Progress on Slim Edges
- Cleaving and Sidewall Passivation -

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Outline

- Slim Edges – Motivation
- Technology of cleaving and edge passivation
- First Results
- Current Efforts within RD50 Framework:
    - Irradiation Studies
    - Charge collection at the edge
    - Projects with the community
    - Work on industrialization of the process
    - Recent method advances
- Conclusions and Outlook

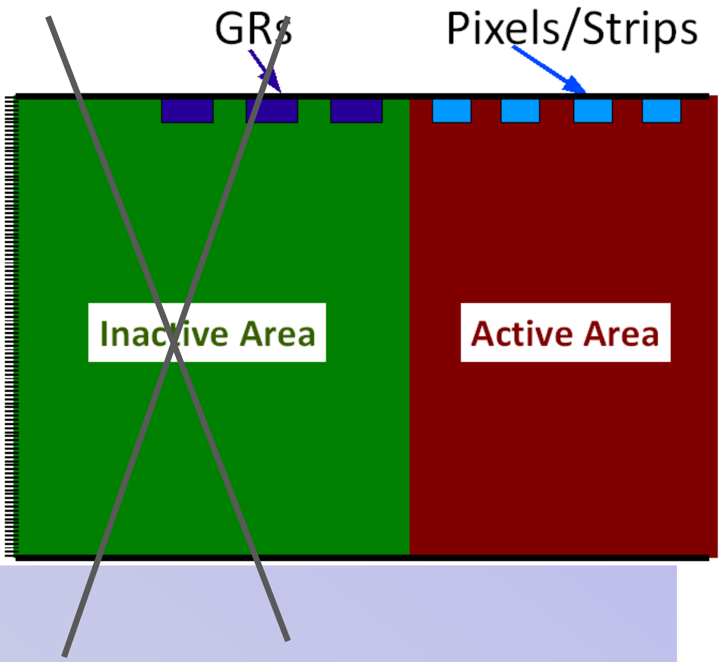
Active edge technology at 2011 IEEE in Valencia: in Session N25 by G.-F. Dalla Betta, M. Bosma, D. T.-E. Hansen

The device processing is done by Marc Christophersen and Bernard F. Phlips at NRL, who are part of the RD50 Project

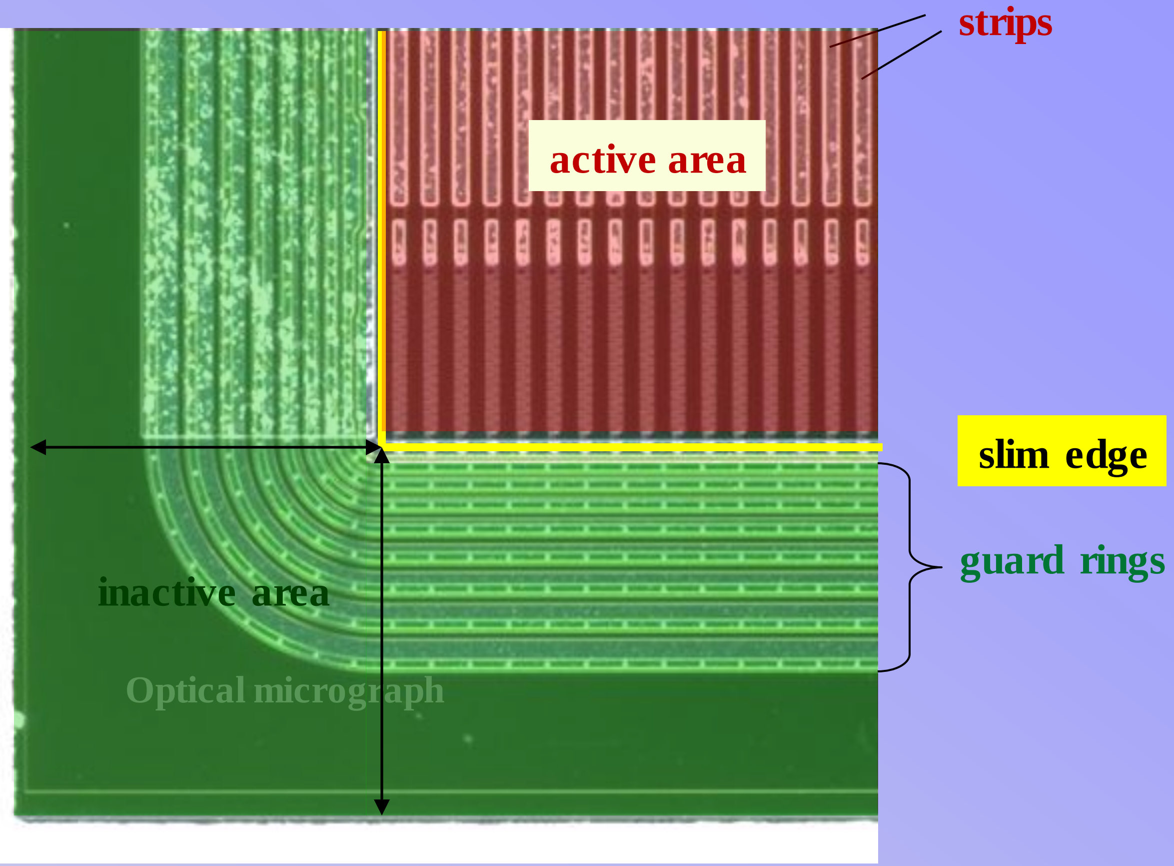
References:
Marc Christophersen at 6th Trento Workshop on Advanced Silicon Radiation Detectors, March 2011.
Vitaliy Fadeyev, Talk N7-1 IEEE 2011 in Valencia, October 2011

