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

Scott Eli[1], Colin Parker[1], Jeffrey Ngo[1],
Vitaliy Fadeyev[1], Hartmut F.-W. Sadrozinski[1],
Marc Christophersen[2], Bernard F. Phlips[2]

(1) Santa Cruz Institute for Particle Physics,
University of California Santa Cruz
(2) Code 7654, U.S. Naval Research Laboratory

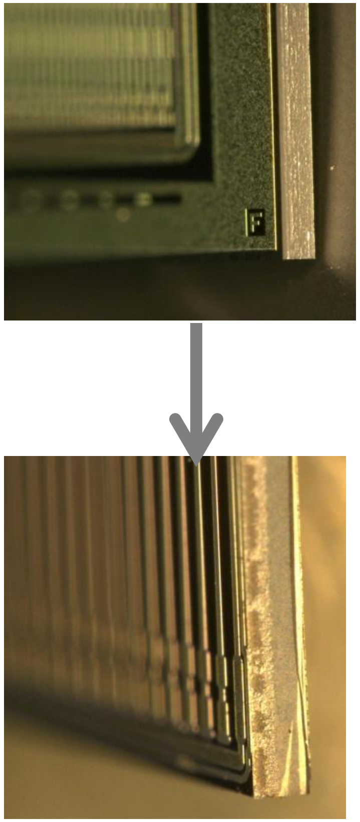
Outline

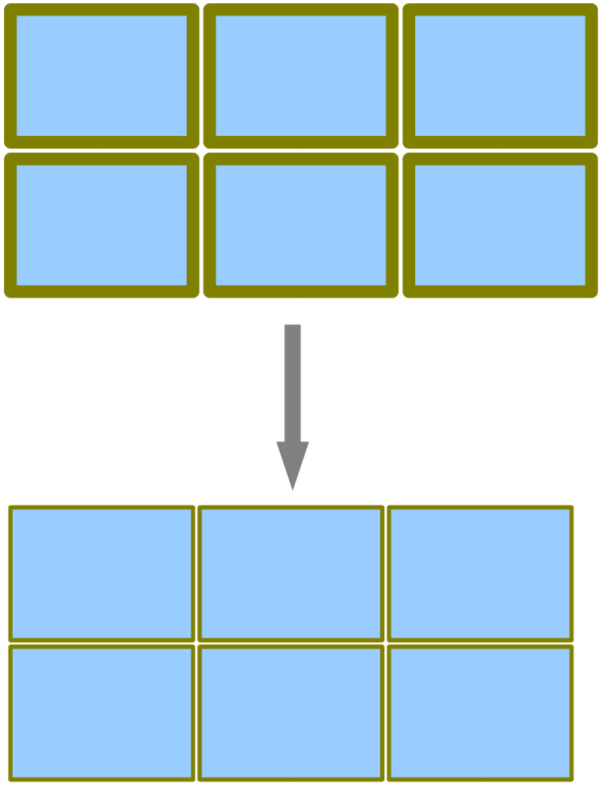
- Slim Edges – Motivation
- SCP Method
- Overview of technology steps and current challenges
- Physics Performance requirements
- RD50 and Matrix of Requests
- Conclusions and Outlook

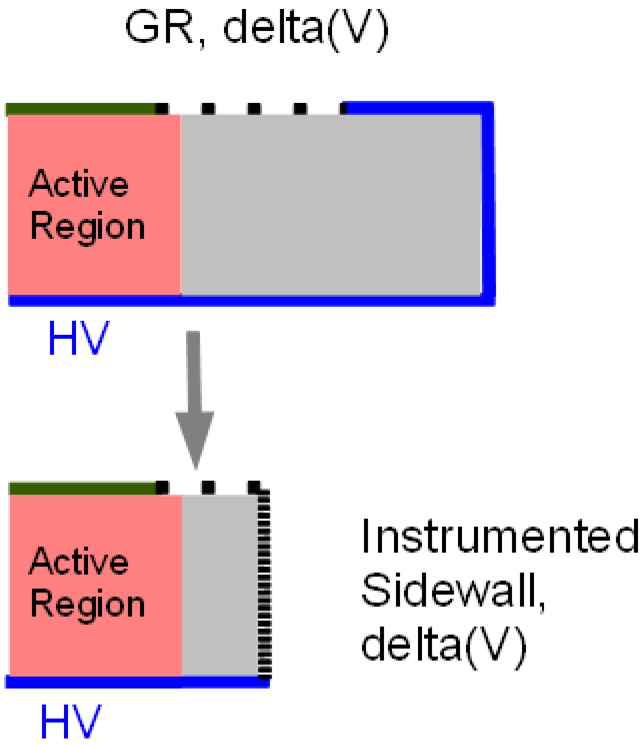
Slim Edges -- Motivation

Basic Idea: 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.

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







GR, delta(V)

Active Region

HV

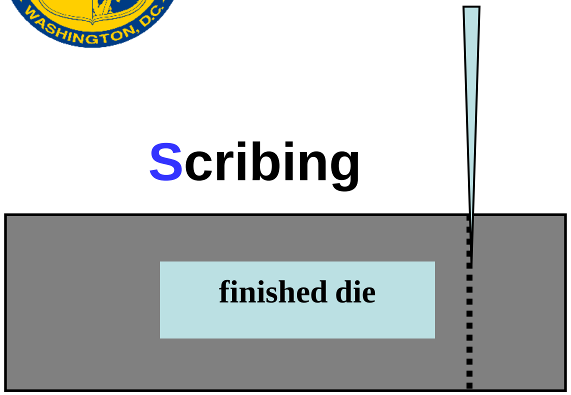
Active Region

HV

Instrumented Sidewall, delta(V)

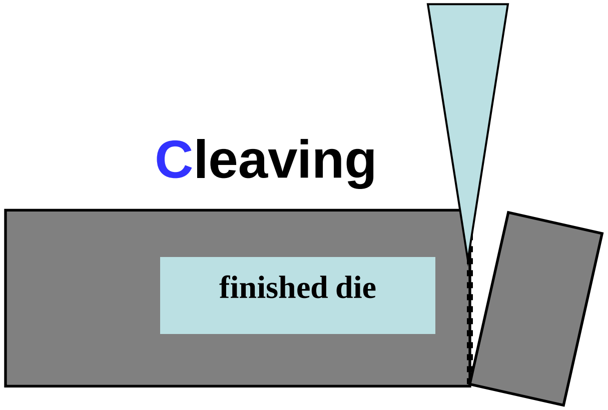
Method -- SCP Treatment

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

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

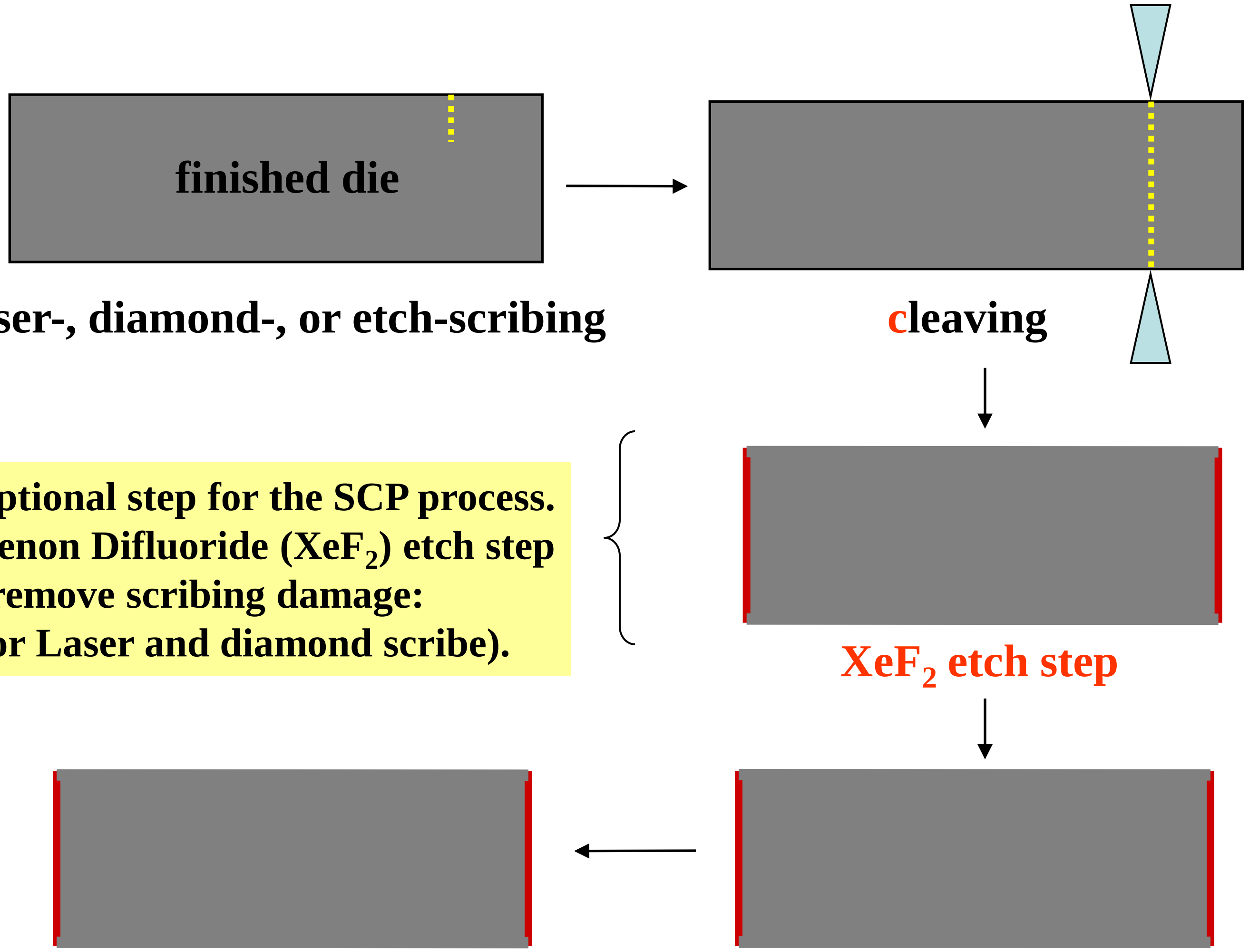
P-type

- ALD of Al_2O_3

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

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

SCP Treatment (Cont)



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).**

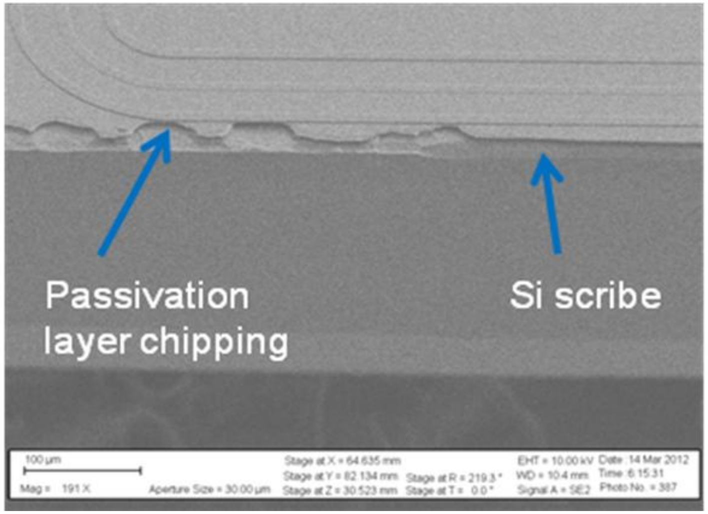
XeF_2 etch step

sidewall passivation

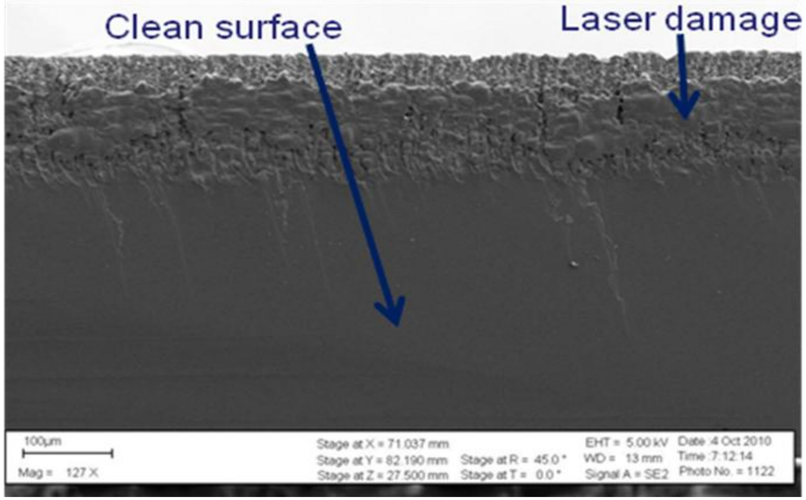
annealing and testing

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

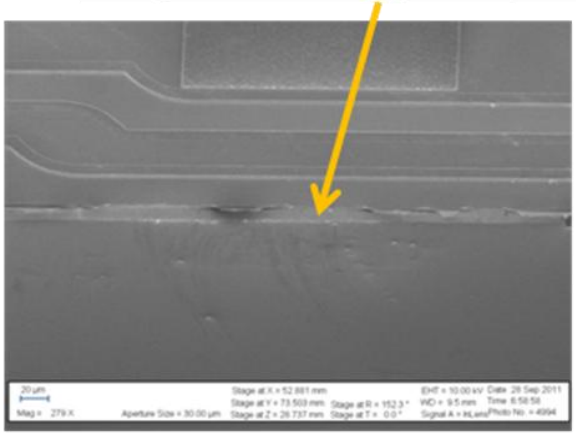
Diamond scribing

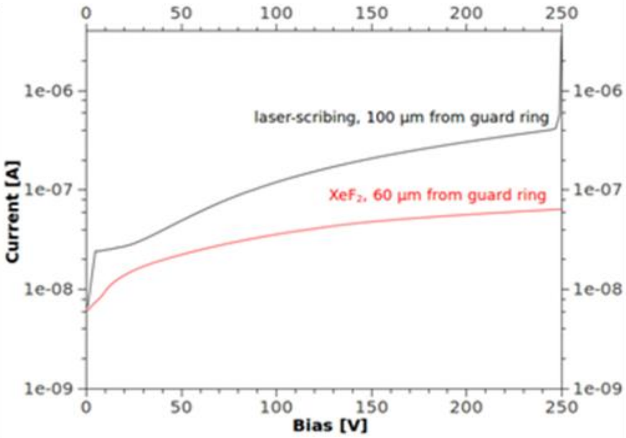


Laser scribing



XeF_2 "scribe" with depth ~ 5 µm

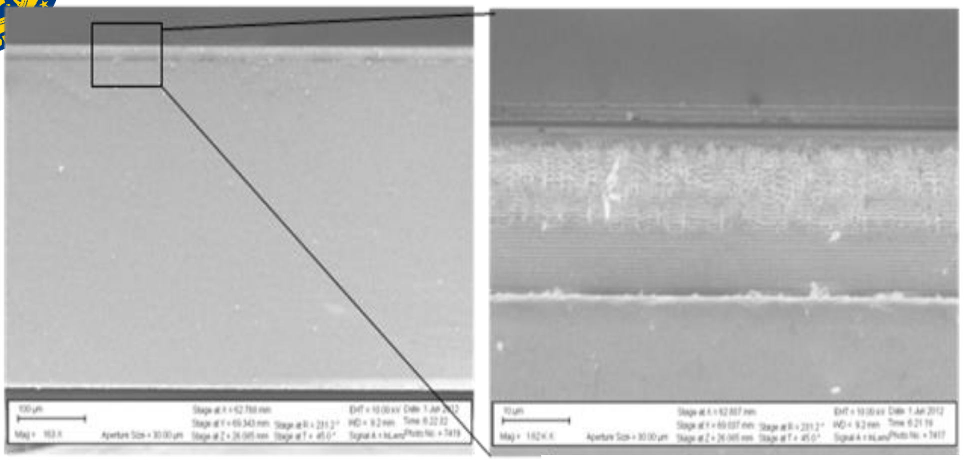


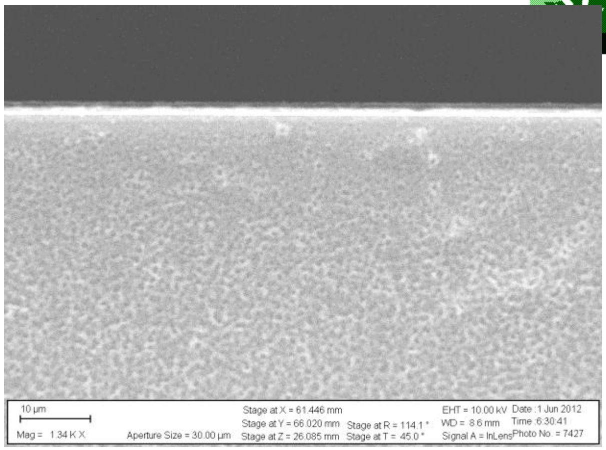


Issues:

