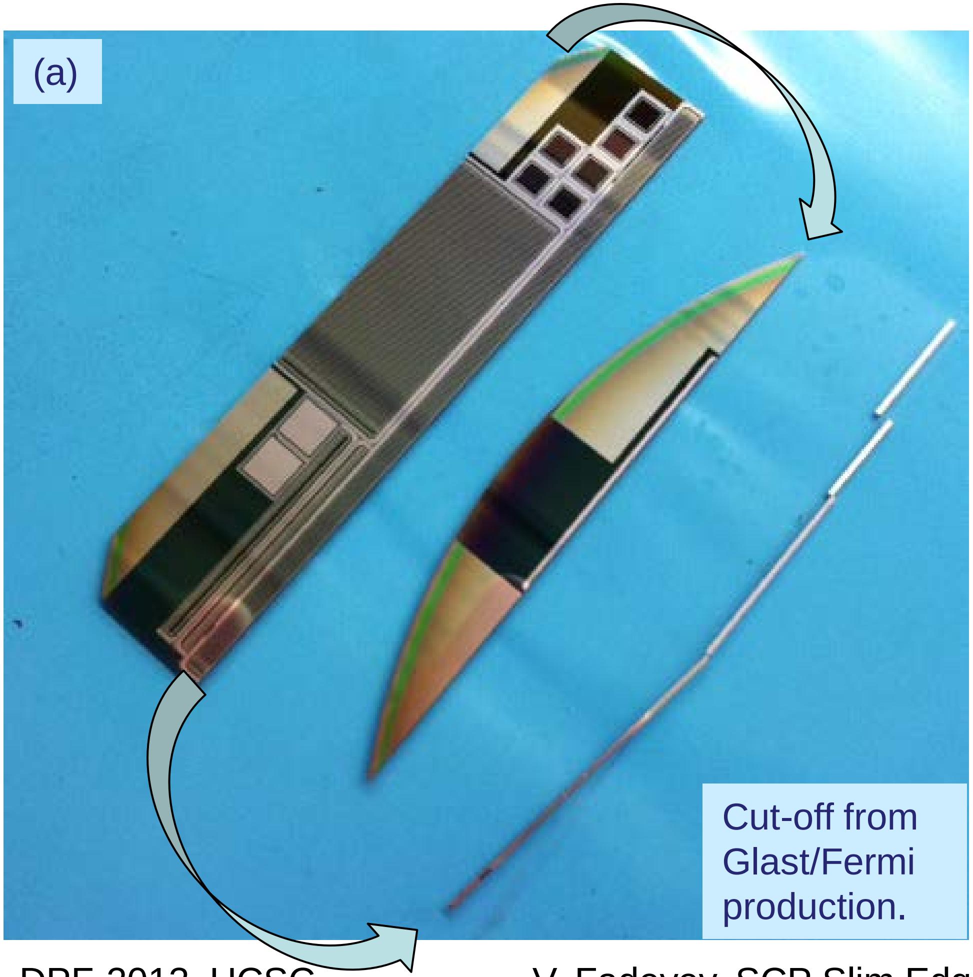
4-inch wafer broken along the scribe lines in a test.

Wafer-based Processing

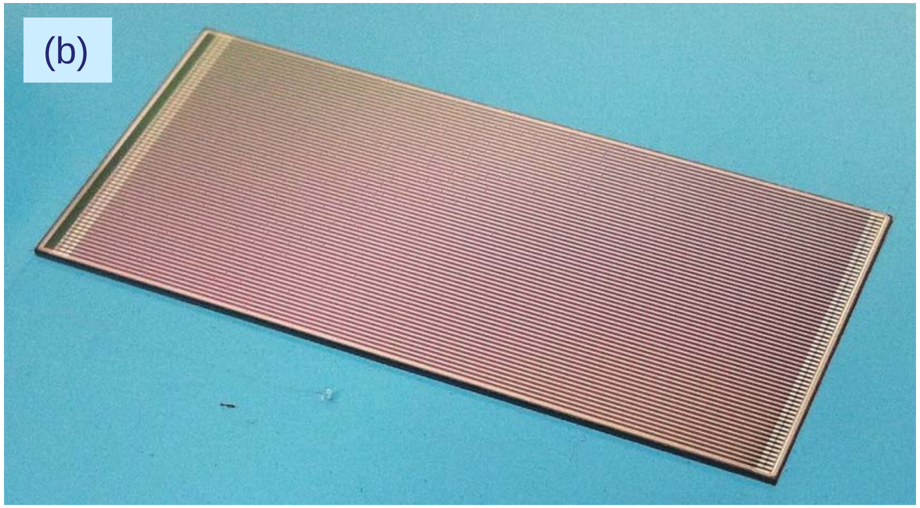
The latest tests with Dynatex machine are extremely promising:

a) 9-cm long narrow section is removed intact (it broke when being peeled off the blue tape). The removed piece is 680 um wide and 400 um thick!

b) 1.6 x 3.5 cm^2 sensor cleaved on 4 sides.



Cut-off from Glast/Fermi production.

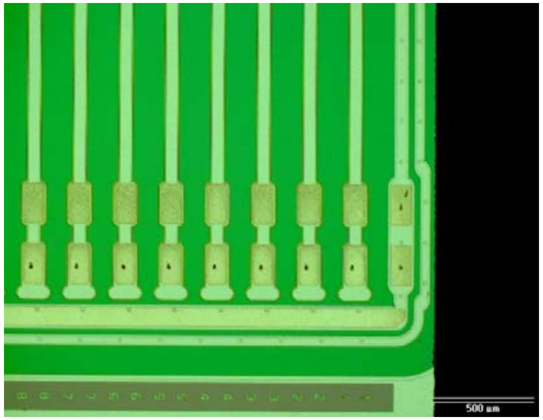


Alternative Wafer Processing

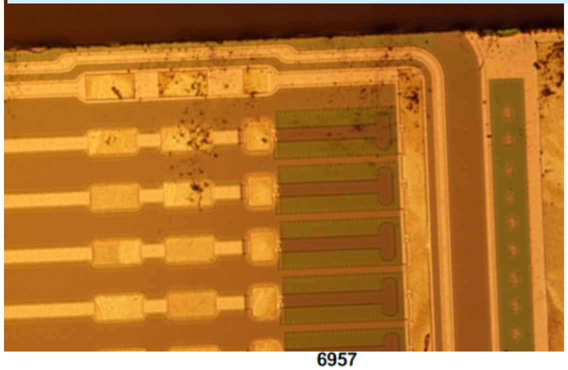
Based on our studies, wafer cleaving provides the best performance due to low defect density on the sidewall. Nonetheless, a process modification is possible:

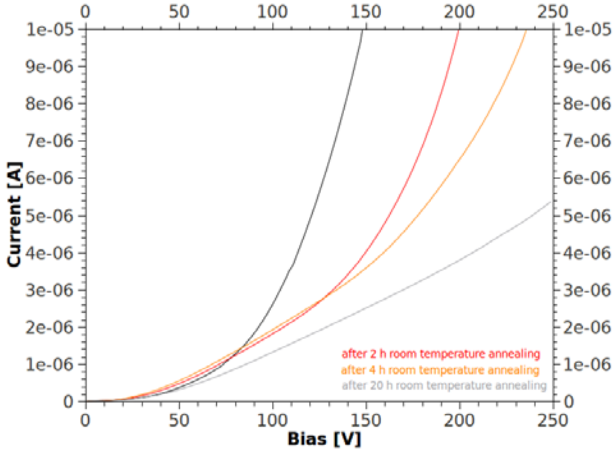
instead of Scribe-Cleave-Passivate,
one can do Cut-DamageRemoval-Passivate.

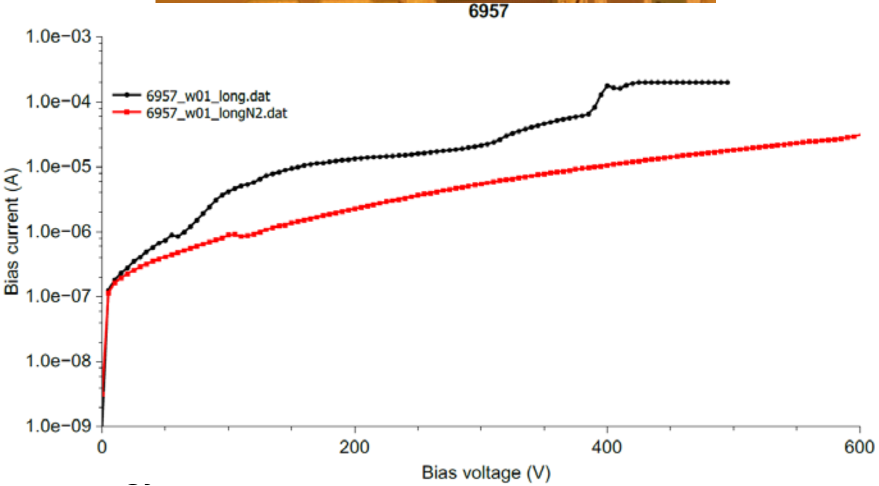
The cut here can be either laser through-cut or conventional saw cut.
This might insure reliability of the singulation process, at the price of possibly higher currents.
An option for difficult cases, e.g. with wrong lattice orientation.