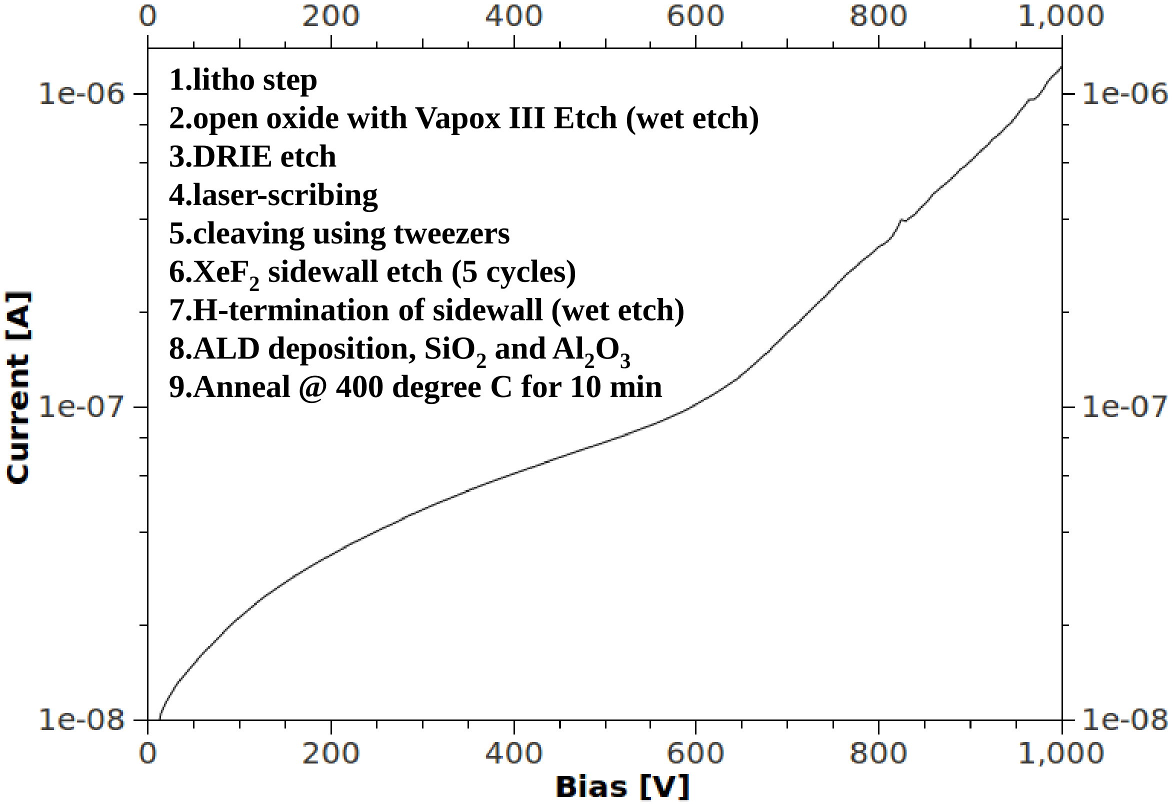
- ➢ Diamond scribing: surface chipping of existing passivation (=> to do again in future runs)
- ➢ Laser scribing: some degree of damage due to affected region of the sidewall
- ➢ XeF2 etching: cleaving by industrial machines is difficult

Scribing Technologies: DRIE



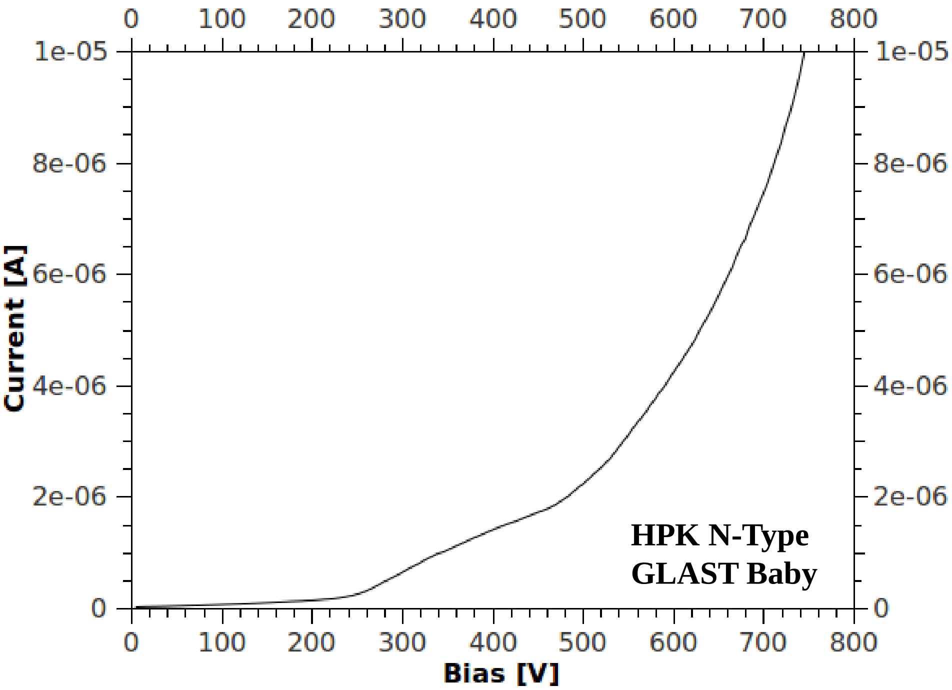


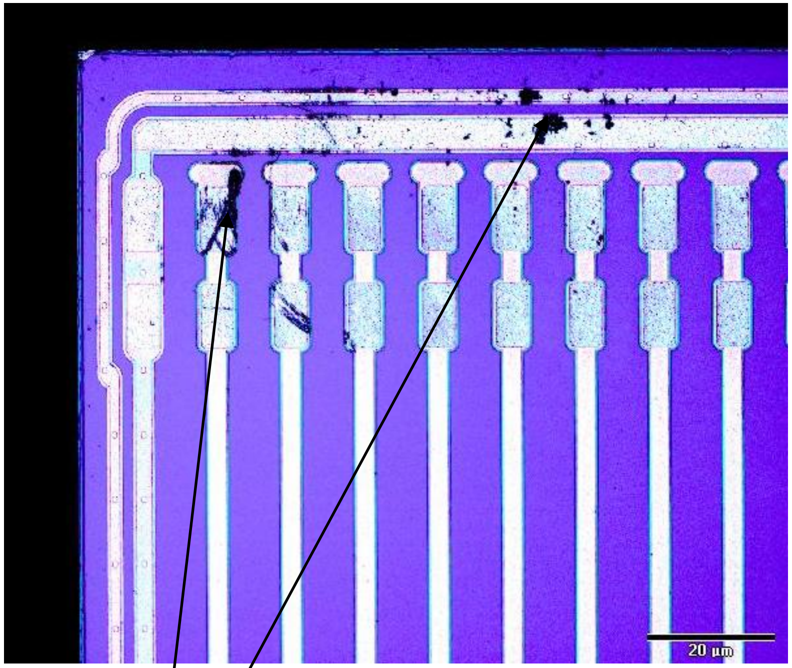
DRIE-based trenching as scribing has a promised of being a “universal” production solution without shortcomings of the other methods.



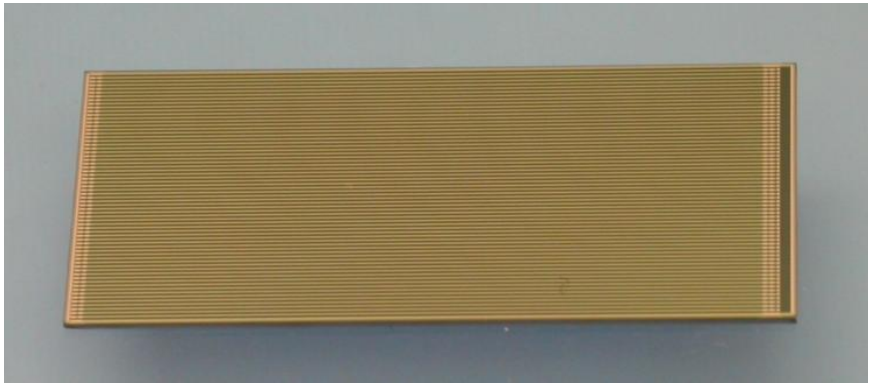
1. litho step
2. open oxide with Vapox III Etch (wet etch)
3. DRIE etch
4. laser-scribing
5. cleaving using tweezers
6. XeF_2 sidewall etch (5 cycles)
7. H-termination of sidewall (wet etch)
8. ALD deposition, SiO_2 and Al_2O_3
9. Anneal @ 400 degree C for 10 min

DRIE Etch-Scribing – All Four Sides





optical micrograph, top-view



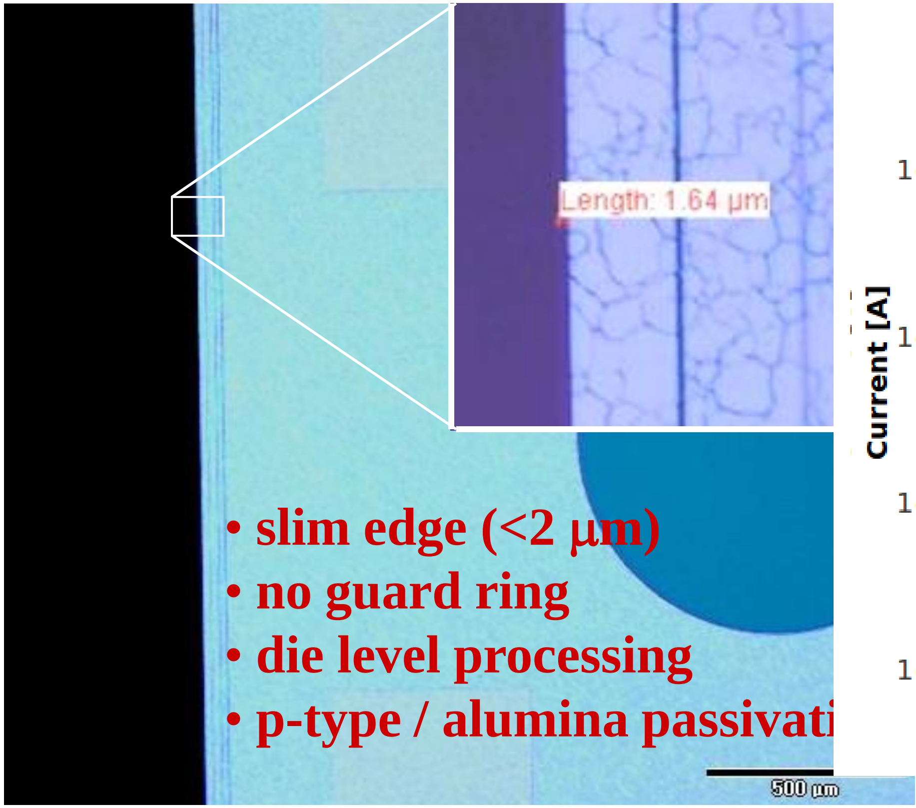
damage from tweezers cleaving

↓

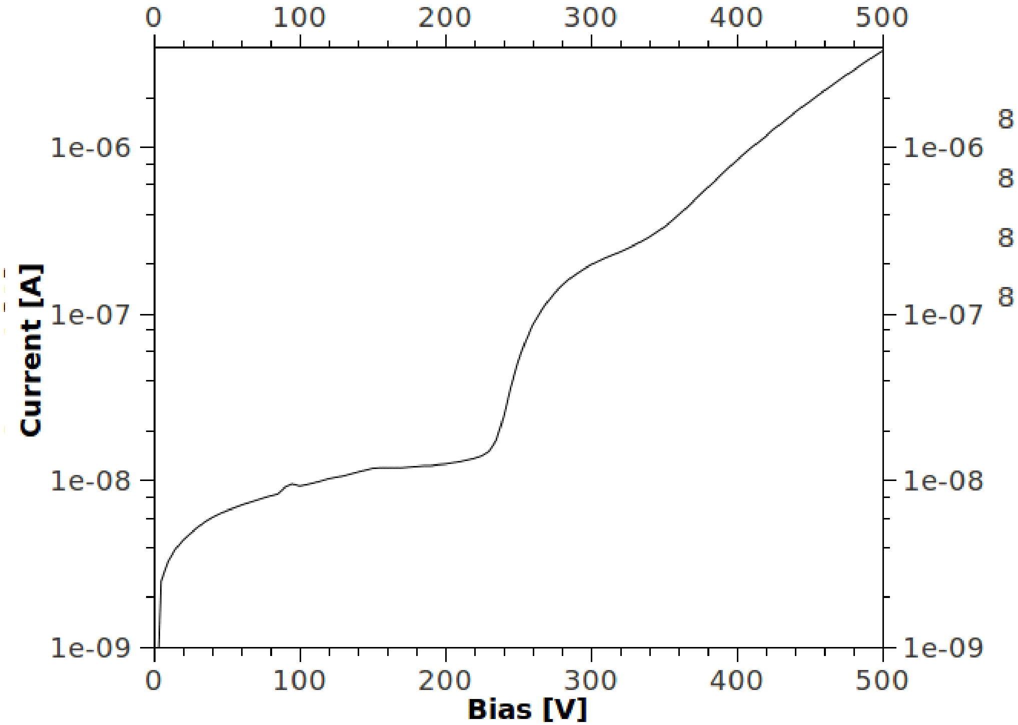
Test DRIE-scribed sensor w/ automated systems

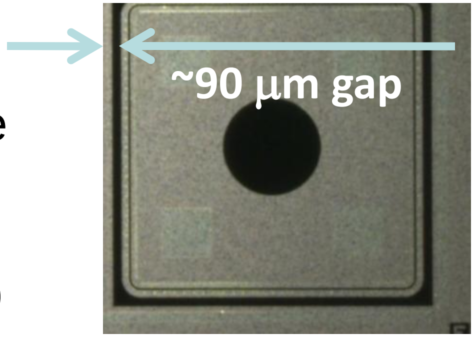
Slim-Edge Sensor

optical micrographs, top-view



- **slim edge (<2 μm)**
- **no guard ring**
- **die level processing**
- **p-type / alumina passivati**



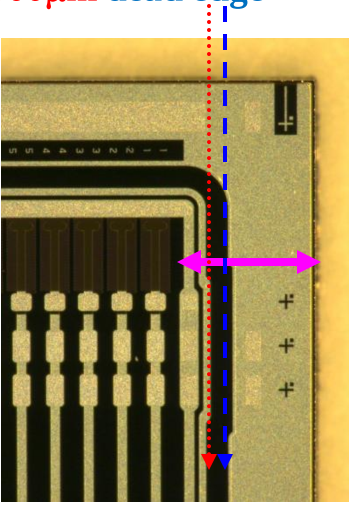


- Using a pad diode from HPK test structure meant to provide control over key sensor parameters for ATLAS07 sensors.
- It features a classic HPK single-guard ring design.
- Simple DC-coupled n-on-p pad. V_{depl} ~ 80 V. Thickness 320 um.

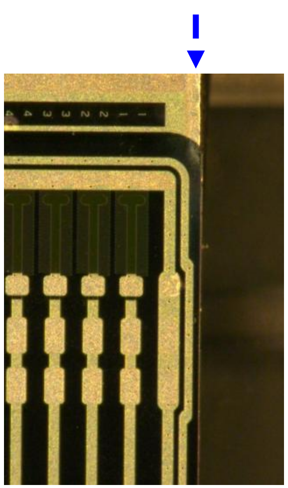
Progress with N-type Sensors

XeF2 scribing + Nitride PECVD

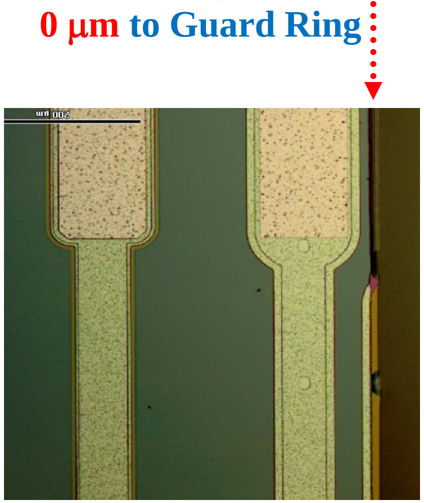
Si SSD with
900µm dead edge

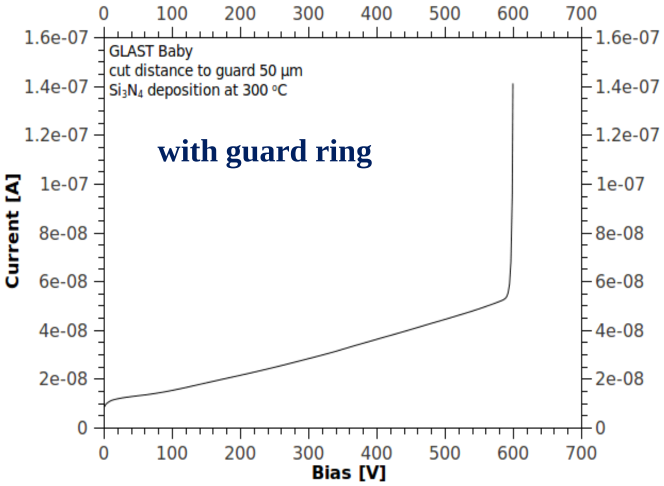


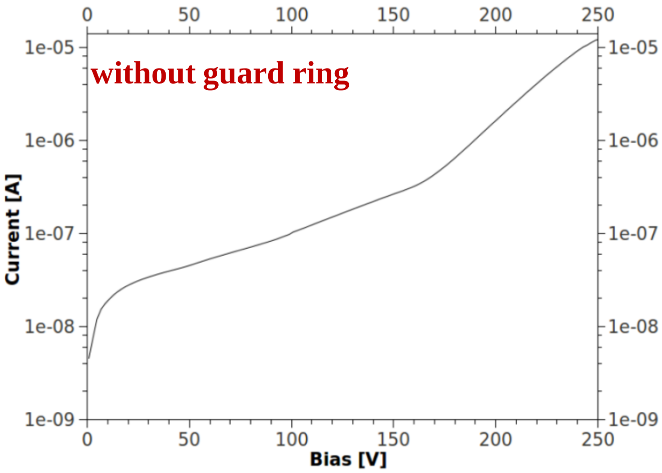
Cut within 50 µm
of Guard Ring



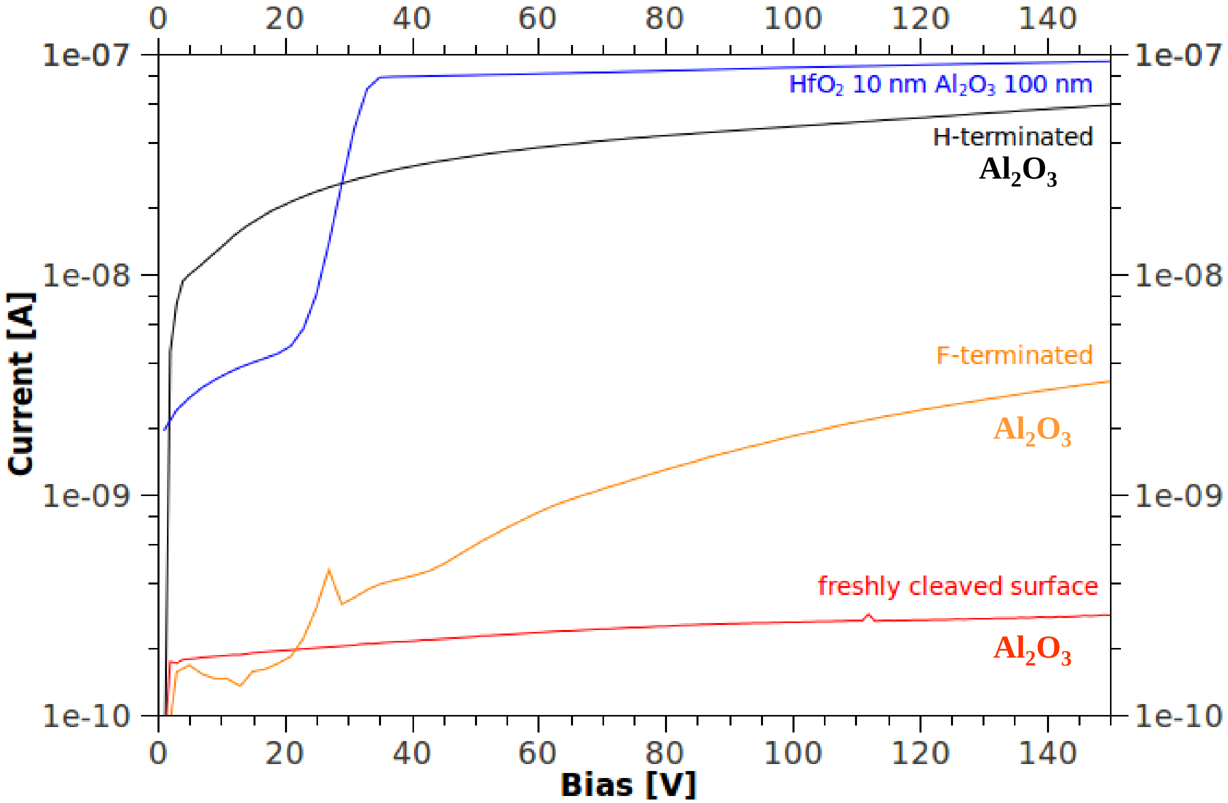
Guard Ring Cut (!)
0 µm to Guard Ring







Effect of Surface Termination – P-Type Si

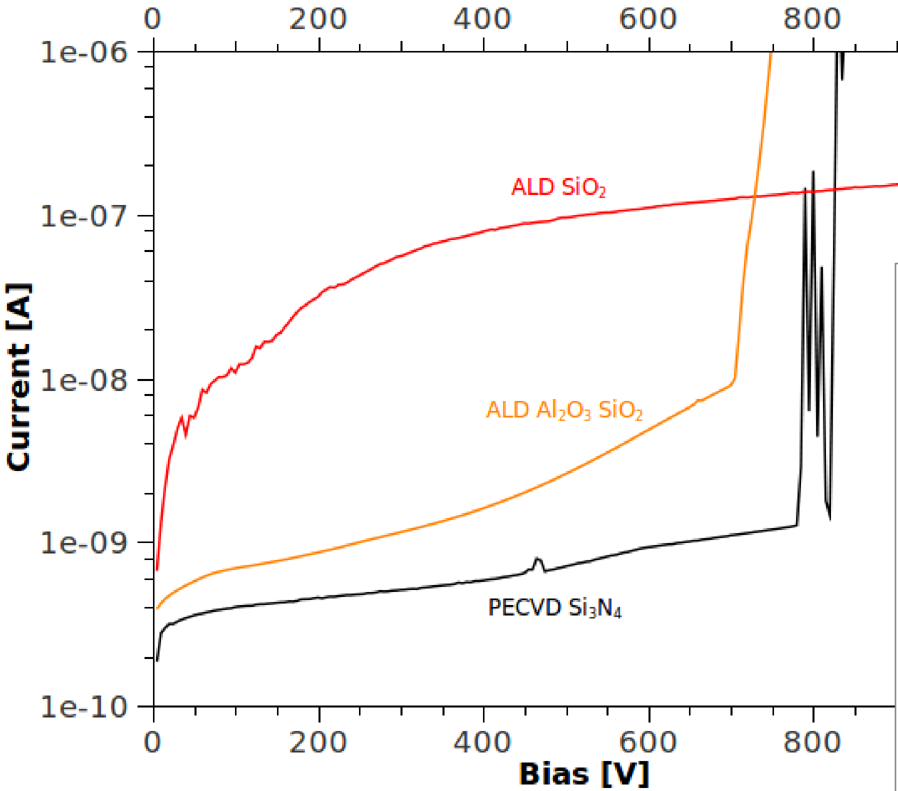


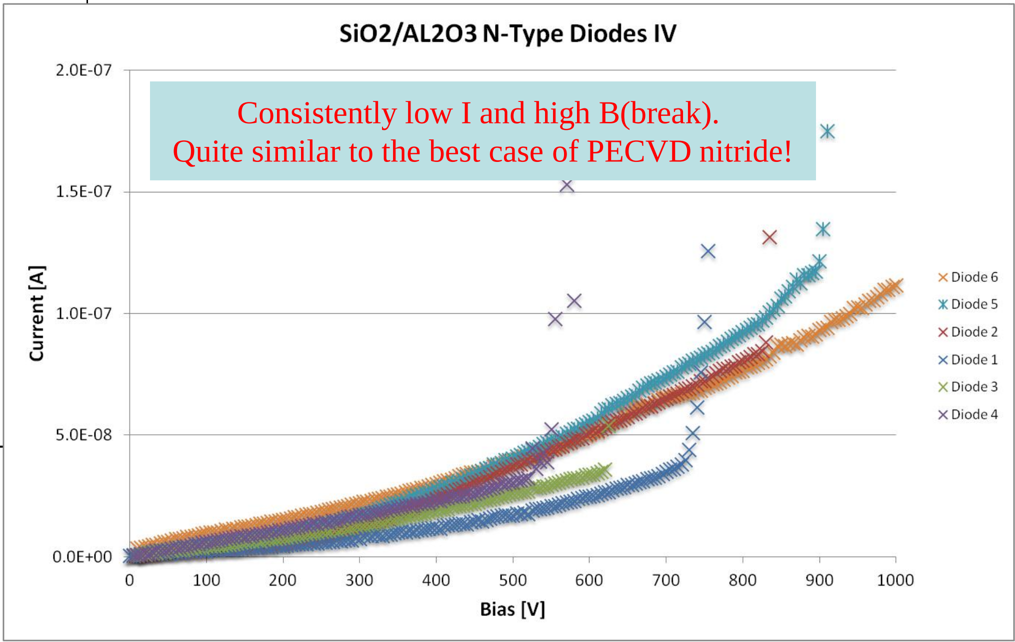
- After all the handling, we need to remove a native oxide. That is done w/ HF and leads to the “H-termination”, which can’t be passivated with alumina Al_2O_3.
- Need to covert the H-termination into F-termination which in combination with alumina ALD should work. Know they chemistry!
- The hunt for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

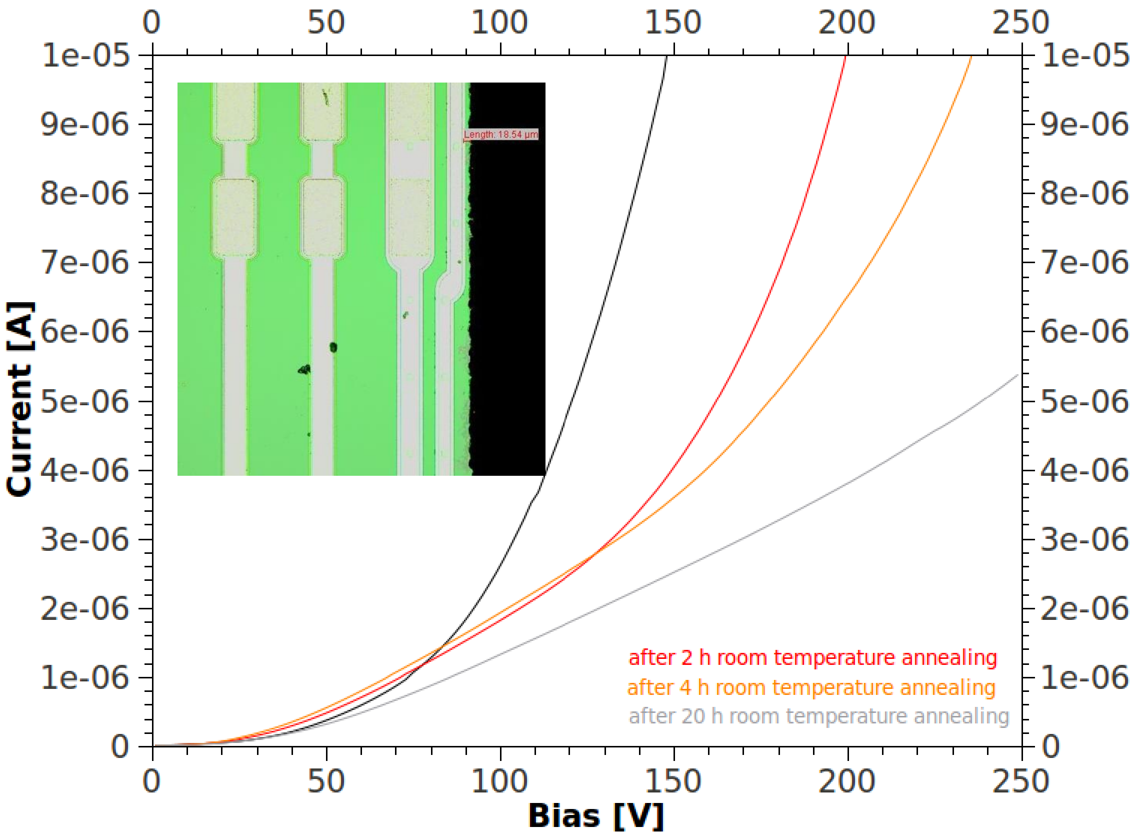
Study with HPK Fermi/GLAST diodes.
The plain ALD SiO2 is worse than the best case of PECVD Si3N4.
But a “nanostack” of ALD SiO2 (10 nm) and Al2O3 (50 nm) works well.
Parameters are from G. Dingemans et al, J. Appl. Phys. 110, 093715 (2011); doi: 10.1063/1.3658246





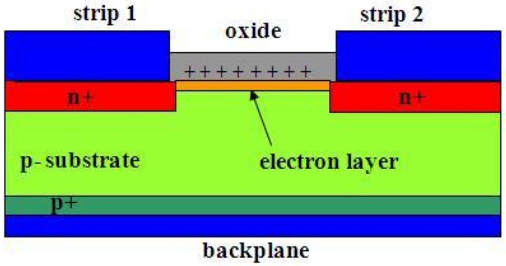
Consistently low I and high B(break).
Quite similar to the best case of PECVD nitride!

(More) Progress with Sidewall Cleaning

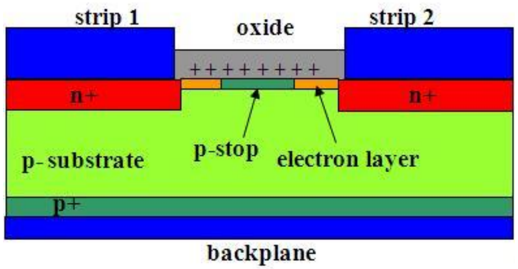


- An extreme case of laser cut-through (=> no cleaving!), followed by the sidewall cleaning and passivation with nanostack.
- The sensors are clearly alive. Observed a post-fabrication room-temperature annealing.
- These are n-type Fermi/GLAST test sensors.

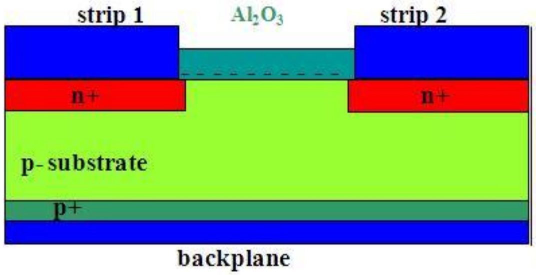
Aside: Passivation for (inter-strip) Isolation



problem

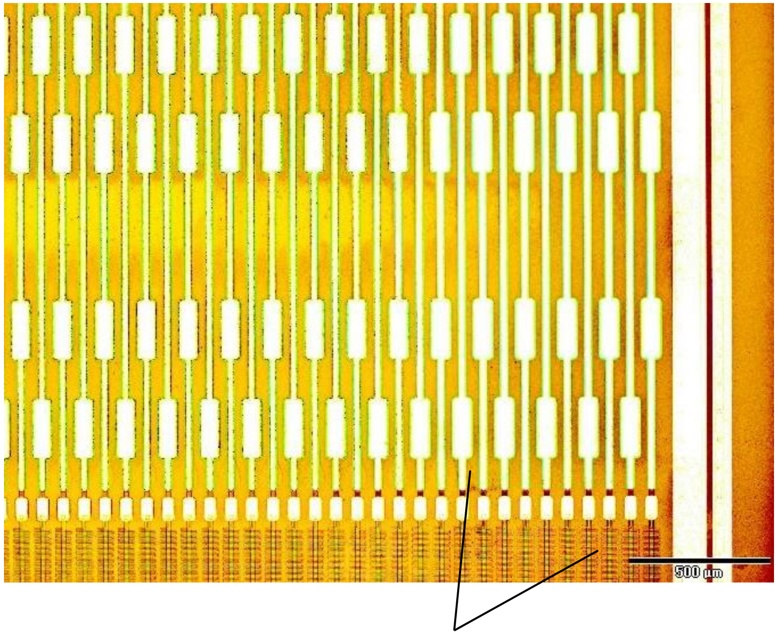


Solution with p-stop



New Solution with alumina

HPK P-Type Strip Sensor



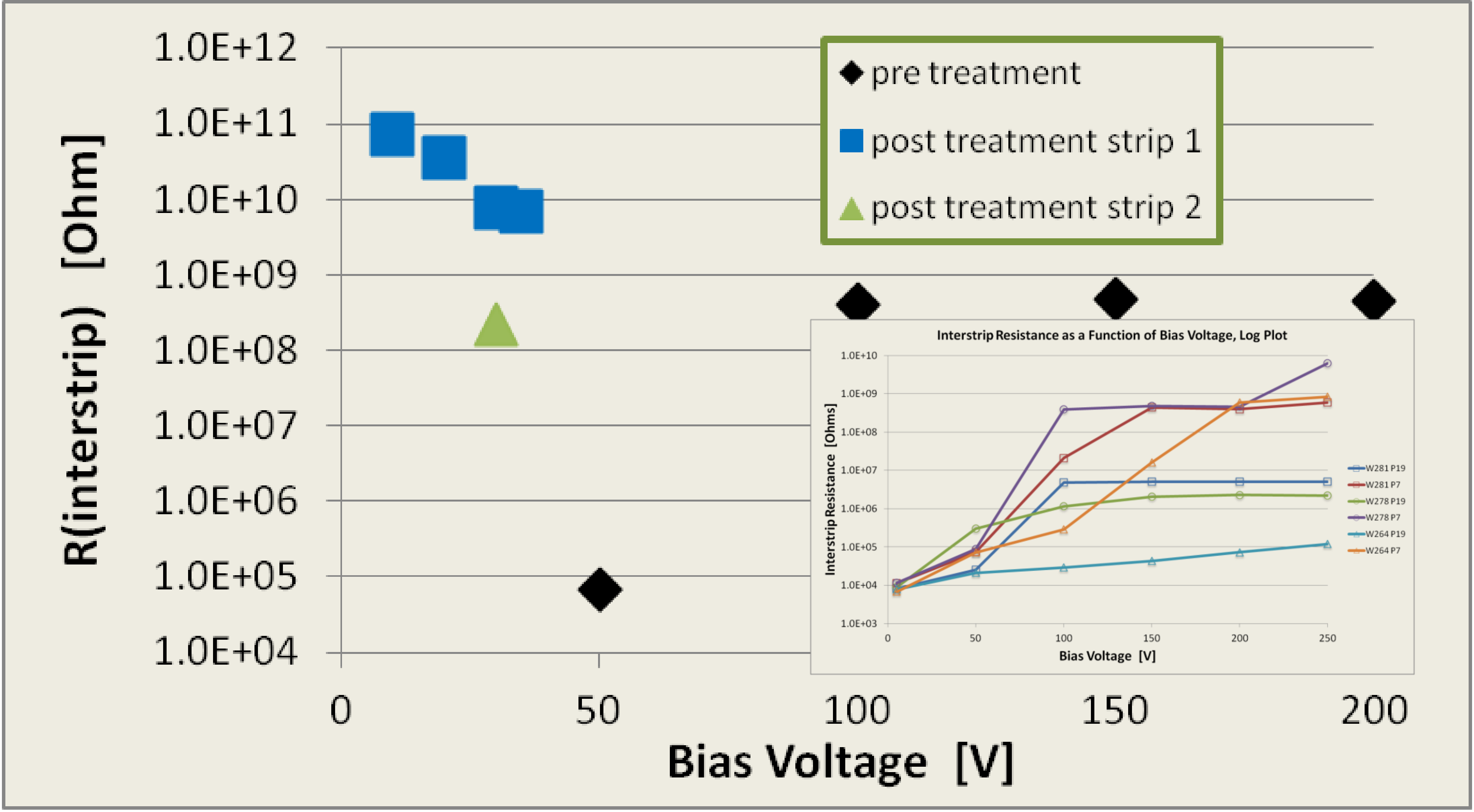
ATLAS07 test sensor without inter-strip isolation (Zone 1 on p-stop wafer) , thanks to Gianluigi Casse.