Post-processed by G. Pellegrini et al.







Charge Collection Testing

Sensor Type	Origin	Edge-Active area Distance [um]	Signal Readout	Beam	Ref
P-type strips	PPS (CIS)	~200	Binary (PTSM)	^{90}Sr	V. Fadeyev *et al* Pixel 2012, NIM A in press
N-type strips	GLAST (HPK)	~200	Analog (ALiBaVa)	^{90}Sr	R. Mori *et al*. 2012 JINST 7 P05002
P-type strips	PPS (CIS)	150	Analog (ALiBaVa)	Focused X-ray	R. Bates *et al.*, 2013 JINST 8 P01018
P-type 3D pixels	IBL (CNM)	50	FE-I3 & FE-I4	CERN Test Beam	S. Grinstein *et al.*, RESMDD12 G. Pellegrini *et al.*, Pixel 2012, NIM A in press
P-type strips	PPS (CIS)		Analog (ALiBaVa)	^{90}Sr	

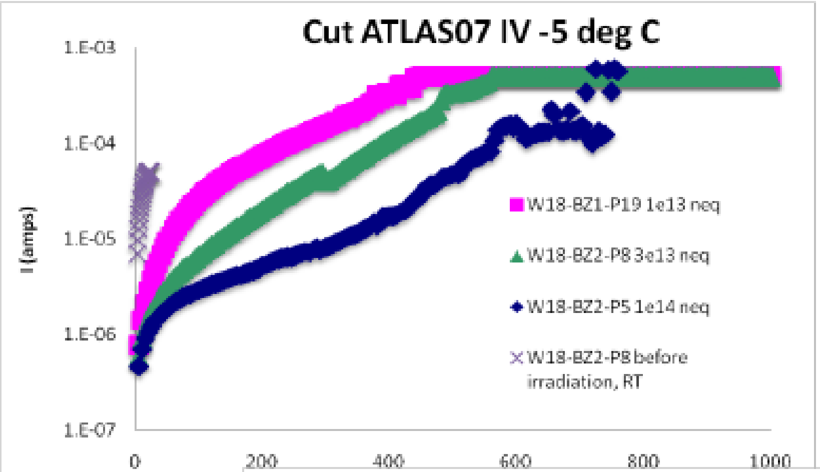
In all cases CCE on the edge was within few % of CCE on other electrodes
→ Caveat: all un-irradiated devices.

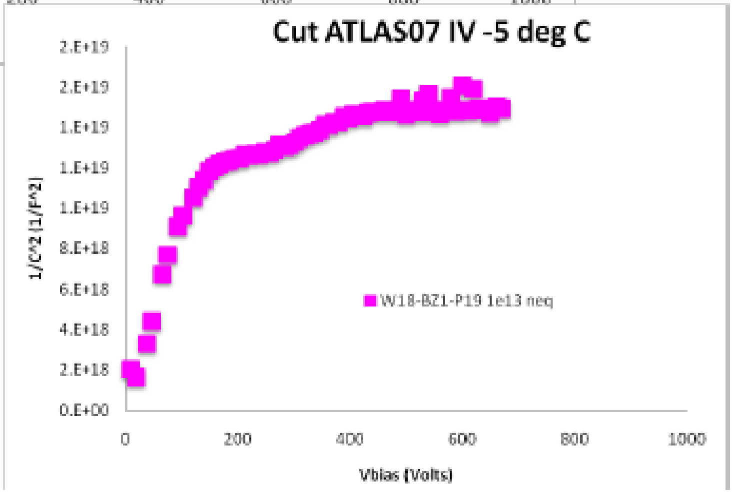
<u>New developments:</u>

- MPI study has device irradiation in progress.
- Glasgow (R. Bates et al) are planning a follow up with irradiated devices.

2010 Proton Irradiation Studies @LANL

“SC only”: No Passivation





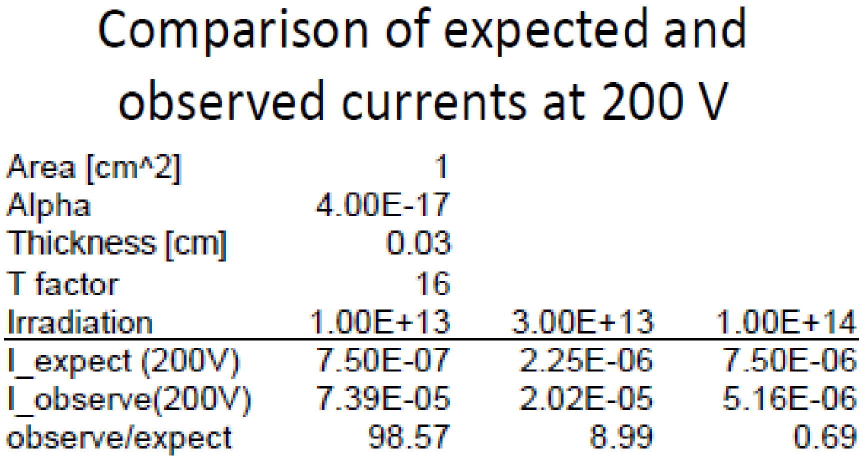
P-type HPK (ATLAS07)

These sensors did not work after cleaving (initial trial without sidewall passivation). Breakdown at ~few Volts.

There is an empirical evidence that the breakdown improves after irradiation.

We put these sensors in proton beam to see if they would indeed improve.

Leakage is initially dominated by the edge current, which is *reduced* with fluence. At 10^{14} neq, I(edge) < I(bulk).



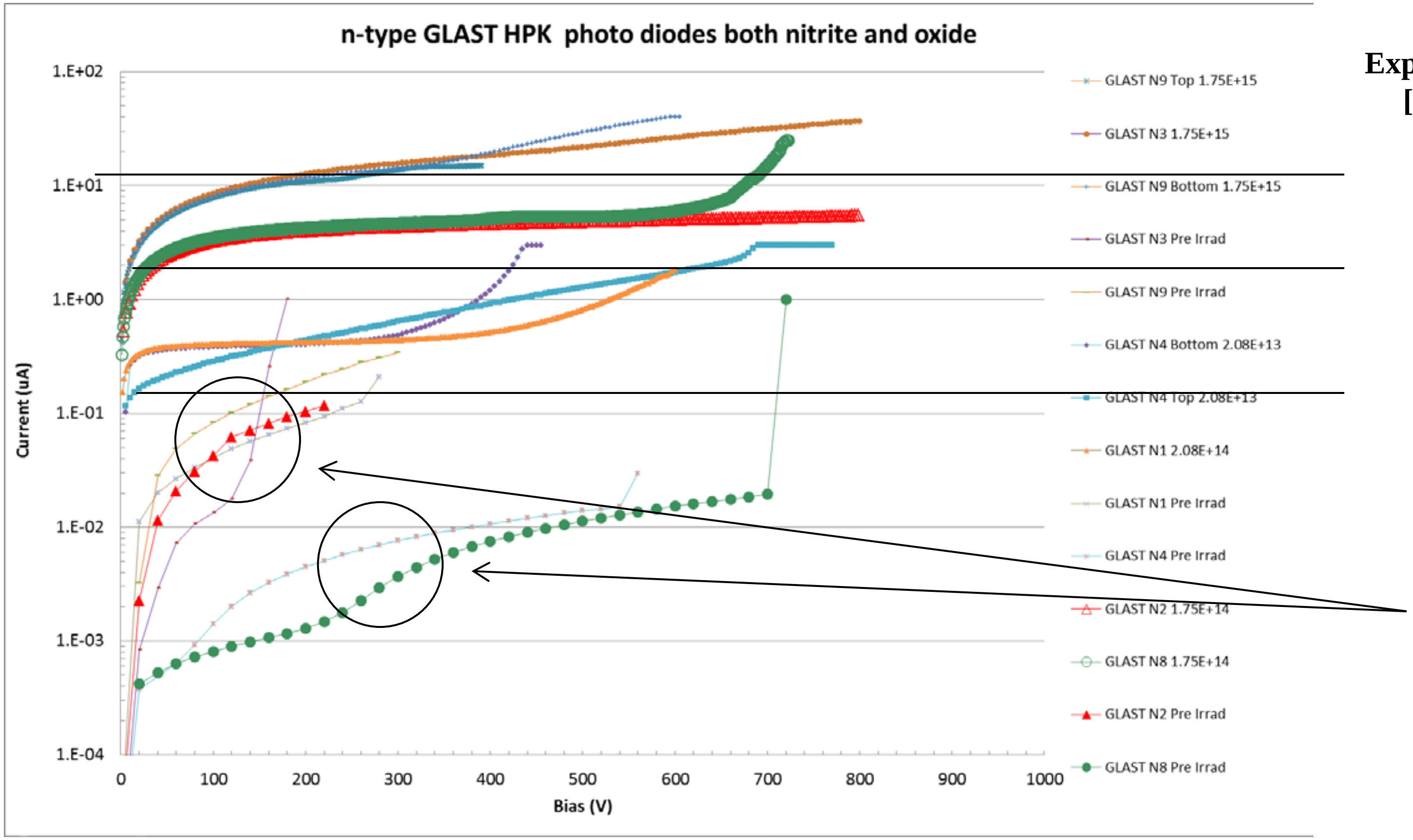
Comparison of expected and observed currents at 200 V

Area [cm^2]	1		
Alpha	4.00E-17		
Thickness [cm]	0.03		
T factor	16		
Irradiation	1.00E+13	3.00E+13	1.00E+14
I_expect (200V)	7.50E-07	2.25E-06	7.50E-06
I_observe(200V)	7.39E-05	2.02E-05	5.16E-06
observe/expect	98.57	8.99	0.69

Observation on “SC only” P-type:

High fluence irradiation -> resistive edge!