Process Sequence:

- **Lithography step**
- **Oxide wet etch with Silox Vapor Etch**
- **Remove photoresist**
- **Cleaning step**
- **H-Termination surface**
- **Surface F-Termination with XeF_2 reaction**
- **Thermal Atomic Layer Deposition of alumina, Al_2O_3**
- **Annealing step in Hydrogen atmosphere (30 min at 350 ºC)**

- **Converting an existing sensor w/o stops into segmented sensor.**
- **All strips are completely surrounded with alumina.**

P-Type: IV Curve with Alumina Layer



- **rather high leakage current after alumina deposition.**

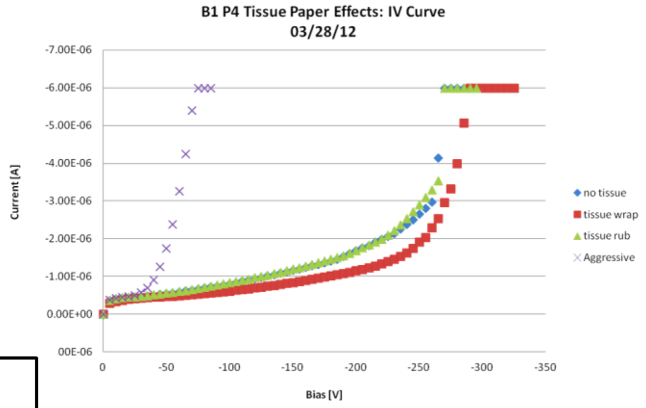
Key Activity: Irradiation Studies : 1. LANL

We have irradiated 12 SCP processed p-type strip devices (CIS courtesy A. Macchiolo) at LANL in Dec 2011

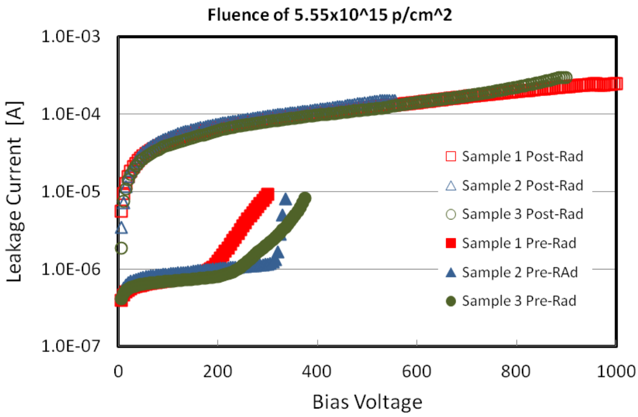
- Results are in-conclusive:
  + Breakdown voltages extended post-rad
  + High fluence devices (3/3 for 1e16neq, 3/3 for 1e15neq) show expected post-rad leakage current
  - Lower fluence devices (1/3 for 1e13neq and 1/3 for 1e14neq) show very early breakdown!!!

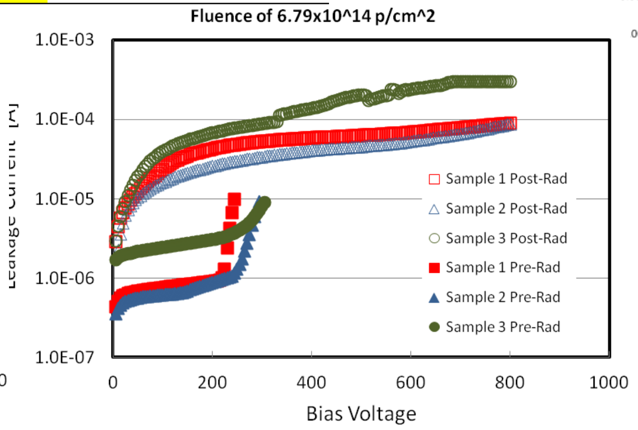
	Before Irradiation	After Irradiation		
Sensor	V(break) at ~10 uA	V(break) at ~100 uA	Fluence	No Guard Rings
B1 P5	30	460	10^13	1
B1 P6	290	165	10^13	1
B2 P1	410	80	10^13	3
B1 P8	15	90	10^14	5
B2 P10	310	80	10^14	5
B2 P6	390	100	10^14	1
B2 P8	300	>800	10^15	4
B2 P9	310	335	10^15	5
B2 P11	250	>800	10^15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



In the future we will add ~1 um parylene coating on top of sidewall passivation. This should allow better handling and mounting options.

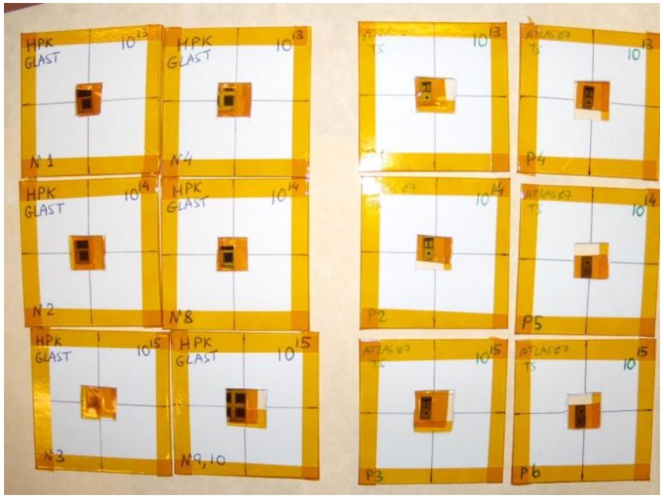


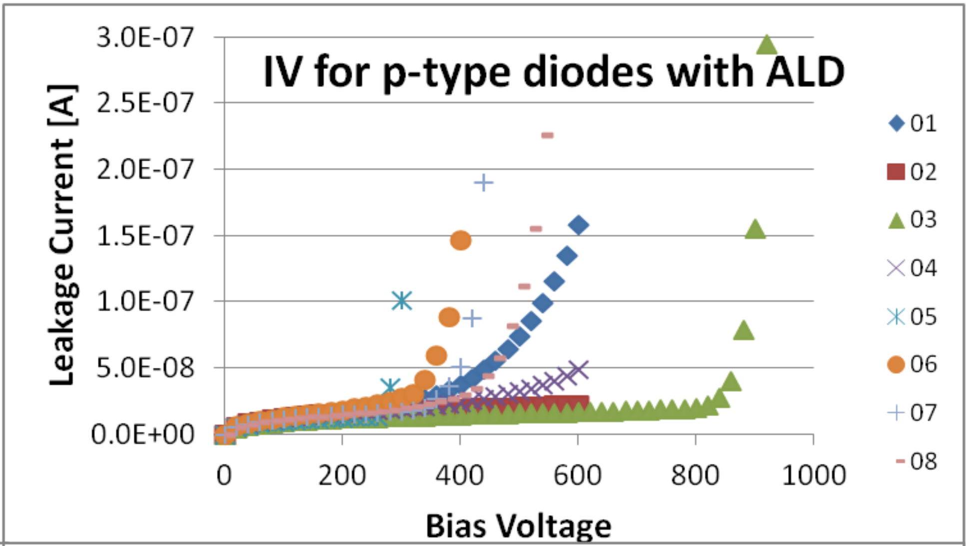


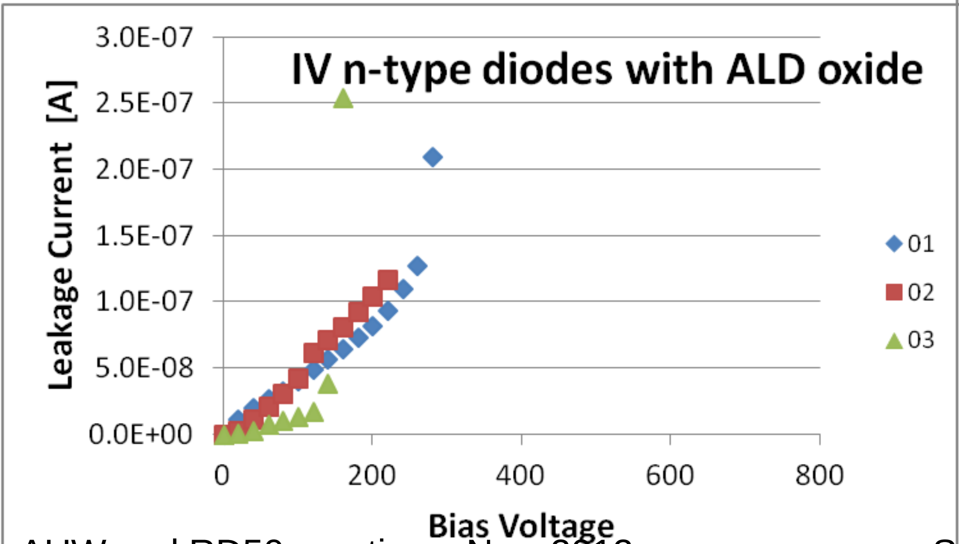
Irradiation Studies contd. : 2. CERN

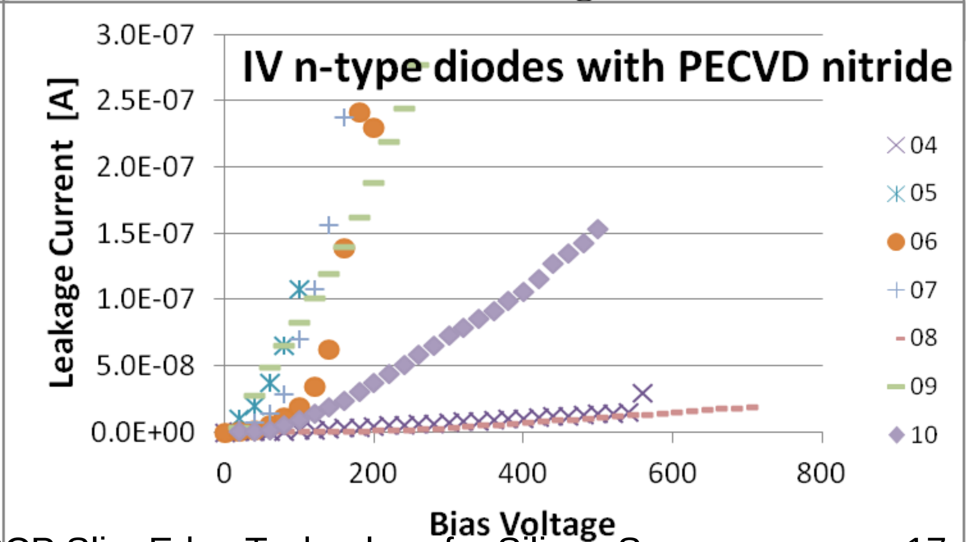
A new round of irradiations at SPS (help from G. Casse & M. Glaser) this summer:

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



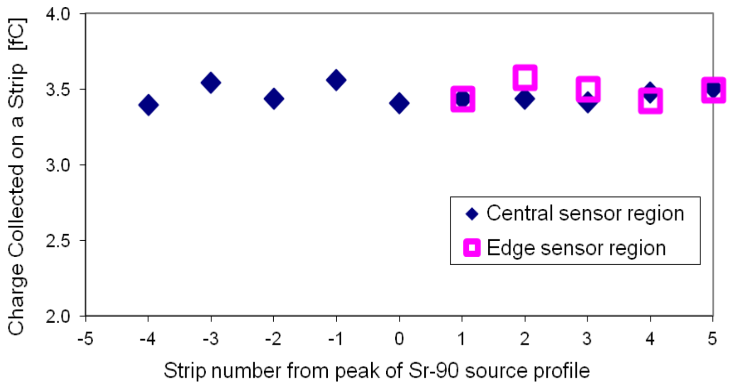


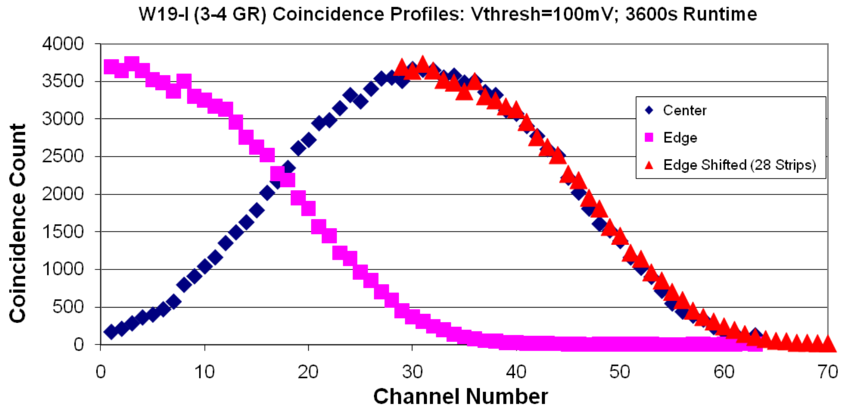




Charge Collection Testing

Sensor Type	Origin	Edge-Active area Distance [um]	Signal Read out	Beam	Ref
P-type strips	PPS (CIS)	~200	Binary (PTSM)	^{90}Sr	V. Fadeyev *et al* Pixel 2012, submitted to NIM A
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.*, submitted to JINST
P-type 3D pixels	IBL (CNM)	50	FE-I3 & FE-I4	CERN Test Beam	S. Grinstein *et al.*, RESMDD12





SCP: RD 50 Matrix

This development became an RD50 project in June 2011
We are very happy to fulfill “slim edge” requests from the RD50 Collaboration

Institute	Contact Person	Sensors	Status
CNM Barcelona	G. Pellegrini	3D diodes, strips, pixels	2nd round of tests (FE-I3 and FE-I4 pixels)
FBK Trento and INFN Trento	G.-F. Dalla Betta	3D diodes, strips	2nd round of tests ongoing
MPI Muenchen	A. Macchiolo	P-type planar pixels	In progress**
UNFN Bari	D. Creanza	N-type “SMART” detectors	First processed devices sent for evaluation**
JSI Ljubljana	G. Kramberger	P- and N- type strip devices	Sent processed devices for laser TCT studies
Glasgow U.	R. Bates	P- and N- type strip devices	Devices sent, used in precision X-ray scan
TU Dortmund	T. Wittig	IBL-style n-on-n sensors	Initial tests done, iterations with IBL sensors

Also interest from other parties, e.g. 3-D integration sensors at FNAL (Ron Lipton).

**In these instances we are limited by the available margin around the device and performance of the “tweezers” technique. Automated cleaving machines should work better on whole wafers.

Conclusions and Future Work

- Scribe-cleave-passivate (SCP) method of making a slim edge device holds a lot of promise.
- Work goes on in the framework of PPS and RD50 collaboration.
- The method development continues, particularly toward industrialization of the technology:
  - Search for best production-level scribing technology
  - N-type device passivation amenable for automation
  - Better p-type surface termination
- Physics performance: Radiation tolerance, Charge collection
- We are thrilled to perform dedicated studies and service for the community

Acknowledgements

We would like to thank the Institute for Nanoscience (NSI) at the Naval Research Laboratory (NRL) and the NSI staff members.

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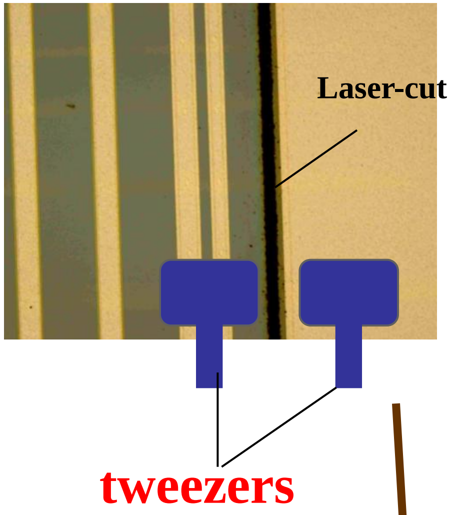
U.S. Department of Energy and National Science Foundation.

Back-Up Slides

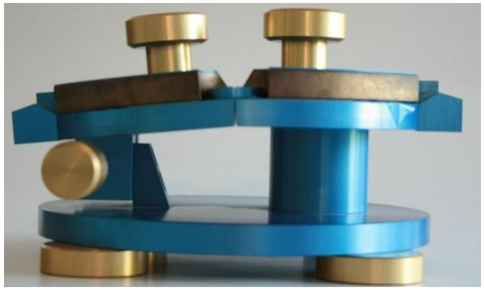
R&D for Large-Scale Application of SCP

Key issues in making further progress:
replacement of tweezer-based cleaving!



Build

Wafer Brech Maschine
Courtesy PSI and Uni Bonn



Contract

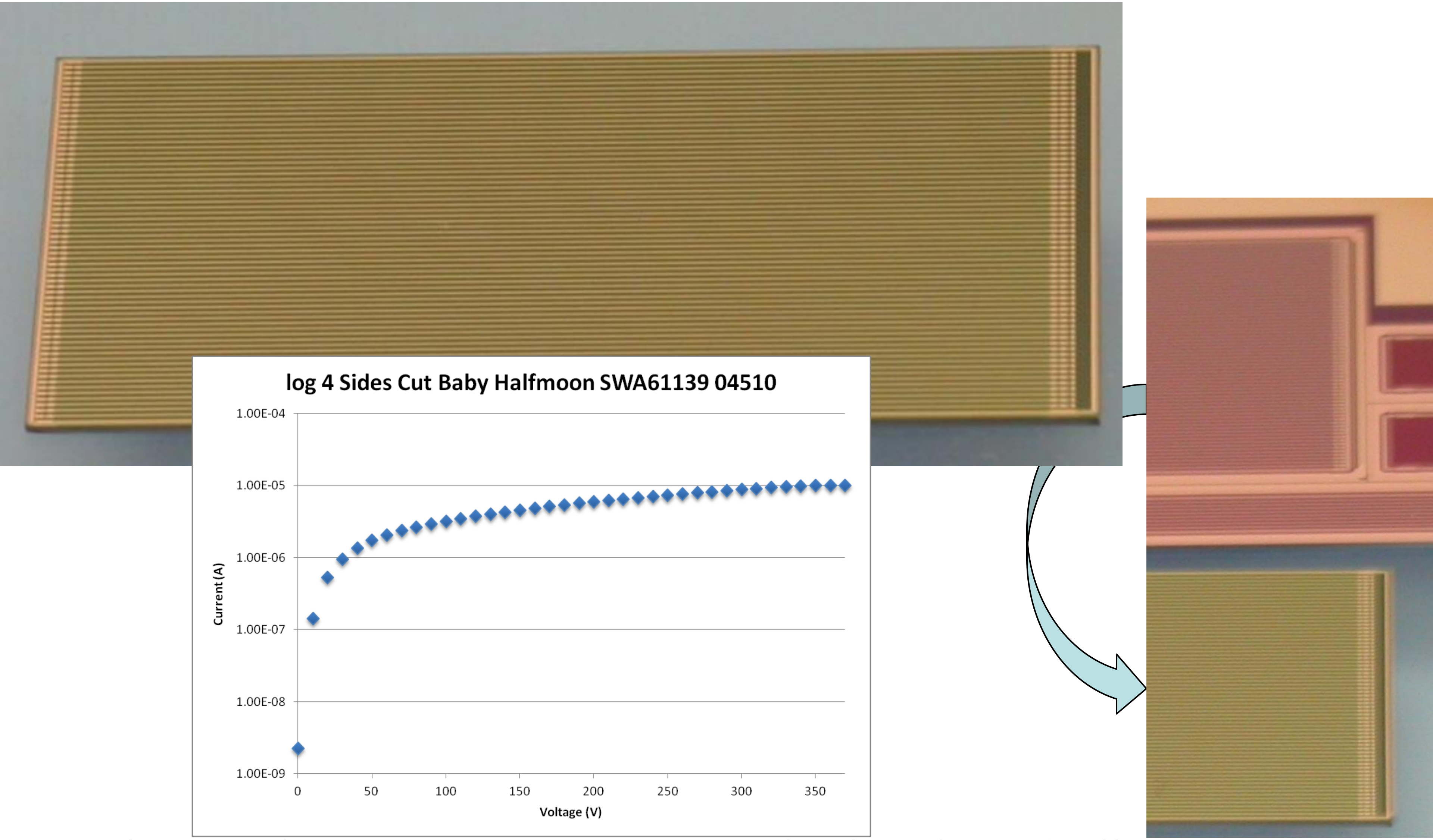
Industrial-scale cleaving machines:
- ○ Dynatex (manufacturer)
- ○ Loomis Industries (manufacturer)
- ○ Kavli Nanosciences Institute @ CIT (facility)

LOOMIS
Patented Scribe and Break Dicing Technology
LSD-150
Scriber-dicing machine

dynatex INTERNATIONAL
semiconductor dicing equipment and materials
GST-150
ScriberBreaker

Four-side Cleaving

An example of a device cleaved on all four sides.
This is the ideal goal!



Industrialization: Automated Processing

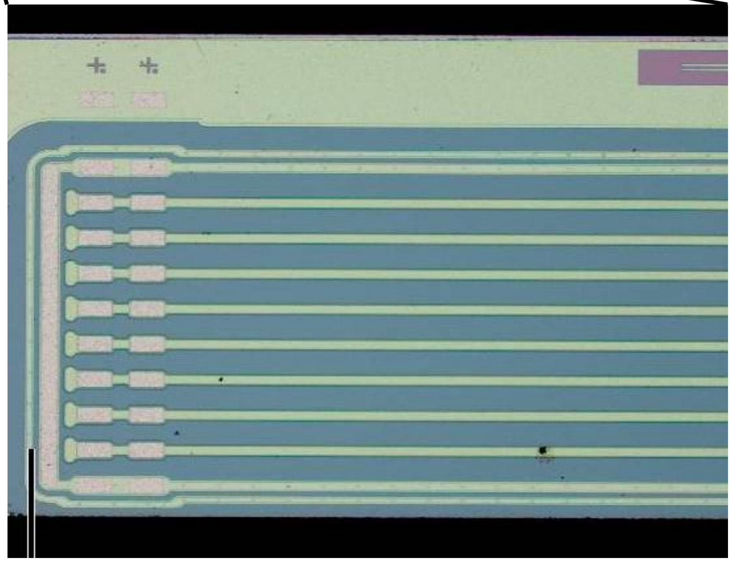
Production-ready device singulation is different from initial trials:

1) Automated scribing
2) Automated cleaving
3) Done on all four sides

overview photos

Cleaving tests done at **Loomis Industries**, makers of cleaving machines.

Loomis was able to cleave the laser-scribed sensors , but not etch-scribed ones.



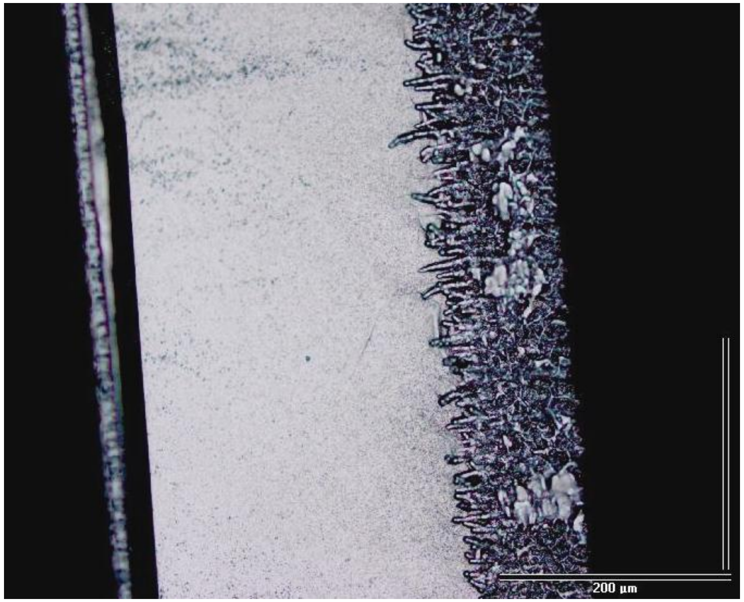
Optical micrograph, "skinny"

Industrialization: Automated Processing

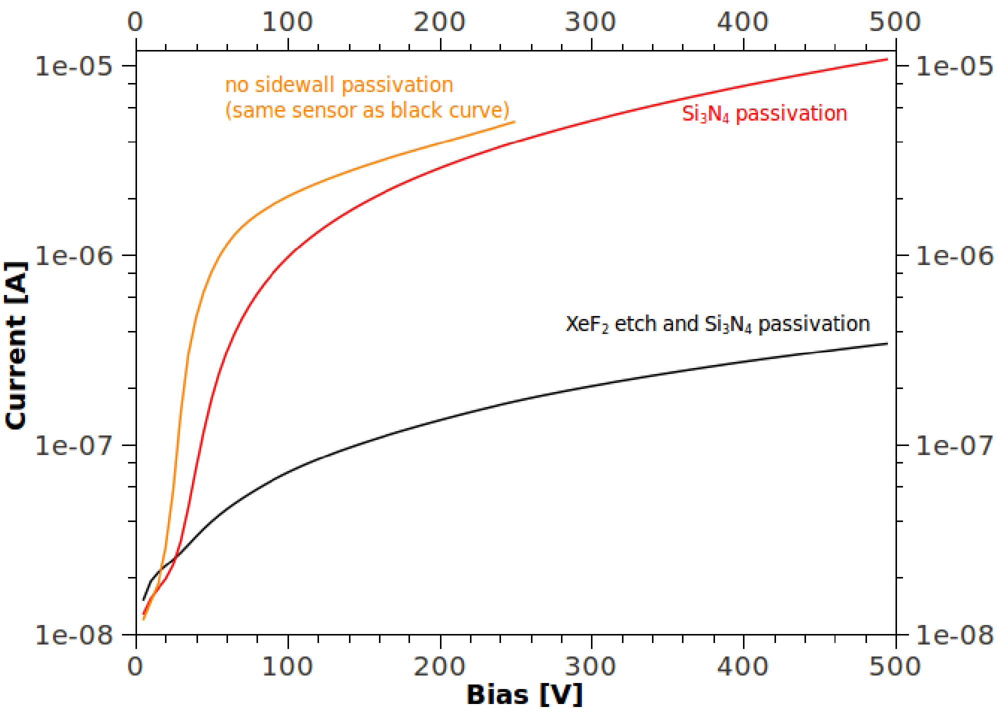
Production-ready device singulation is different from initial trials:

1) Automated scribing
2) Automated cleaving
3) Done on all four sides

Initially had high current after cleaving, even with passivation.
A key improvement was XeF2 etching of the sidewall, that removed the surface damage.



Sidewall surface after etching step.



Industrialization: Realistic Singulation

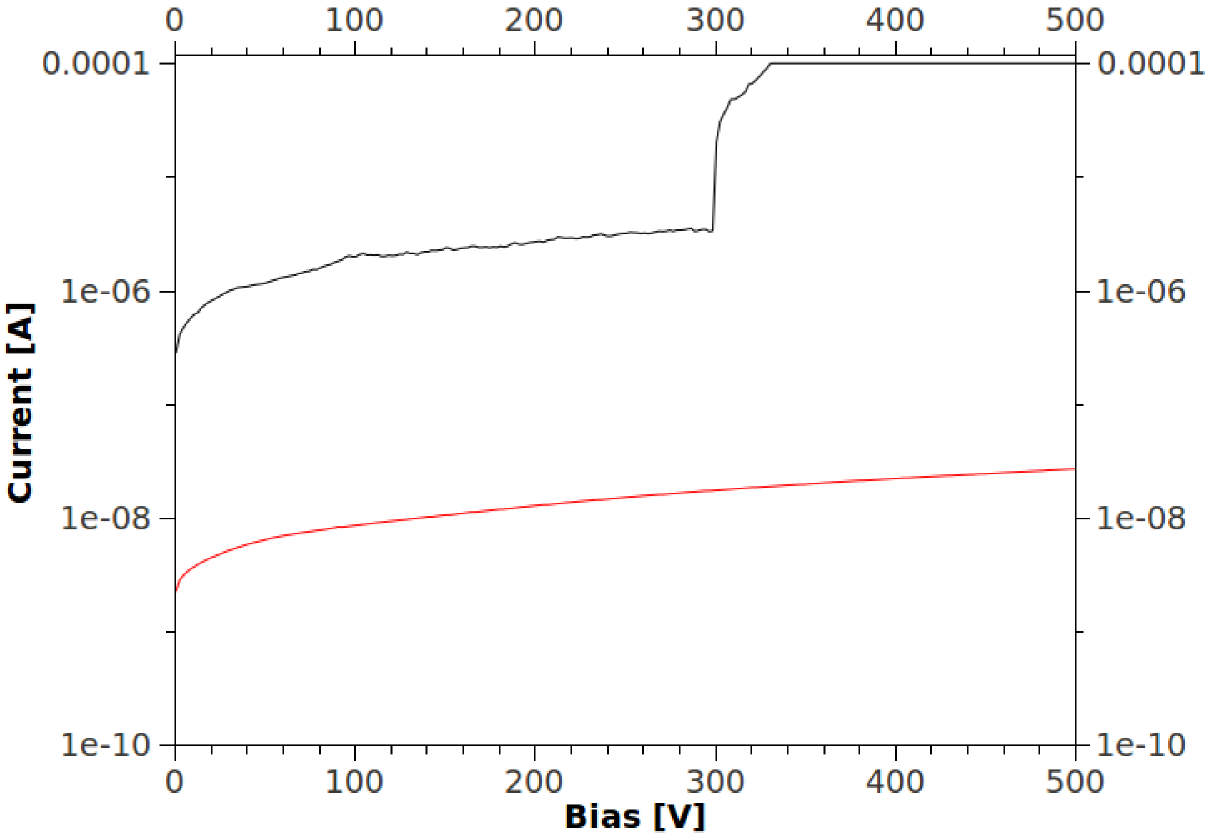
Production-ready device singulation is different from initial trials:

1) Automated scribing
2) Automated cleaving
3) Done on all four sides

4-side cleaving means intersecting cleaved wall with ‘sharp corner”.

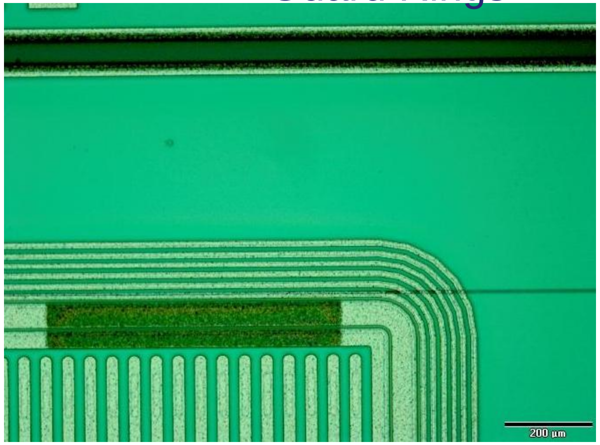
This leads to high current.

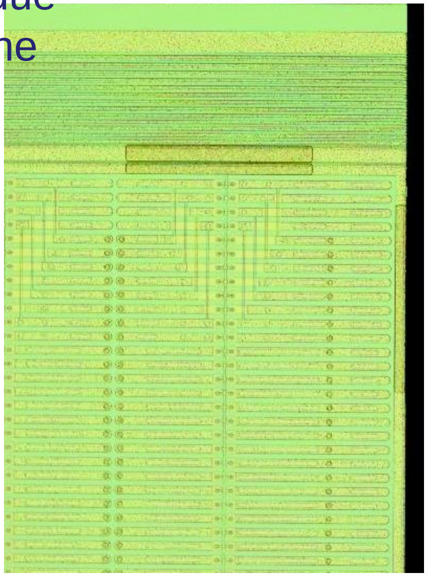
XeF2 etching of the sidewall drastically reduces the current – by two orders of magnitude!



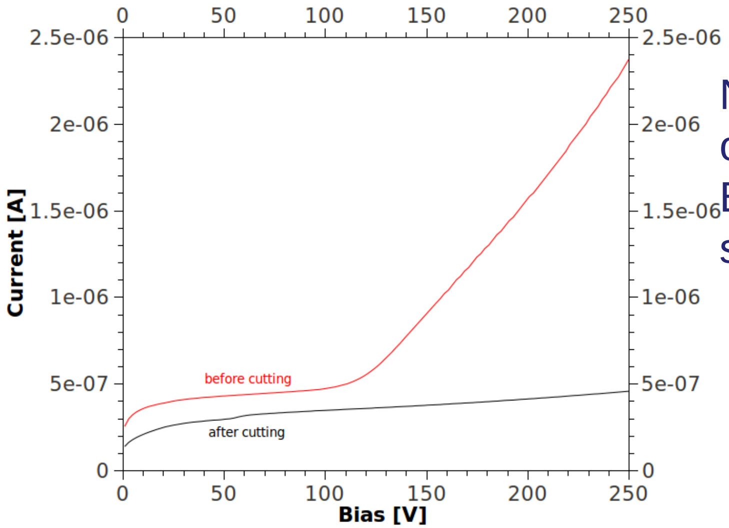
MPI Devices

Initially had issues with post-processing etch-scribing, due to presense of metal on the Guard Rings

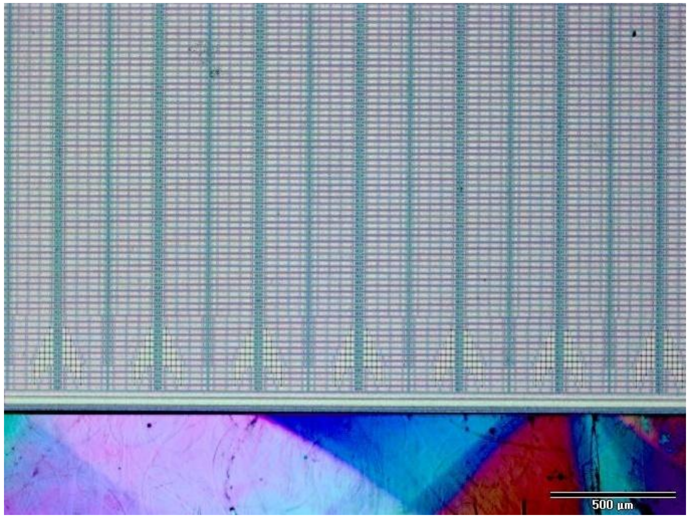


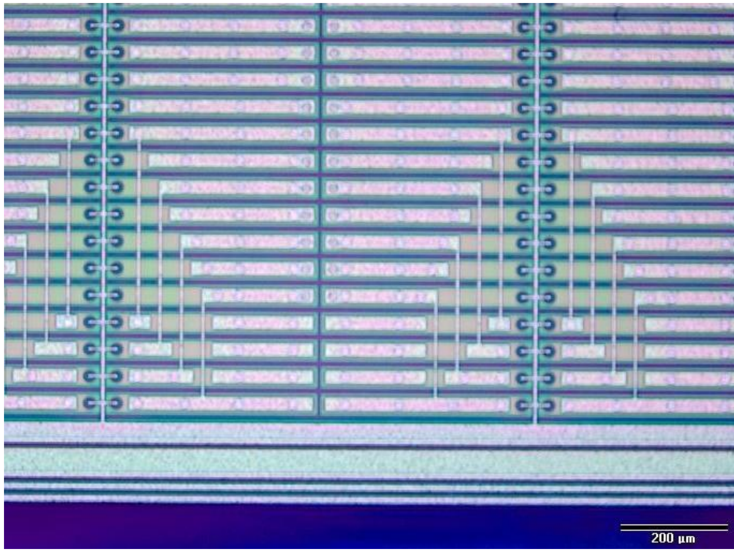


No Guard Ring on one end
But the sensor is still working!