N-type GLAST HPK Photo Diodes with SCP edge both nitrite and oxide passivation



Expected current [uA] @ -5 C

13.3

1.33

0.16

Pre-rad

Observations on N-type:

Low fluence (1e13, < inversion) edge isolation due to passivation (Nitrite/nanostack)

High fluence (>1e14, > inversion): resistive edge

…No dependence on type of passivation, leakage current close to bulk expectation

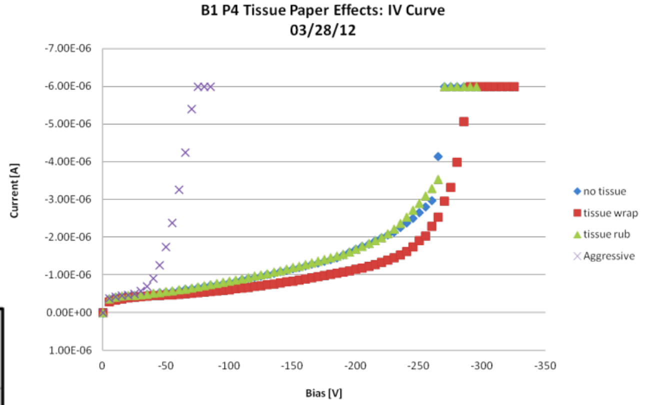
2011 Proton Irradiation @LANL

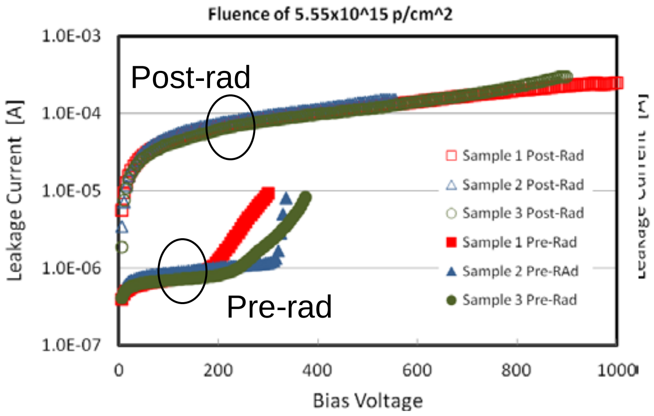
Irradiated 12 SCP processed p-type strip devices (CIS courtesy A. Macchiolo) at LANL (thanks S. Seidel). Results are in-conclusive:

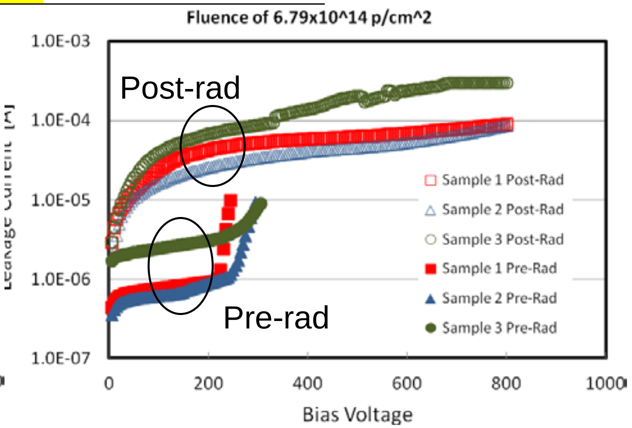
- **+ Breakdown voltages extended post-rad**
- **+ High fluence devices (3/3 for 1e16neq, 3/3 for 1e15neq) show expected post-rad leakage current**
- **- Lower fluence devices (1/3 for 1e13neq and 1/3 for 1e14neq) show earlier breakdown!**

	Before Irradiation	**After Irradiation**		
Sensor	V(break) at ~10 uA	V(break) at ~100 uA	Fluence	No Guard Rings
B1 P5	30	460	10^13	1
B1 P6	290	165	10^13	1
B2 P1	410	80	10^13	3
B1 P8	15	90	10^14	5
B2 P10	310	80	10^14	5
B2 P6	390	100	10^14	1
B2 P8	300	>800	10^15	4
B2 P9	310	335	10^15	5
B2 P11	250	>800	10^15	2
B2 P2	305	390	10^16	1
B2 P3	340	330	10^16	3
B2 P4	380	425	10^16	3

A parallel investigation of the robustness of the passivation layer revealed a possible susceptibility to rough handling. There is no proof that this has skewed the irradiation results.

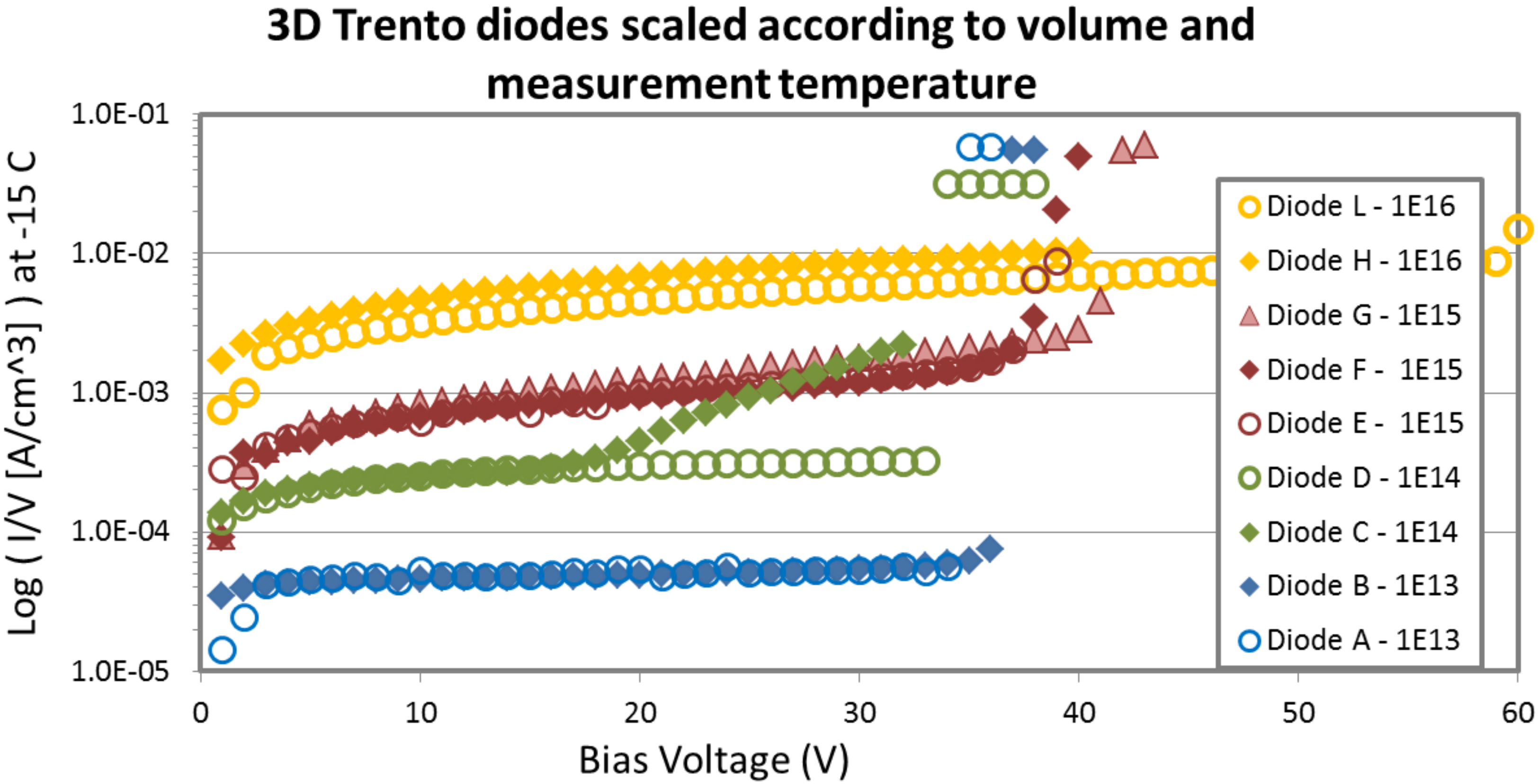






… was followed up at CERN irradiation run in 2012 with protons. Results were similar, indicating either continuous packaging issues, or a real problem at low fluences.