The scribing issue was later solved:





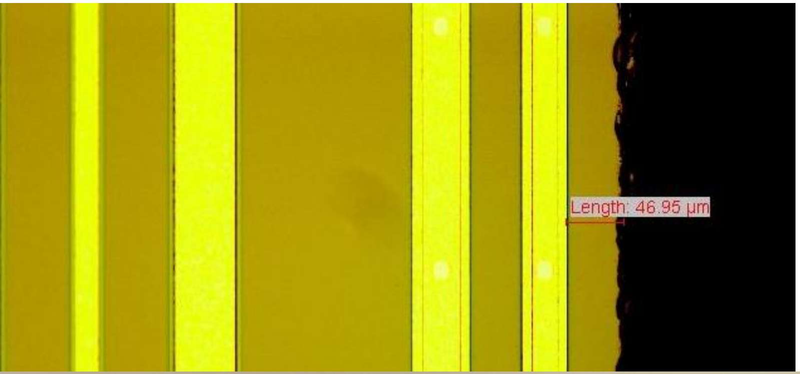
Narrow Edge Limitation

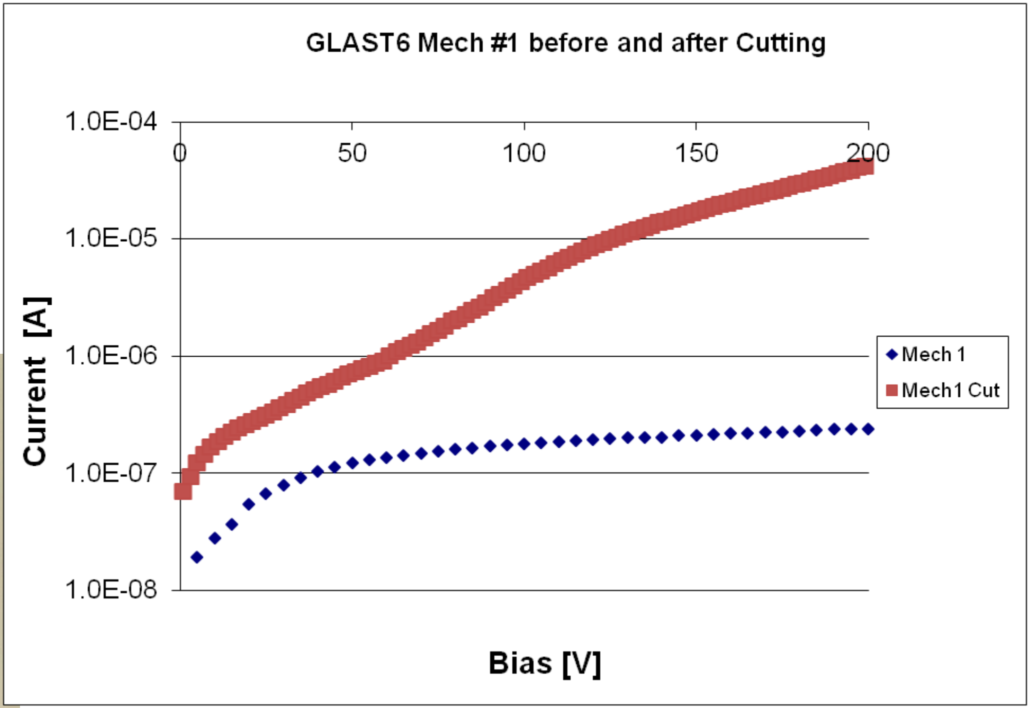
We had difficulty cleaving sensors when the width of removed material is not much larger than the device thickness. This impeded progress on some of RD50 requests.

These issues can be addressed with the existing “building blocks”:

1) (deep) laser scribe, 2) tweezer cleaving, 3) damage removal, 4) passivation.

The laser scribe has to be deep in this case, which is not ideal, but it works, as shown in the example below: 11x6 cm^2 early GLAST prototype sensor without the passivation.

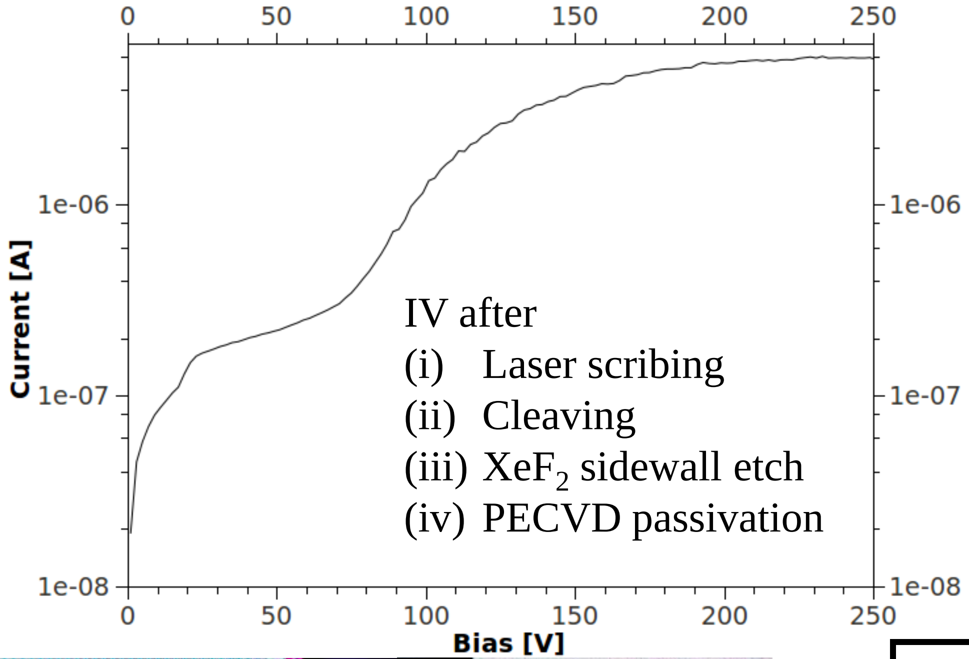




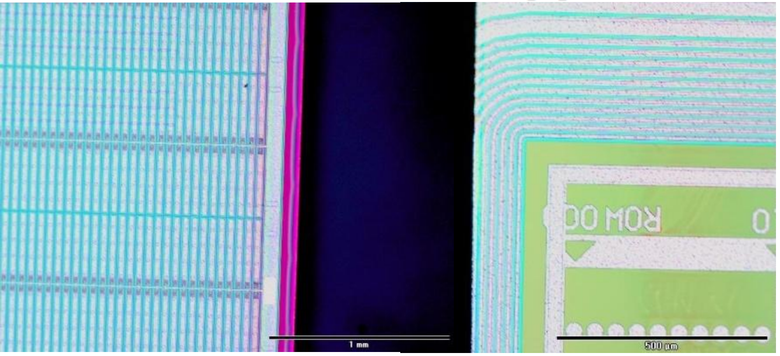
Dortmund Devices (n-on-n)

Sensors from IBL runs, a special batch with 100 wafers. Would like to find out how SCP would work, and to make samples for irradiations.

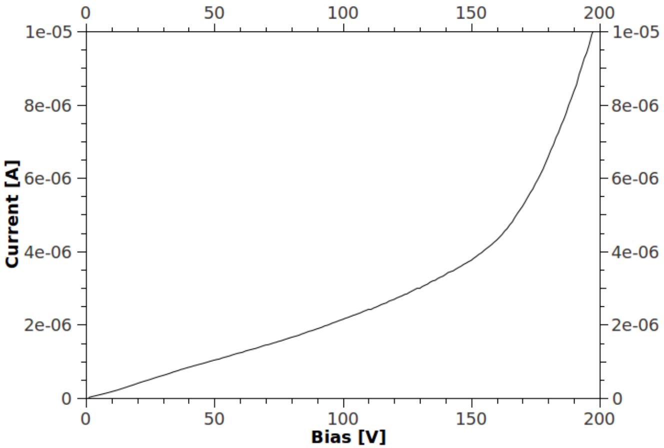
Laser-scribed device

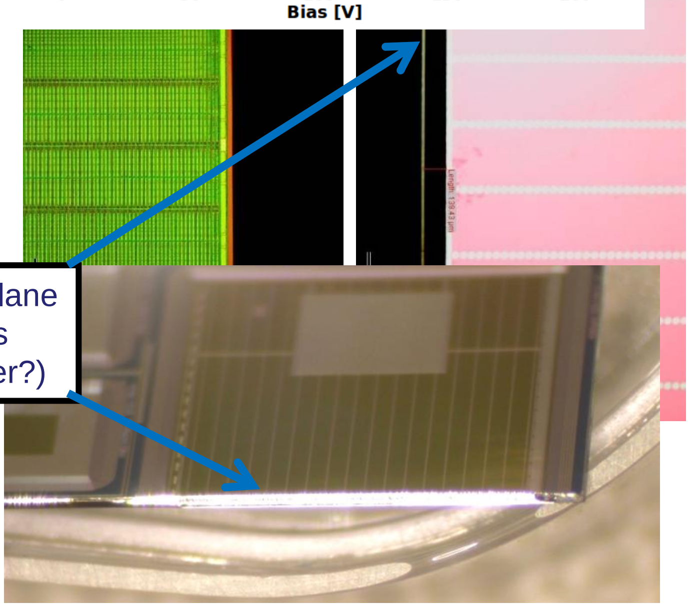


IV after
(i) Laser scribing
(ii) Cleaving
(iii) XeF_2 sidewall etch
(iv) PECVD passivation



Etch-scribed device

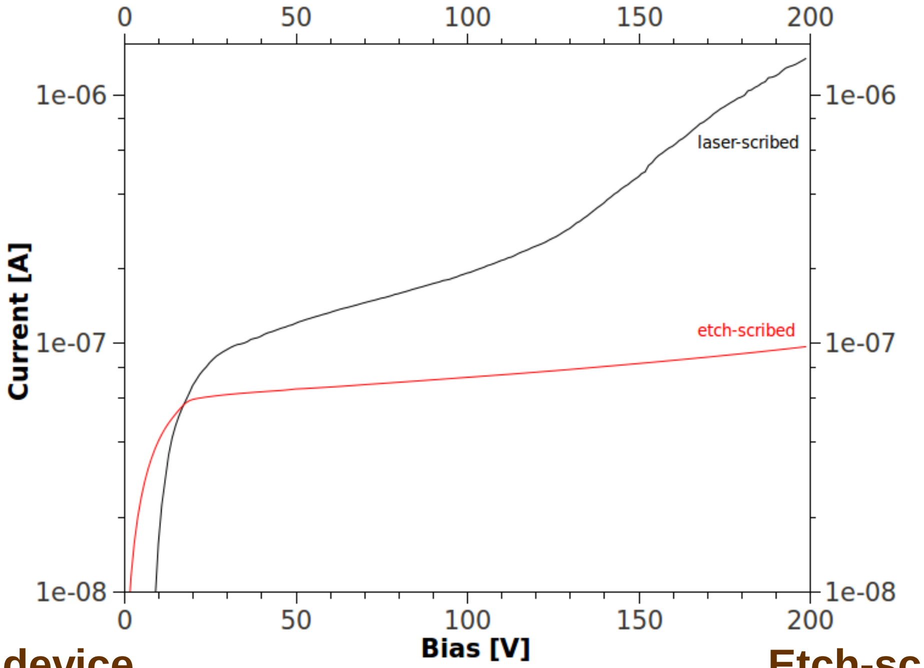




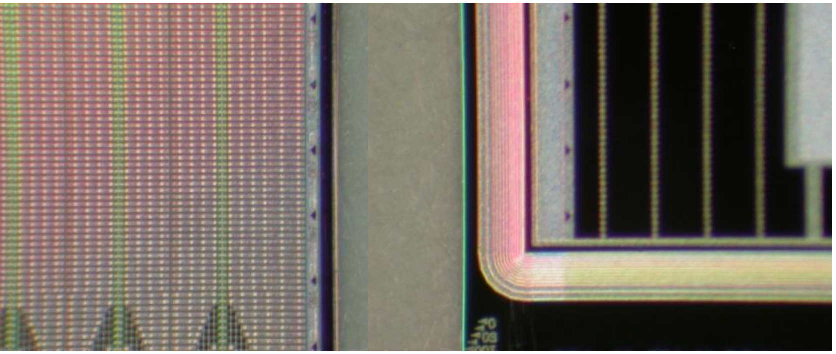
Tilted cleaving plane
(Due to stress
from nitride layer?)

Dortmund Devices (n-on-n), Cont.

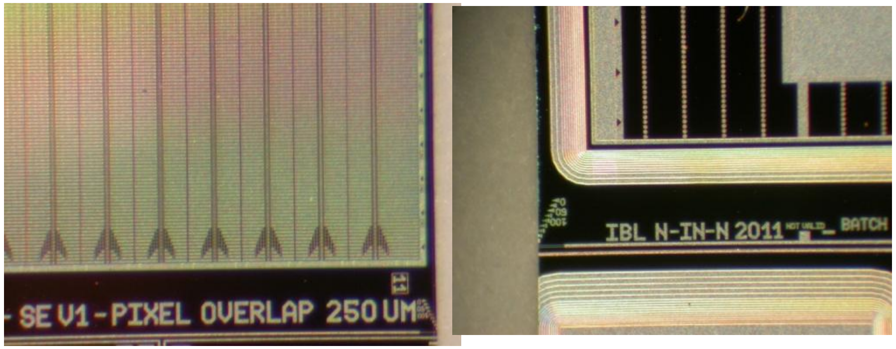
Devices cut outside GR: etch-scribing works better, no issues with cleaving.



Laser-scribed device

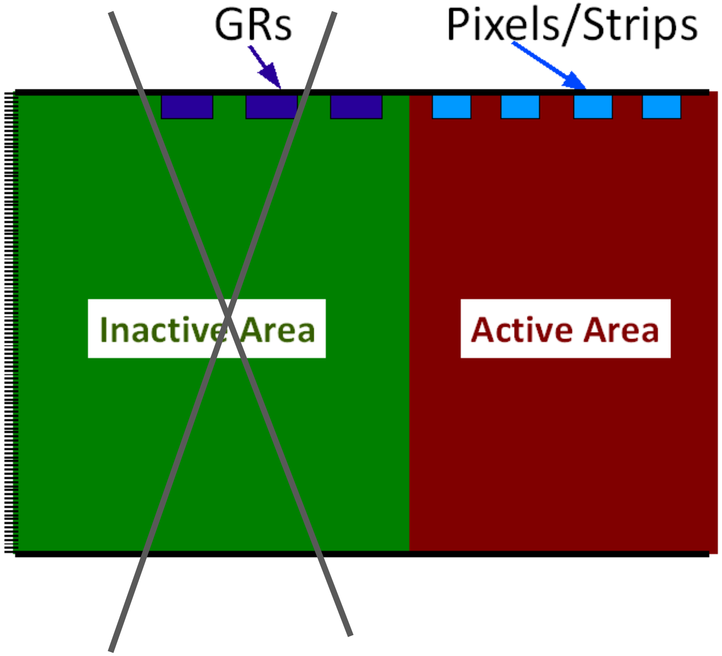


Etch-scribed device

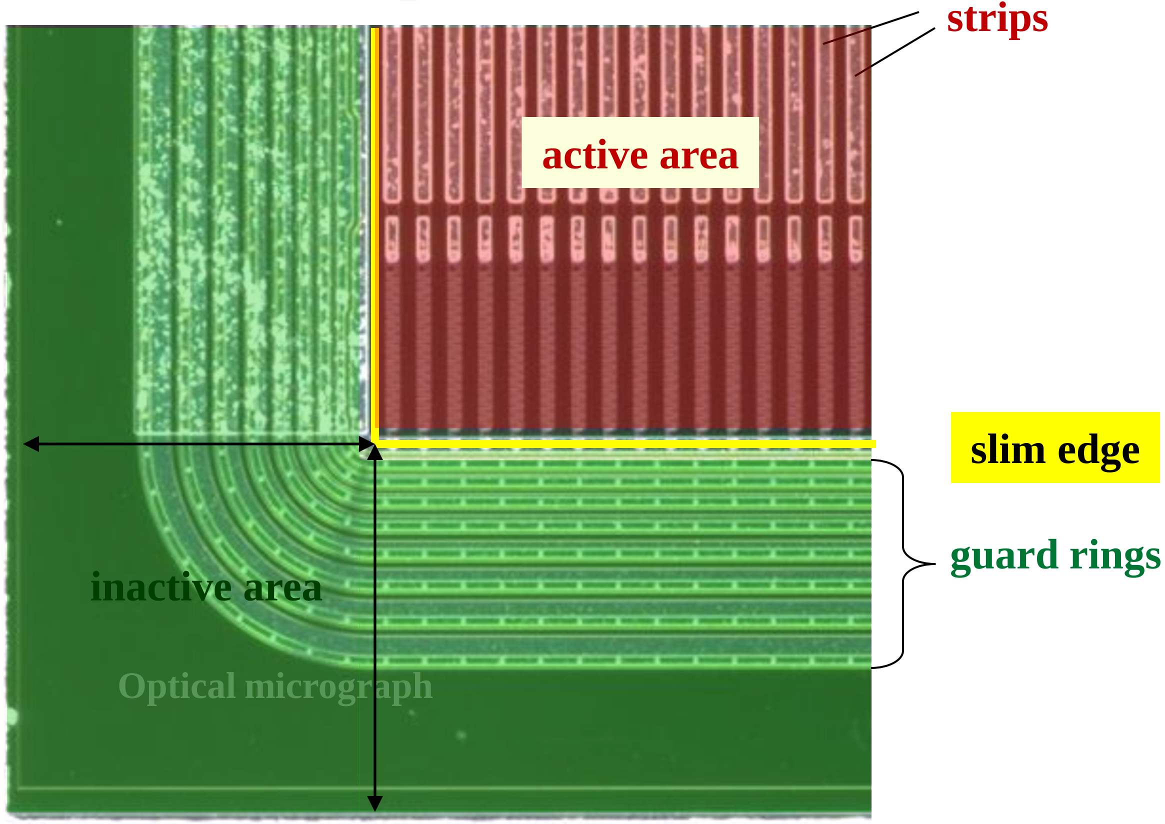


Motivation – Slim Edges

Side View



Top View



Slim edges offer:

- **reduced inactive area =>**
- **more hermetic coverage**

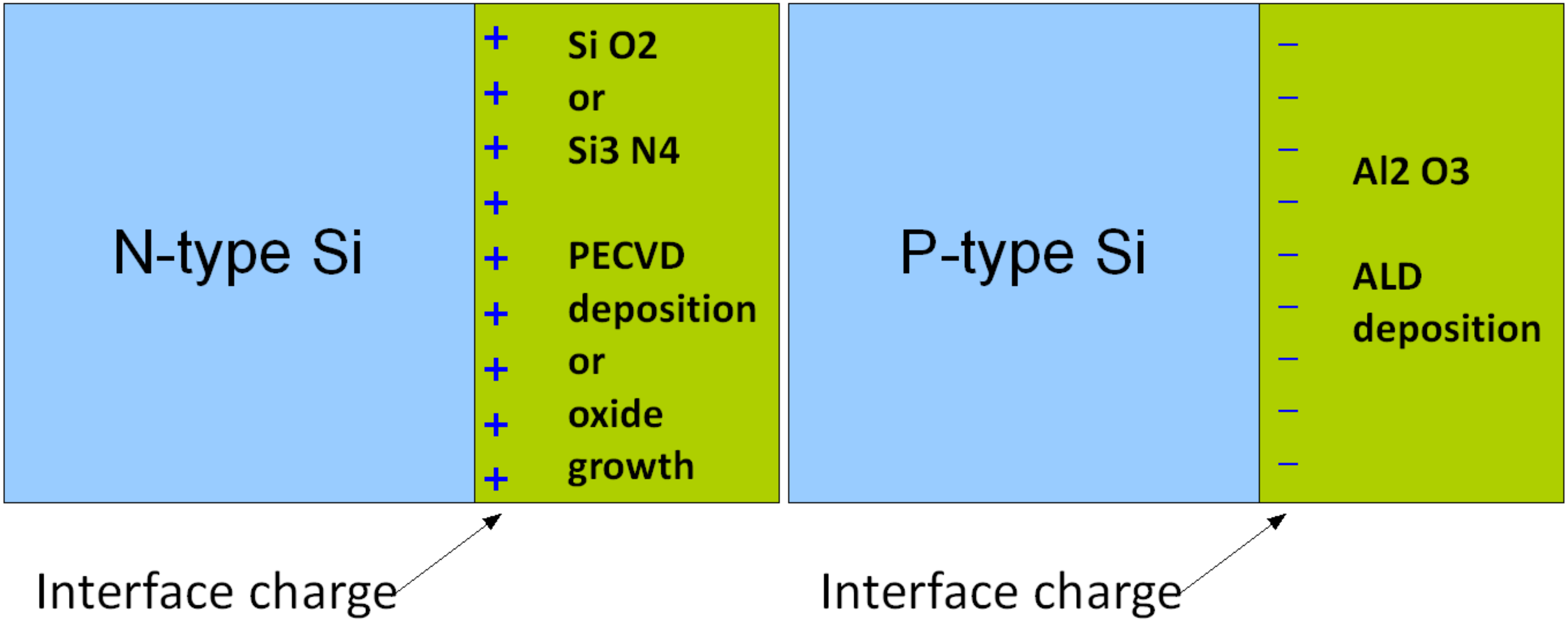
(better tiling of sensors)

This is especially important for pixels and large-area systems

Our Approach:

- **treat finished devices on the single die level**
- **treat p- and n-type devices**
- **minimize leakage current**
- **achieve uniform bias dependence of charge collection**

Passivation Options



N-type Si

Si O2
or
Si3 N4

PECVD
deposition
or
oxide
growth

P-type Si

Al2 O3

ALD
deposition

Interface charge

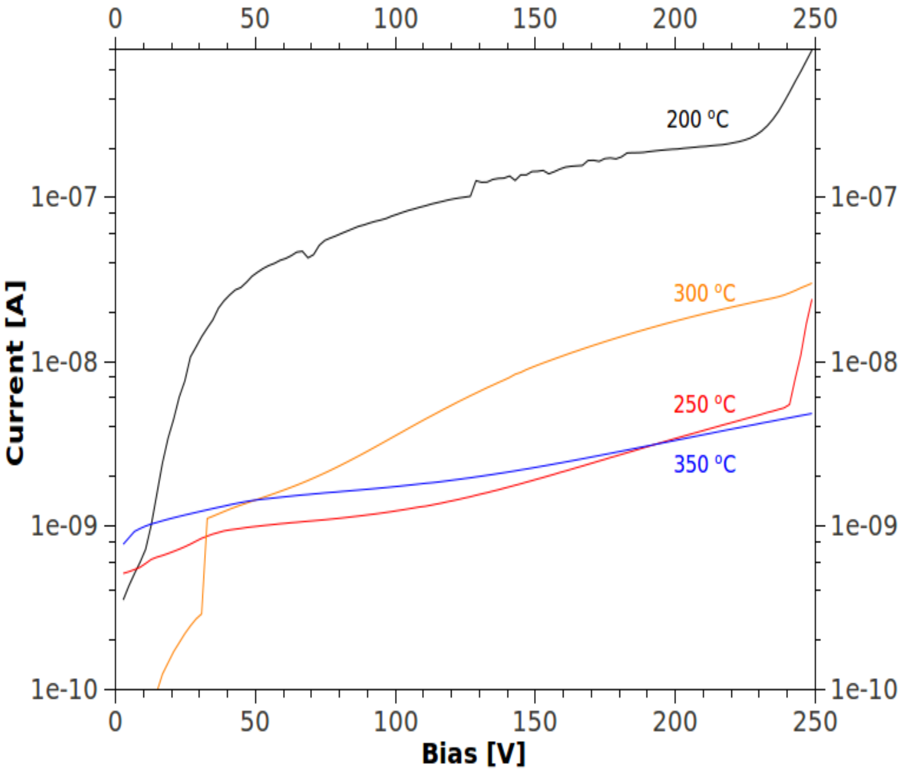
Interface charge

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.**

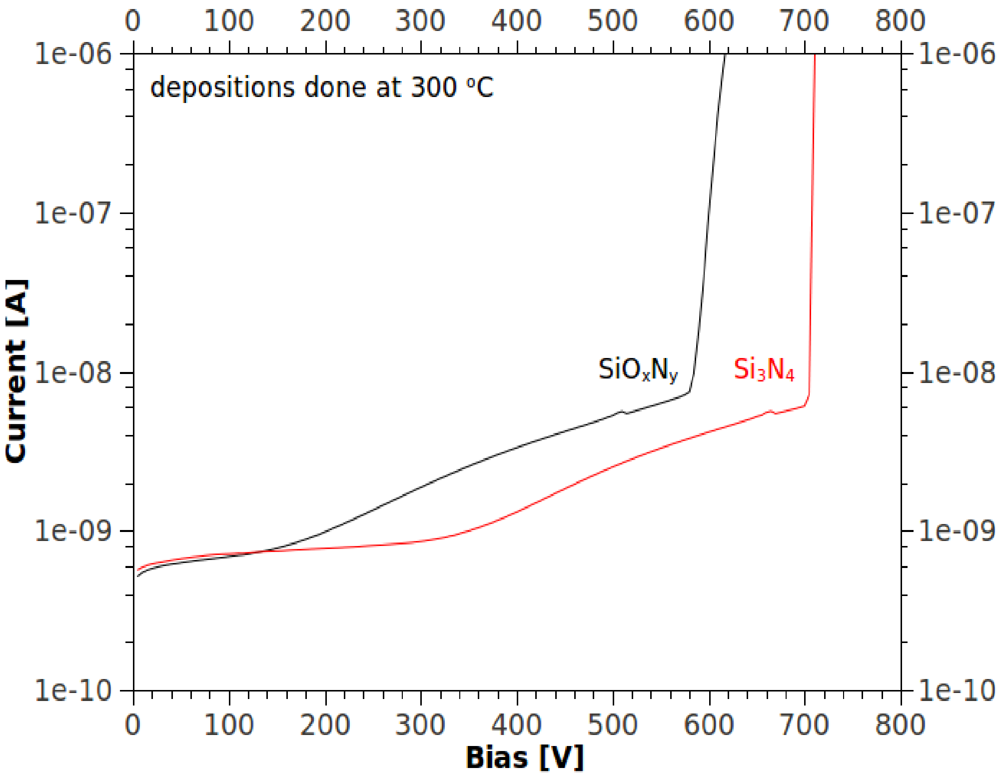
Progress with Passivation (N-type Diodes)

Si Oxide PECVD



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

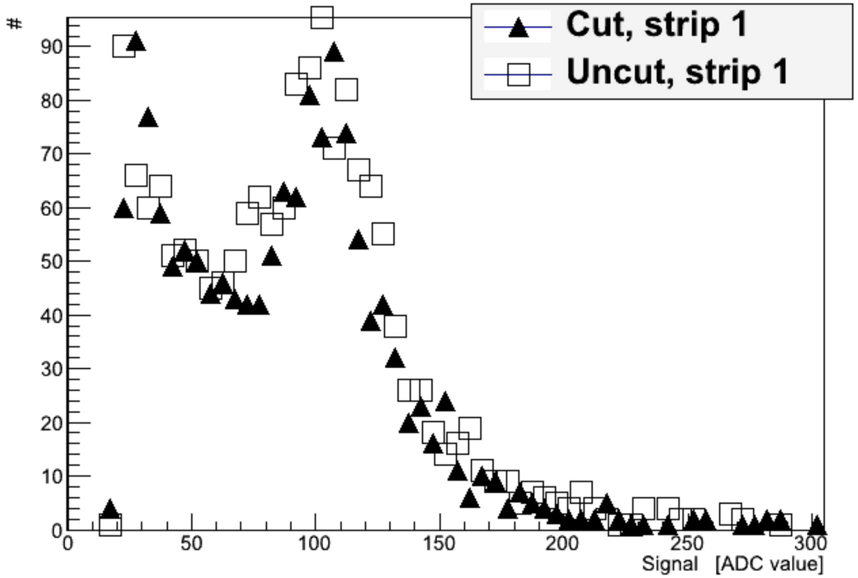
Si Nitride PECVD



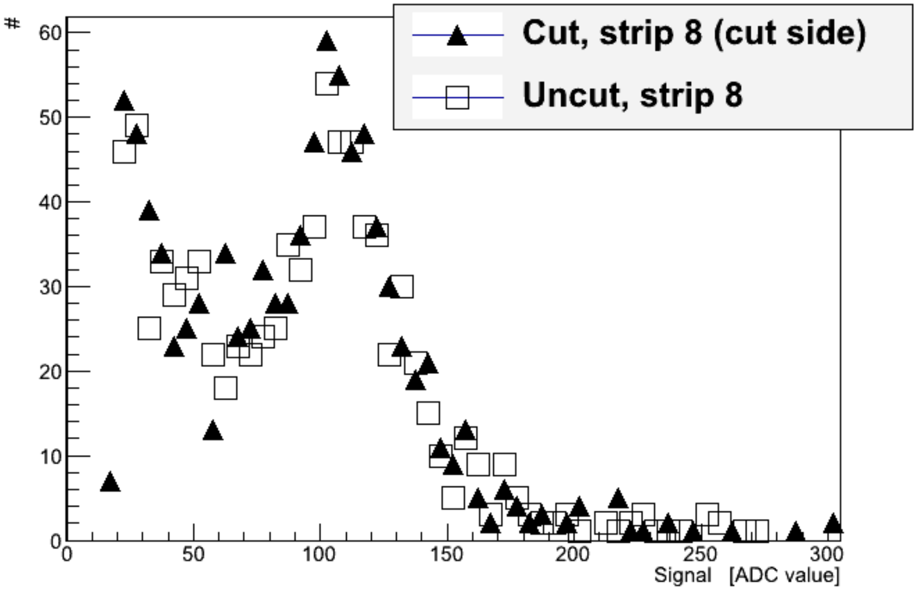
Much improved leakage current and breakdown voltage with Si Nitride.

Charge Collection with AliBaVa

AliBaVa allows pulse height readout => More direct view of the signal.
Data taken and analyzed by R. Mori of Florence.



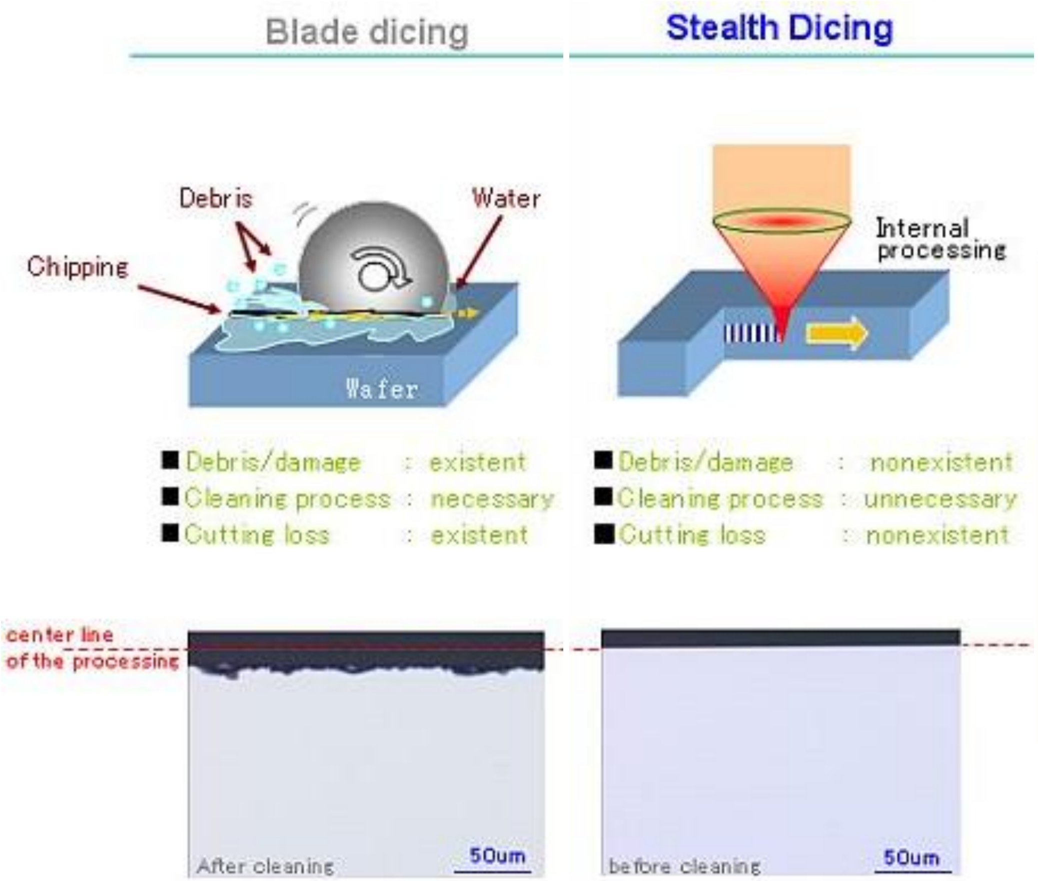
Edge strips at the normal (wide) edge



Edge strips at the slim (cut) edge

- **A comparison of the data from two n-type Fermi detectors from HPK, one after slim edge processing, another without. The cut is 100 um from the GR.**
- **The pulse height for the “outer” strip (closest to the edge) might be less by about 4%. The low-side tail is due to absence of neighbor for clustering.**

Industrial Applications of Laser-Scribing & Cleaving

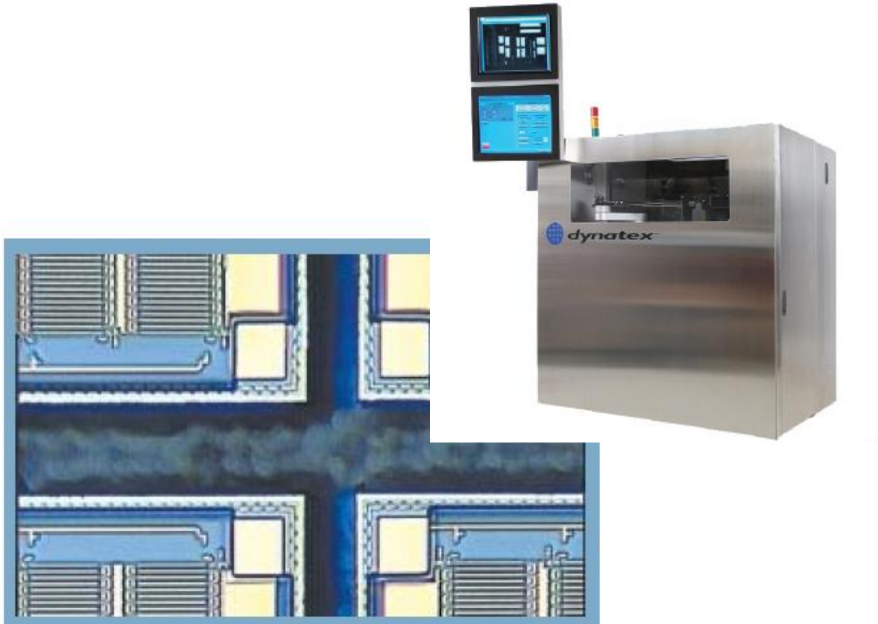


Blade dicing:
- Debris/damage : existent
- Cleaning process : necessary
- Cutting loss : existent

Stealth Dicing:
- Debris/damage : nonexistent
- Cleaning process : unnecessary
- Cutting loss : nonexistent