P-type 3D sensors irradiated at Ljubljana, (PI G.-F. Dalla Betta)



Observation on SCP P-type with neutrons:

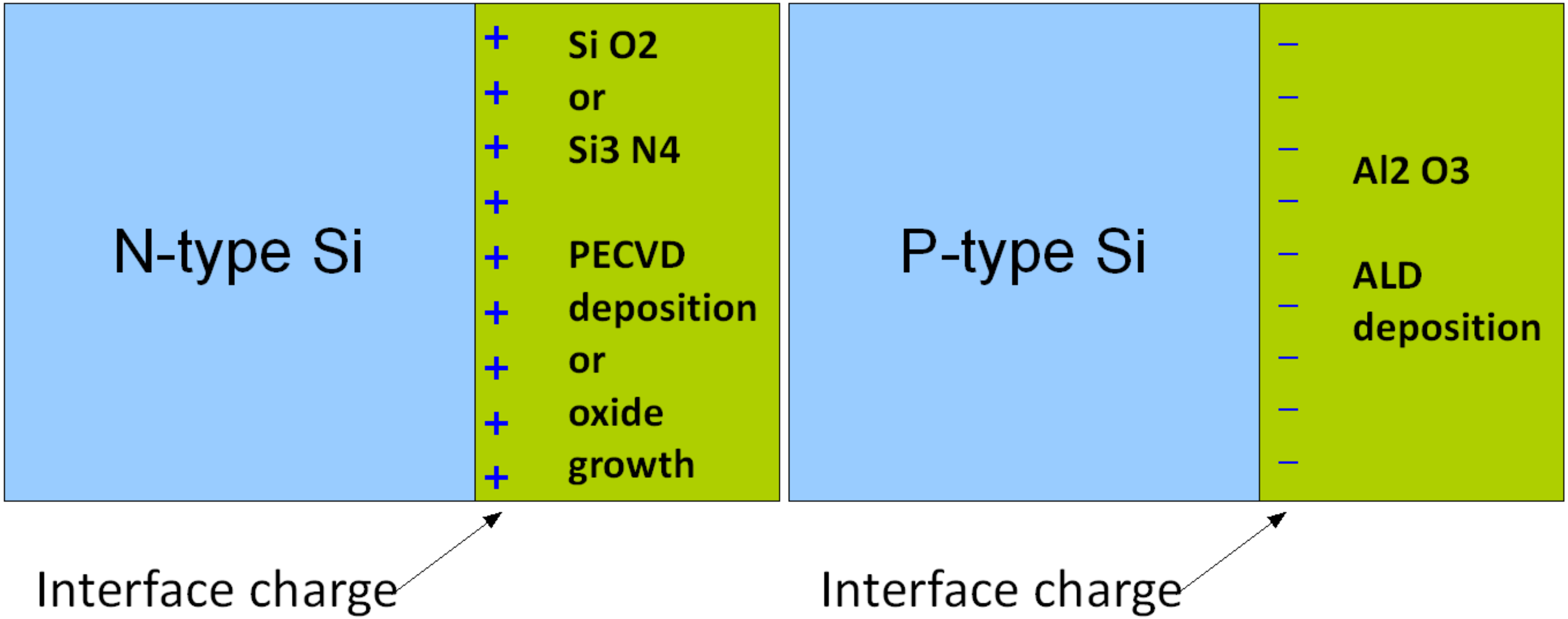
3D neutron-irradiate sensors show approximate scaling with fluences:
no high currents for low fluences !
=> See vastly different fluence scaling. Either due to field geometry or non-ionizing dose.

Conclusions and Future Work

- We are pursuing a method of making devices with reduced peripheral material ("slim edges"). This is an alternative to making "active edge" sensors, which typically requires very specialized processing.
- A lot of fabrication aspects are figured out. Currently focusing technical developments on wafer-level processing.
- The method rose a lot of interest in the community. We are collaborating with many RD50 groups on further development and application to their particular sensor designs.
- Sensor sensitivity near the edge:
  - Had multiple studies of CCE near the edge on un-irradiated sensors. So far no issues.
  - Will be interesting to see results from irradiated devices: MPI and U. of Glasgow studies.
- Radiation hardness of the passivation:
  - N-type devices seem to be rad-hard. This is expected, since the properties of the sidewall after irradiation should be similar to the case of top surface on conventional sensors. (Same passivation, similar surface properties.)
  - There appears to be an issue with rad hardness on p-type devices for fluences <10^14 neq/cm^2.
  - This has to be related to properties of dielectric (alumina) after irradiation. There is a project, lead by G. Pellegrini (CNM) to fabricate MOS-like structures with alumina to find more details about it.
  - Studies of neutron-irradiated p-type 3D sensors are in progress. Preliminary data indicate no issues. This is either due to different field geometry or non-ionizing dose.

Back-Up Slides

Passivation Options



N-type Si

+ + + + + + + + +

Si O2
or
Si3 N4

PECVD
deposition
or
oxide
growth

Interface charge

P-type Si

– – – – – – – – –

Al2 O3

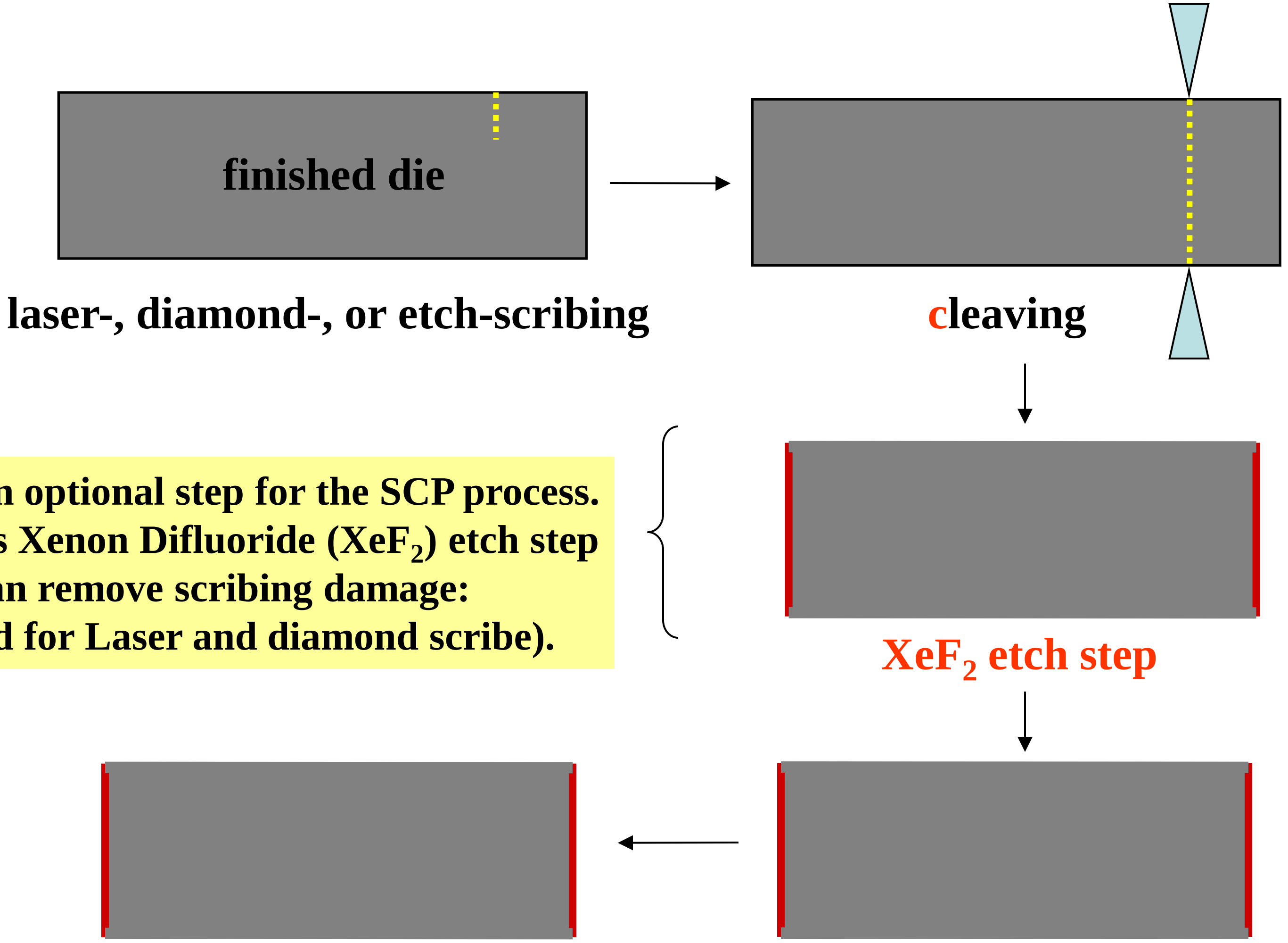
ALD
deposition

Interface charge

Surface passivation makes the sidewall resistive. N- and p-type devices require different technologies.

- For n-type devices one needs a passivation with *positive* interface charge. SiO_2 and Si_3N_4 layers works well.
- For p-type material a passivation with negative interface charge is necessary. We found that Al_2O_3 works in this case.

SCP Treatment (Cont)



finished die

laser-, diamond-, or etch-scribing

cleaving

This is an optional step for the SCP process.
A gaseous Xenon Difluoride (XeF_2) etch step
can remove scribing damage:
needed for Laser and diamond scribe).

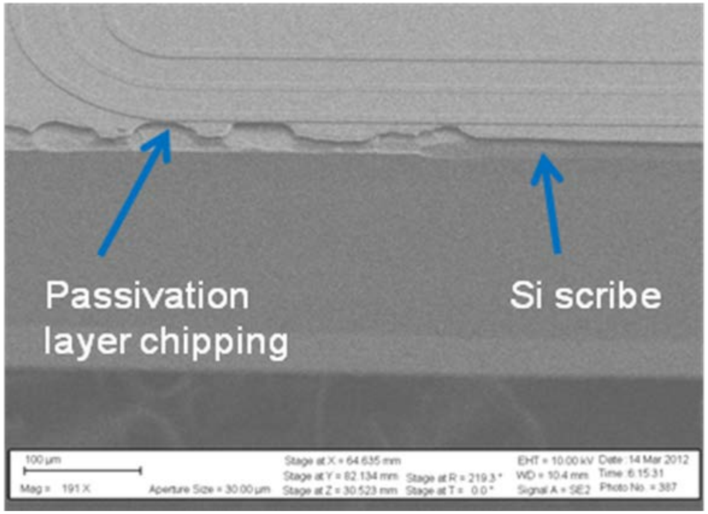
XeF_2 etch step

sidewall passivation

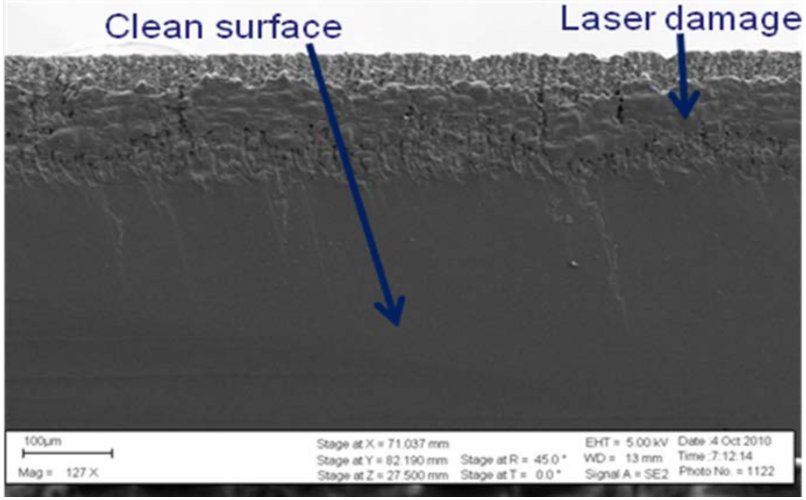
annealing and testing

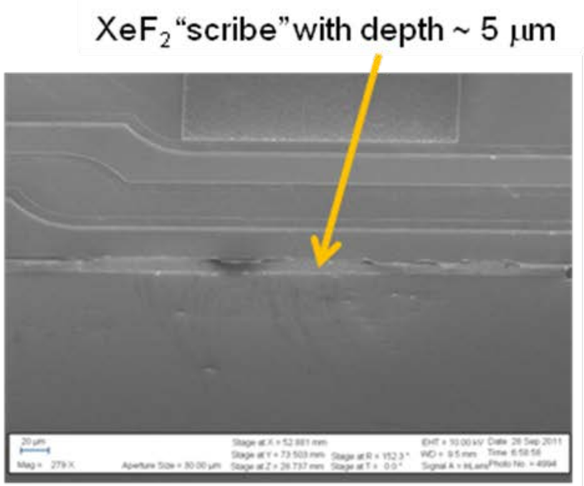
Scribing Technologies: Diamond-, Laser-, and Etch-based

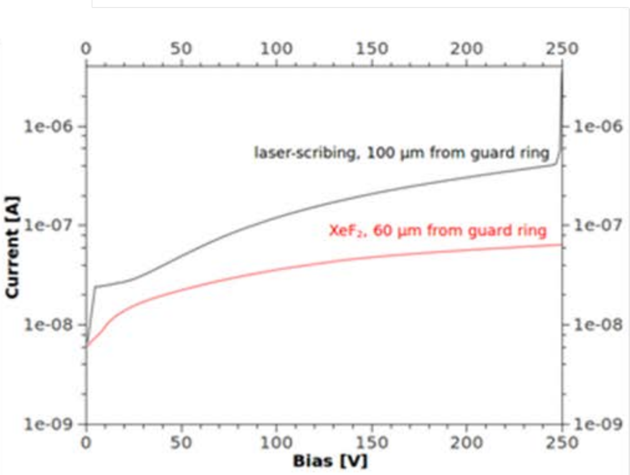
Diamond scribing



Laser scribing



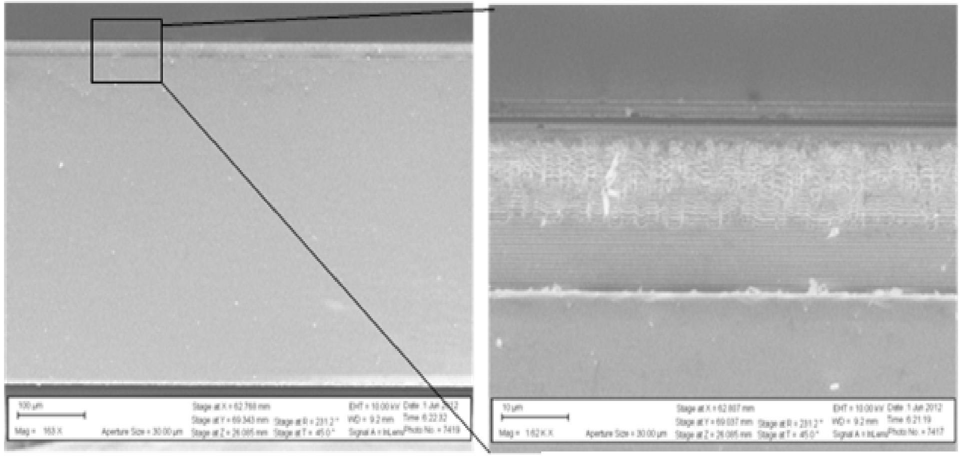


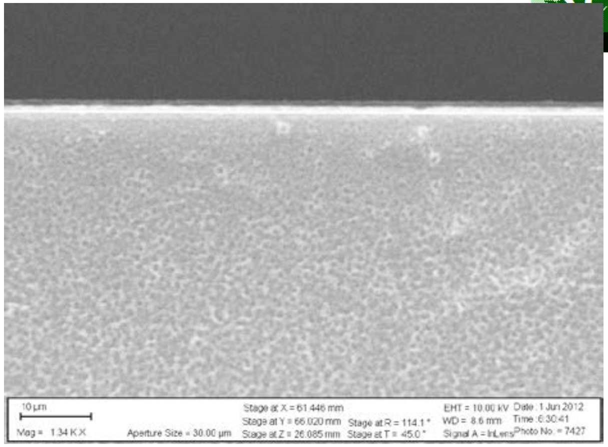


Issues:

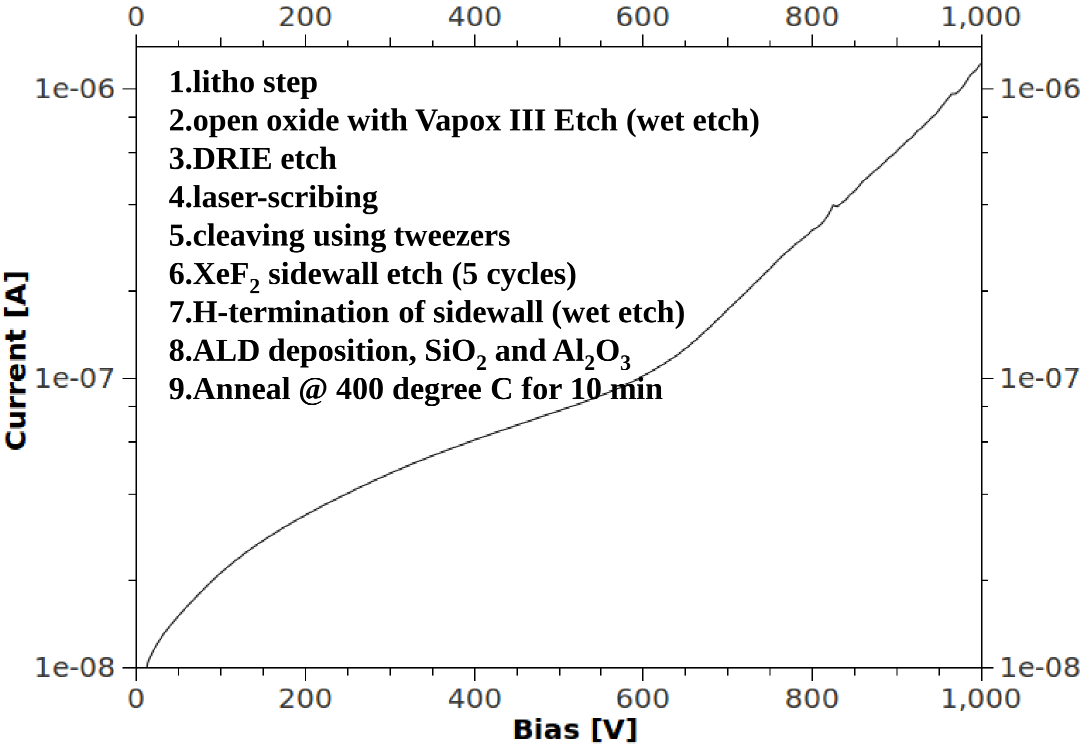
- ➢ Diamond scribing: surface chipping of <u>existing</u> passivation (=> to do again in future runs)
- ➢ Laser scribing: some degree of damage due to affected region of the sidewall
- ➢ XeF2 etching: cleaving by industrial machines is difficult

Scribing Technologies: DRIE



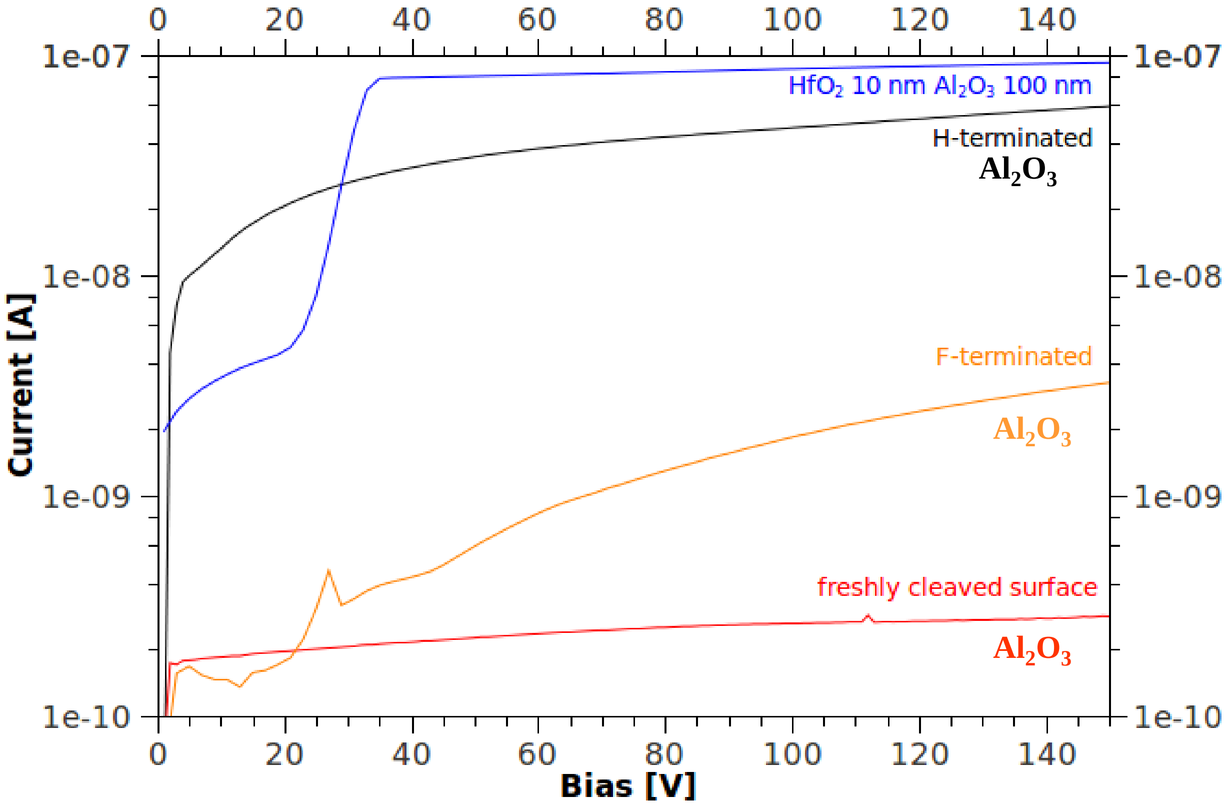


DRIE-based trenching as scribing has a promised of being a “universal” production solution without shortcomings of the other methods.



1. litho step
2. open oxide with Vapox III Etch (wet etch)
3. DRIE etch
4. laser-scribing
5. cleaving using tweezers
6. XeF_2 sidewall etch (5 cycles)
7. H-termination of sidewall (wet etch)
8. ALD deposition, SiO_2 and Al_2O_3
9. Anneal @ 400 degree C for 10 min