HAMAMATSU

Dynatex International DTX-200-AB
AUTOMATED BREAKER PRODUCTION SYSTEM

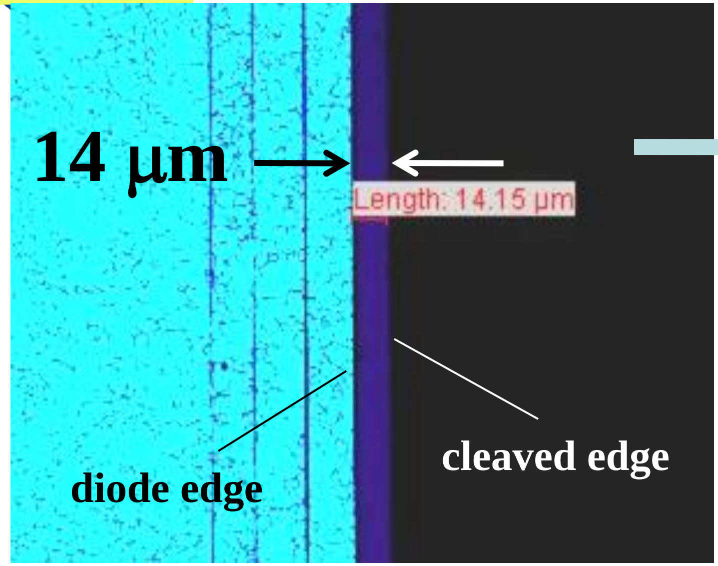


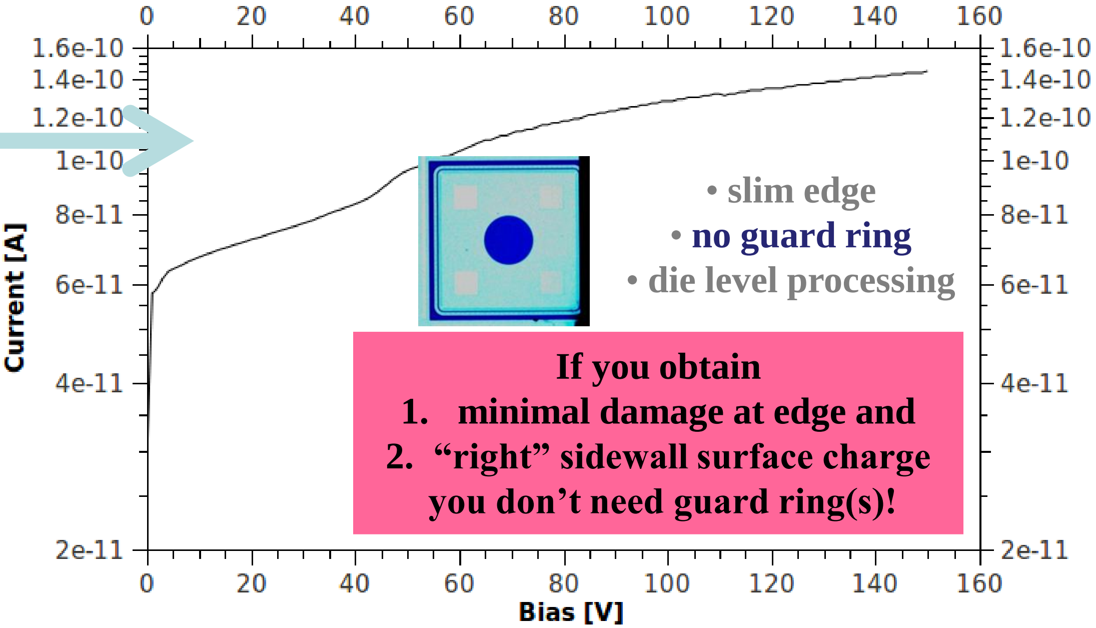
GaAs wafer, diced and expanded. Wafer dicing is well-suited for UV DPSS lasers with their highly focusable, pinpoint-bright beams

- laser-scribing and cleaving common in LED industry
- automated tools for scribing and breaking of devices on wafer-scale

Examples of Processed Devices

Device A



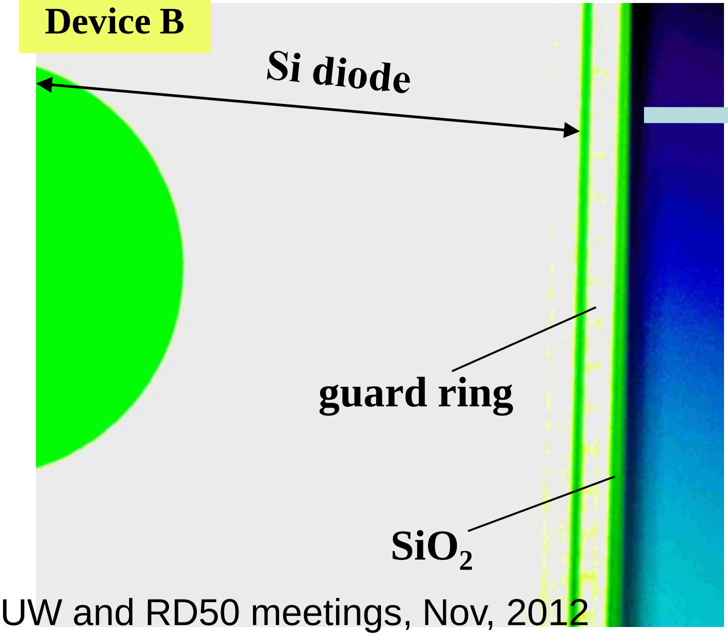


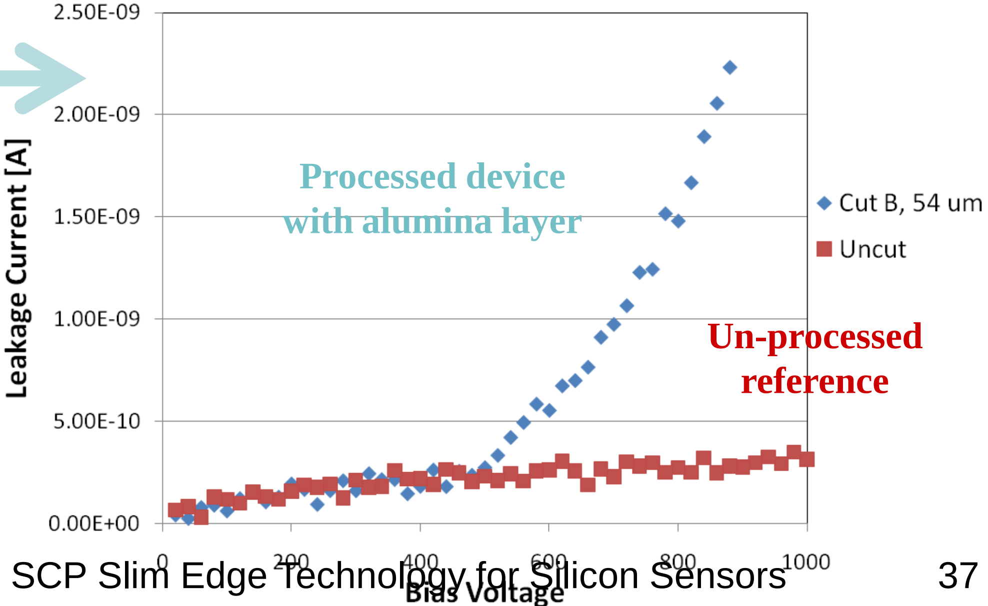
- slim edge
- no guard ring
- die level processing

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

you don't need guard ring(s)!

Device B



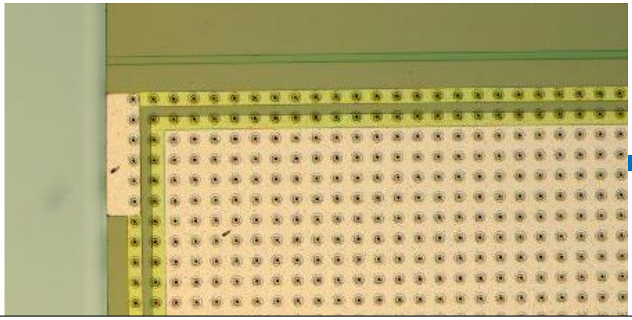


Processed device with alumina layer

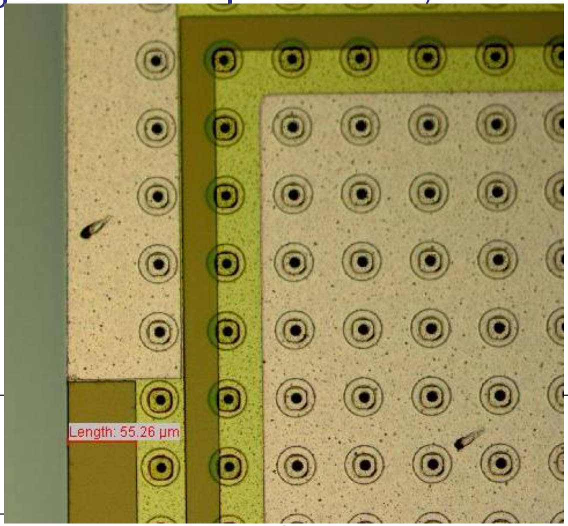
Un-processed reference

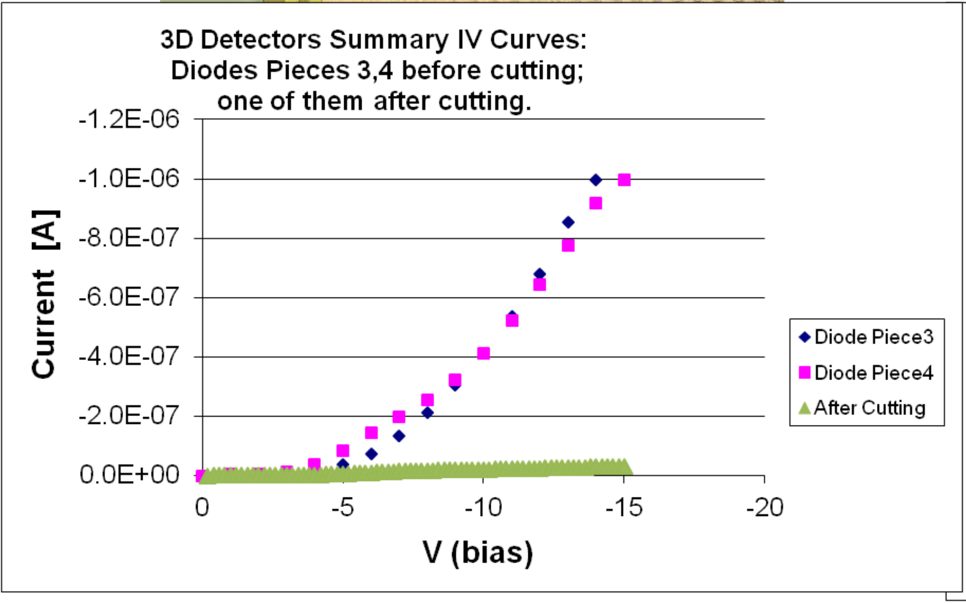
CNM 3D Sensors: p-type (Alumina Passivation)

- This is 3D diode fabricated by CNM. It was cleaved at 55 um away from GR.
- As a result of the scribing, cleaving, and ALD deposition of alumina, the current seems to *improve* a lot. The exact cause is unknown. It might be a temperature cycle post-ALD.

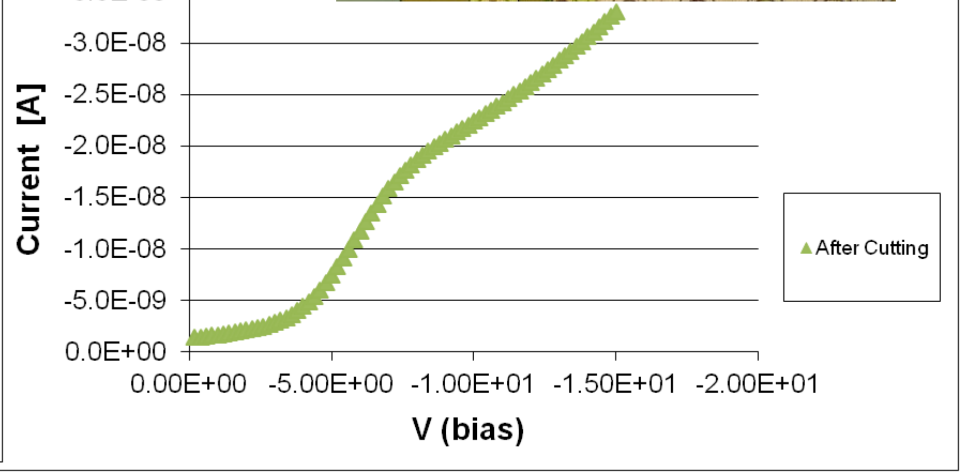


Zoom in





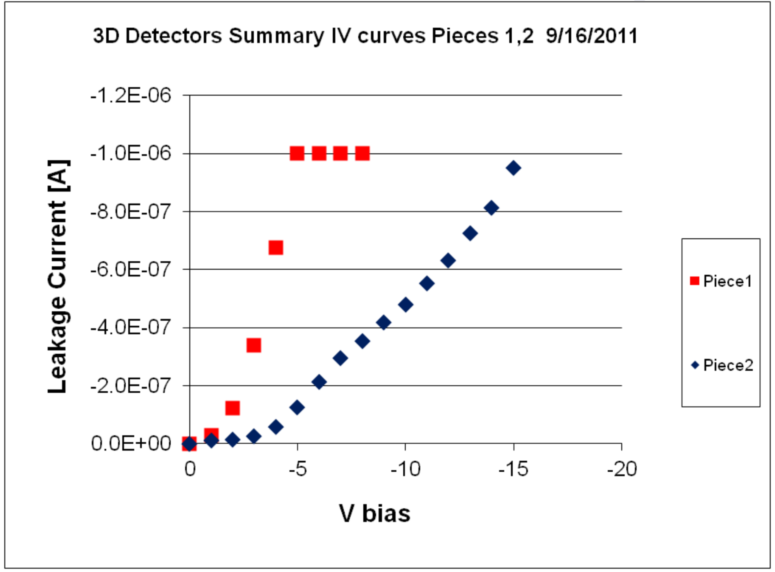
Comparison of before and after cutting

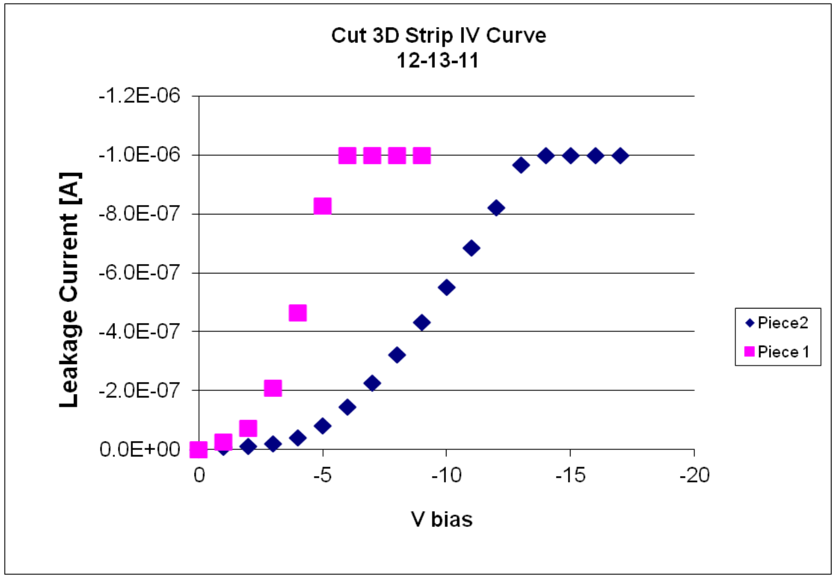


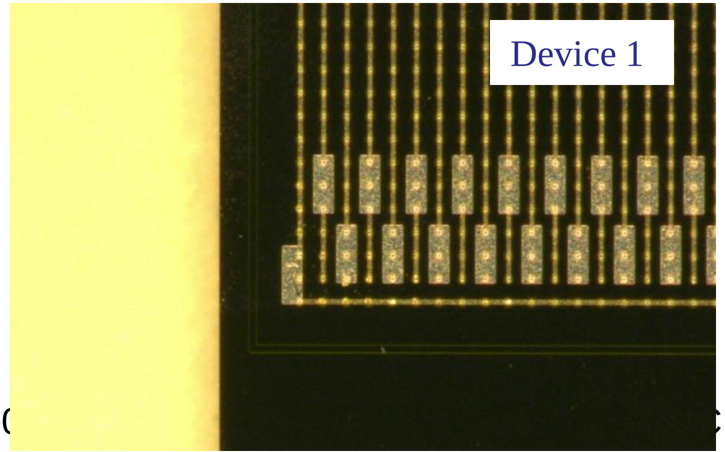
After cutting alone (note different scale).

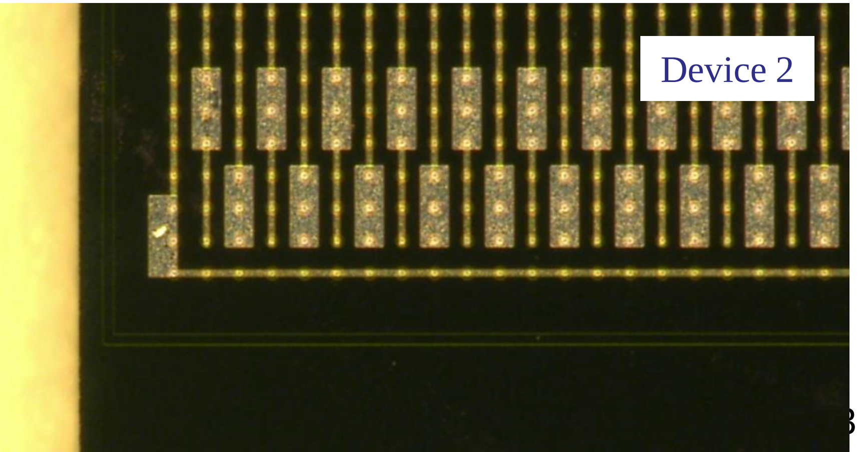
CNM 3D Sensors: p-type (Alumina Passivation), Cont.

- A more typical scenario is no change after slim edge processing, as shown here for two strip sensors.
- There is a next round of processing in progress, with different devices: FE-I3, FE-I4 for AFP detector, also Medipix devices.



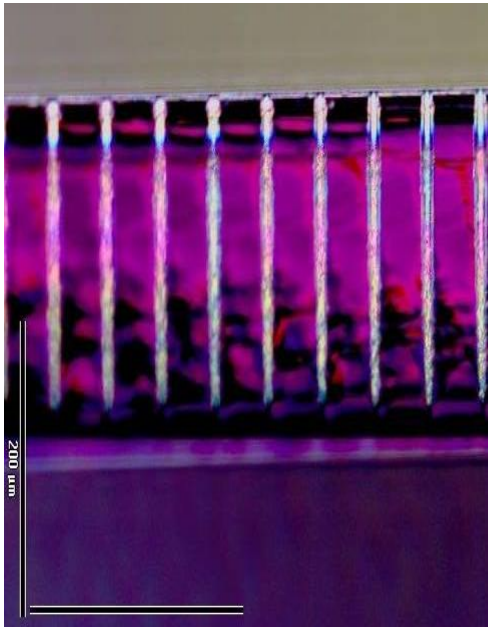






FBK 3D Strip: p-type (Alumina Passivation)

Cleavage plane “follows” row of “guard fence” holes.



No change in leakage current due to SCP slim edge (50 µm distance from cut to guard)

Cleavage plane remains parallel to strip (length of device).