Effect of Surface Termination – P-Type Si

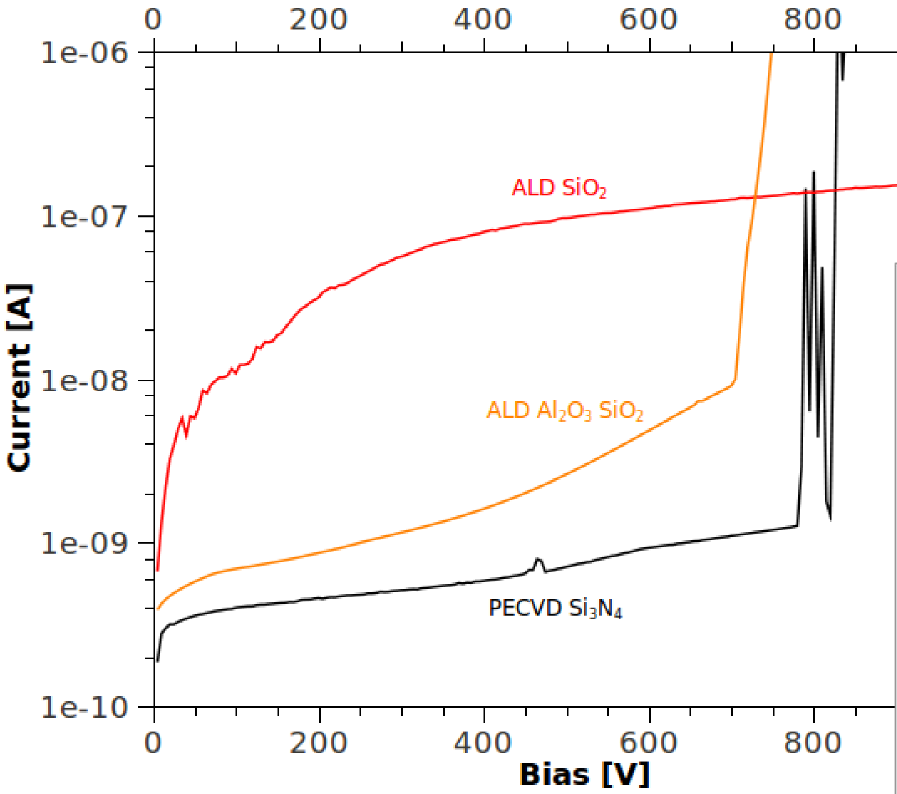


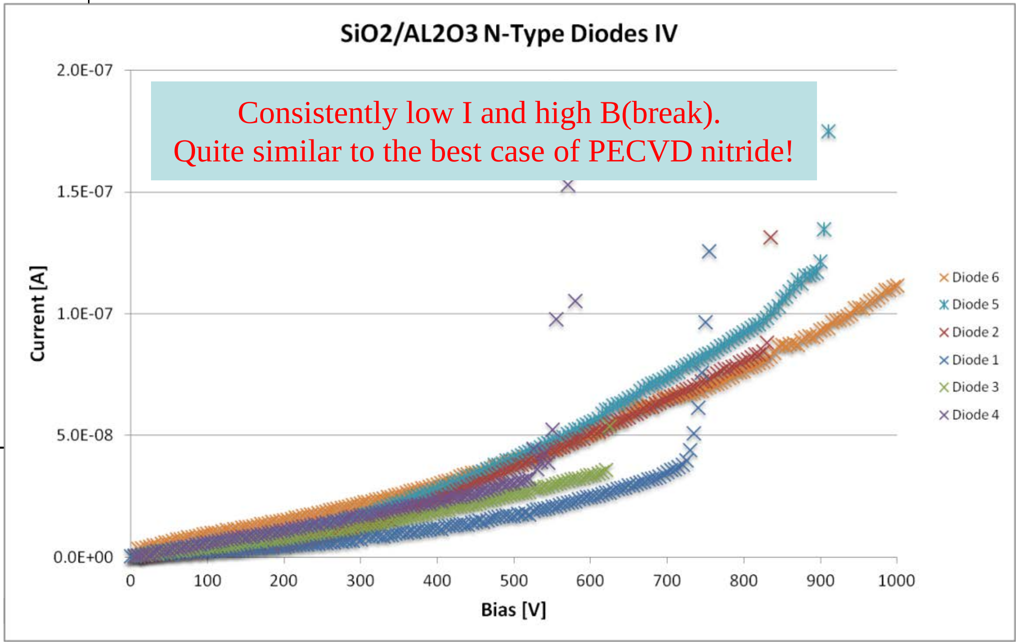
- After all the handling, we need to remove a native oxide. That is done w/ HF and leads to the “H-termination”, which can’t be passivated with alumina Al_2O_3.
- Need to covert the H-termination into F-termination which in combination with alumina ALD should work. Know they chemistry!
- The hunt for on ideal surface termination for p-type Si is still on.

Progress with Passivation (N-type Diodes)

PECVD process has been developed by industry as a wafer process => Small height of the chamber in a typical machine.
This worked well for small size samples, that could be positioned vertically, or slanted. For large sensors this is not quite applicable => replace by ALD method.

Study with HPK Fermi/GLAST diodes.
The plain ALD SiO2 is worse than the best case of PECVD Si3N4.
But a “nanostack” of ALD SiO2 (10 nm) and Al2O3 (50 nm) works well.
Parameters are from G. Dingemans et al, J. Appl. Phys. 110, 093715 (2011); doi: 10.1063/1.3658246



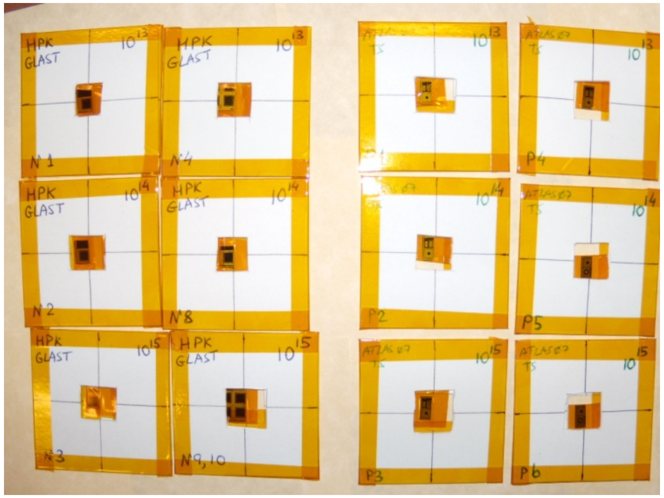


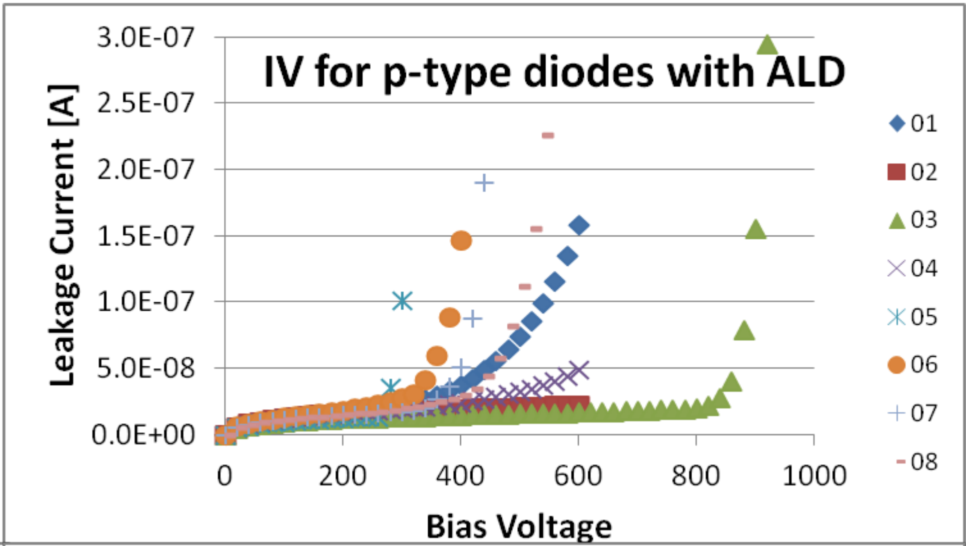
Consistently low I and high B(break).
Quite similar to the best case of PECVD nitride!

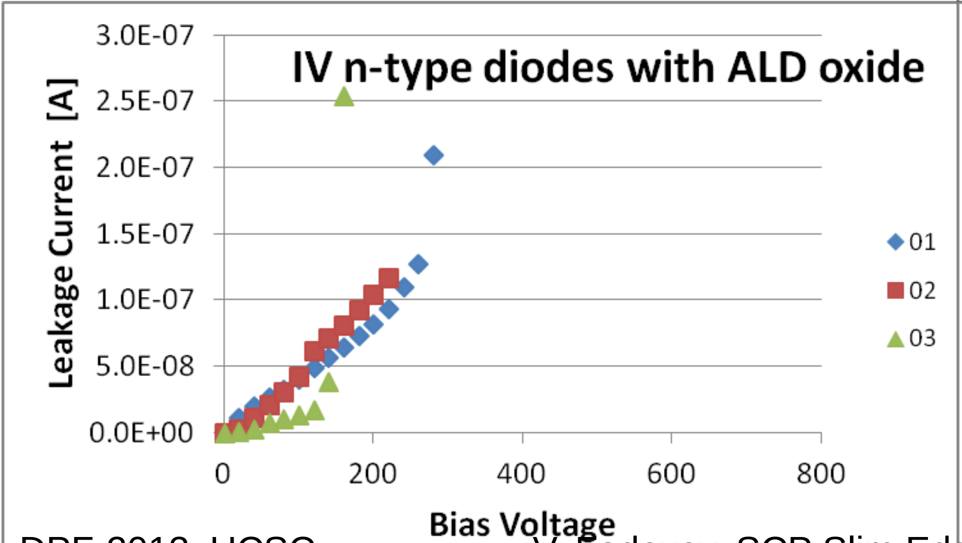
3. 2012 Proton Irradiation @CERN

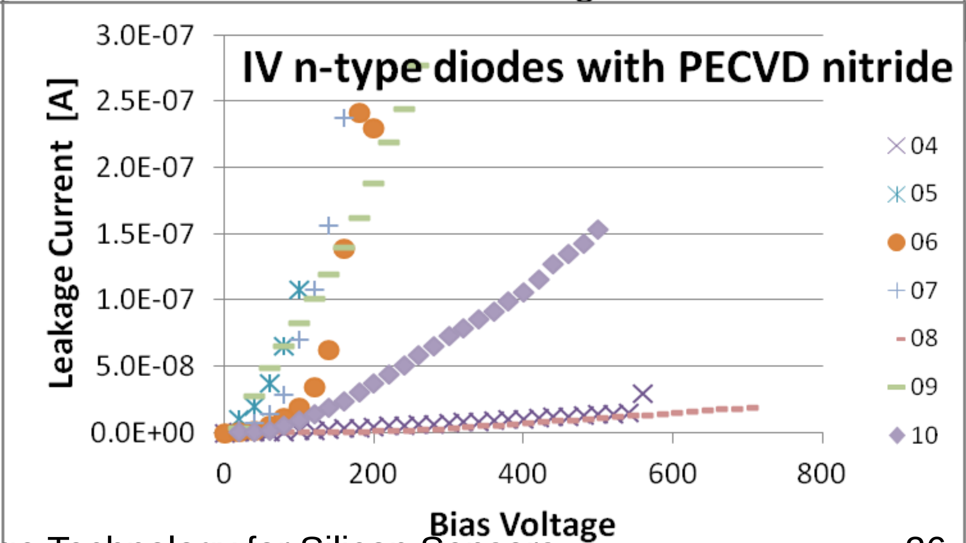
A round of irradiations at SPS (huge help from G. Casse & M. Glaser):

- p-type diodes from ATLAS07 Test Structures
- n-type diodes from Fermi/GLAST Test Structures, with both PECVD nitride and ALD oxide

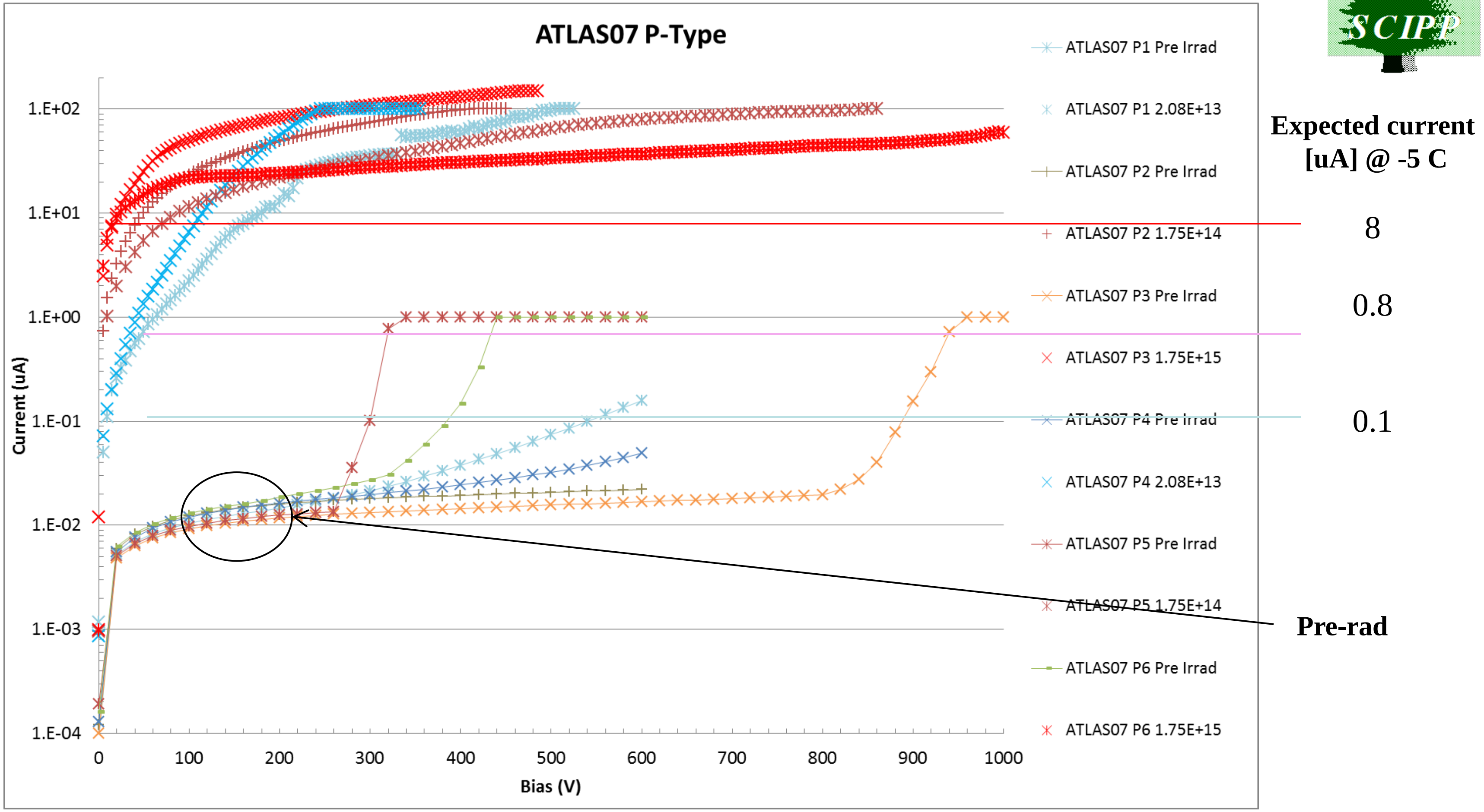








p-type ATLAS07 HPK Photo Diodes



Observation #4 on S-C-P p-type:

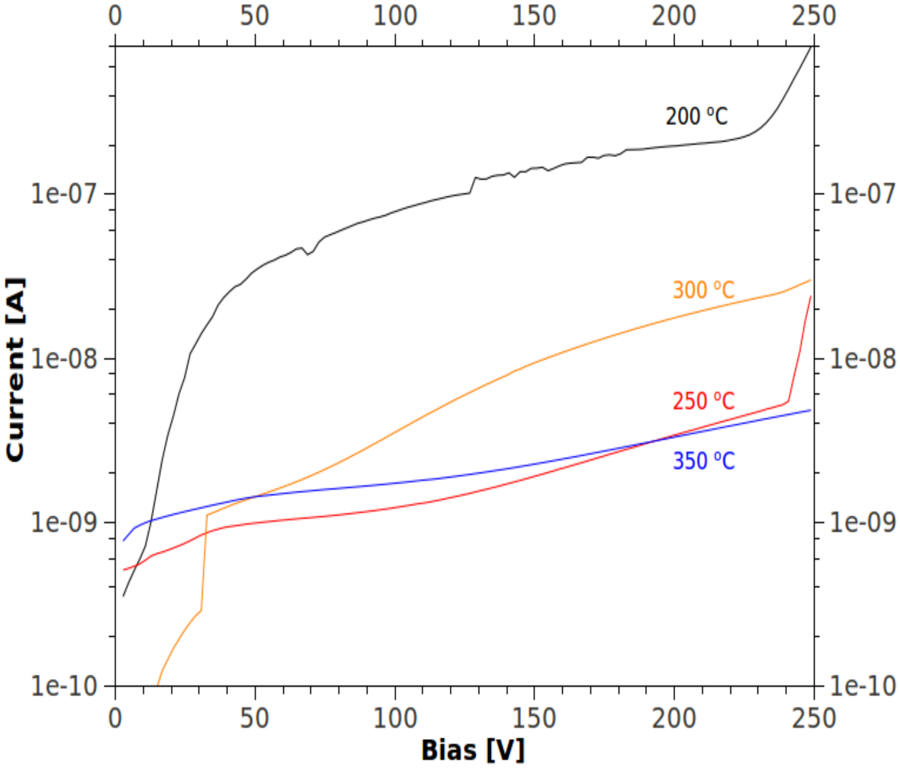
Leakage currents do not scale with fluence

low fluence (< 1e14): reduced edge performance

high fluence (>1e14): resistive edge

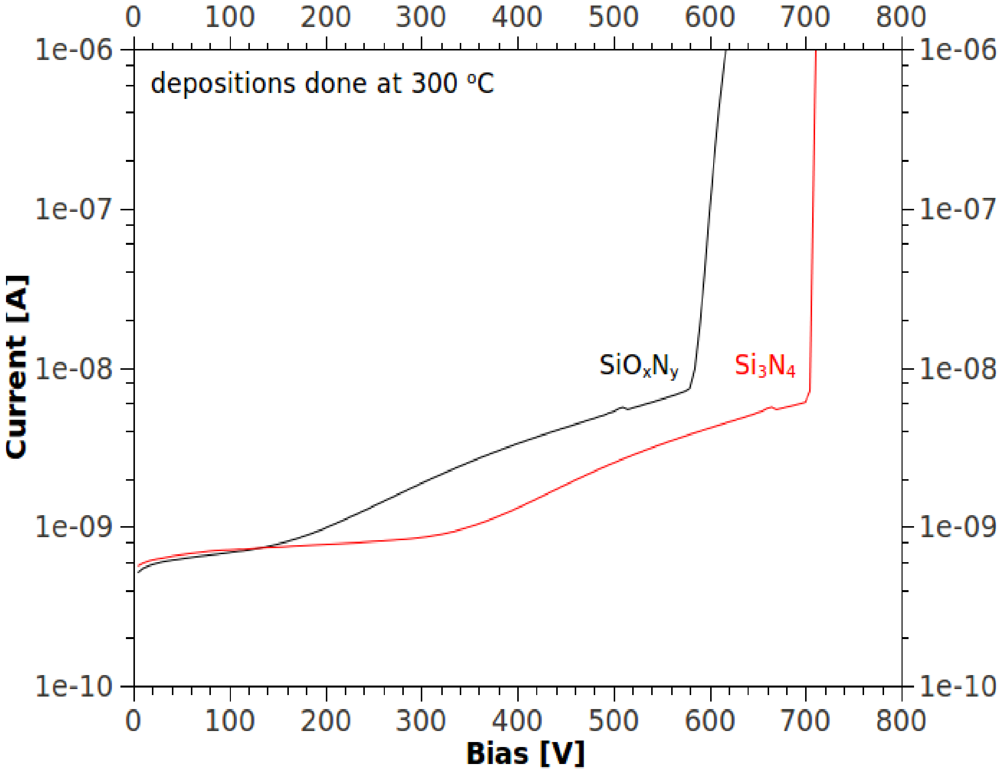
Progress with Passivation (N-type Diodes)

Si Oxide PECVD



Performance dependence on the deposition temperature:
Can work in the T range that is safe for the finished devices!

Si Nitride PECVD



Much improved leakage current and breakdown voltage with Si Nitride.