Motivation – Slim Edges

Side View



Top View

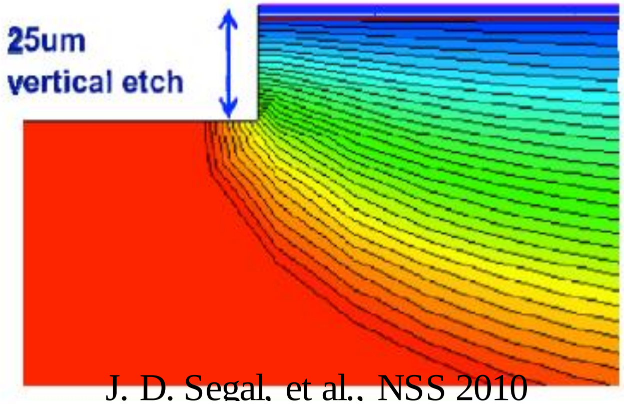


Slim edges offer:

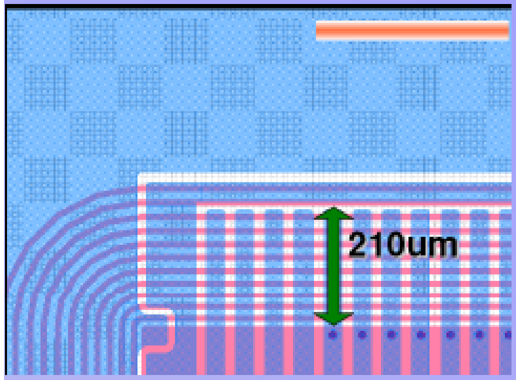
- better tiling of sensors
- reduced inactive area

This is especially important for pixels and large-area imagers

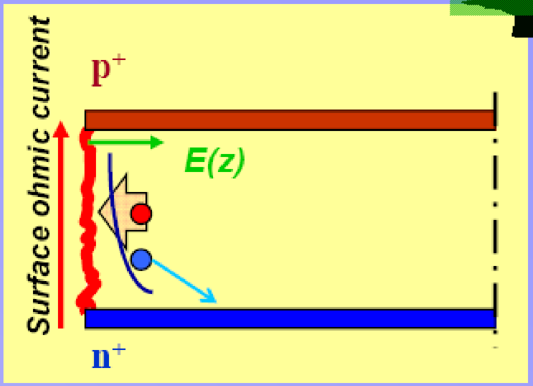
Slim Edges - Approaches



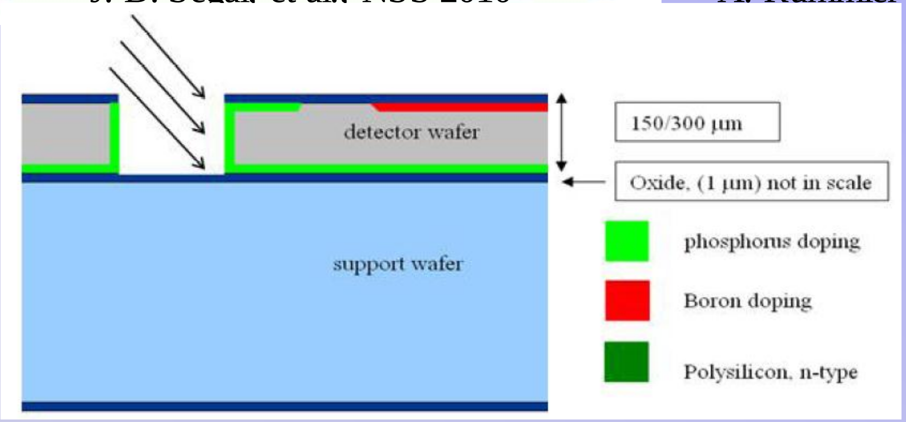
J. D. Segal, et al., NSS 2010



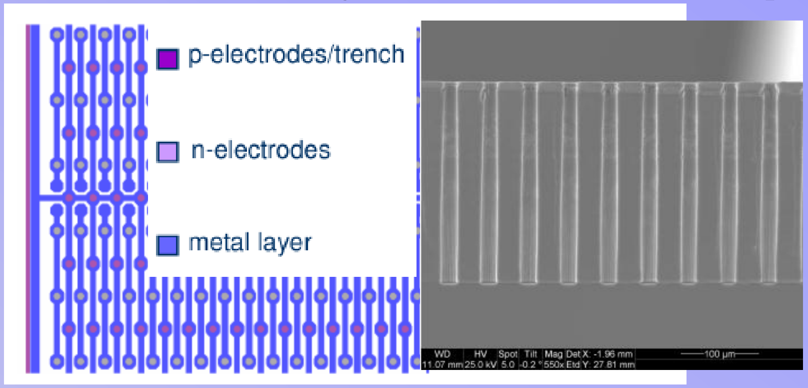
A. Rummler et al., 2010



E. Verbitskaya et al., 13 RD 50 workshop, 2008



J. Kalliopuska, NSS 2010



T.-E. Hansen et al., 2009

Our Approach:

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

Treatment Sequence

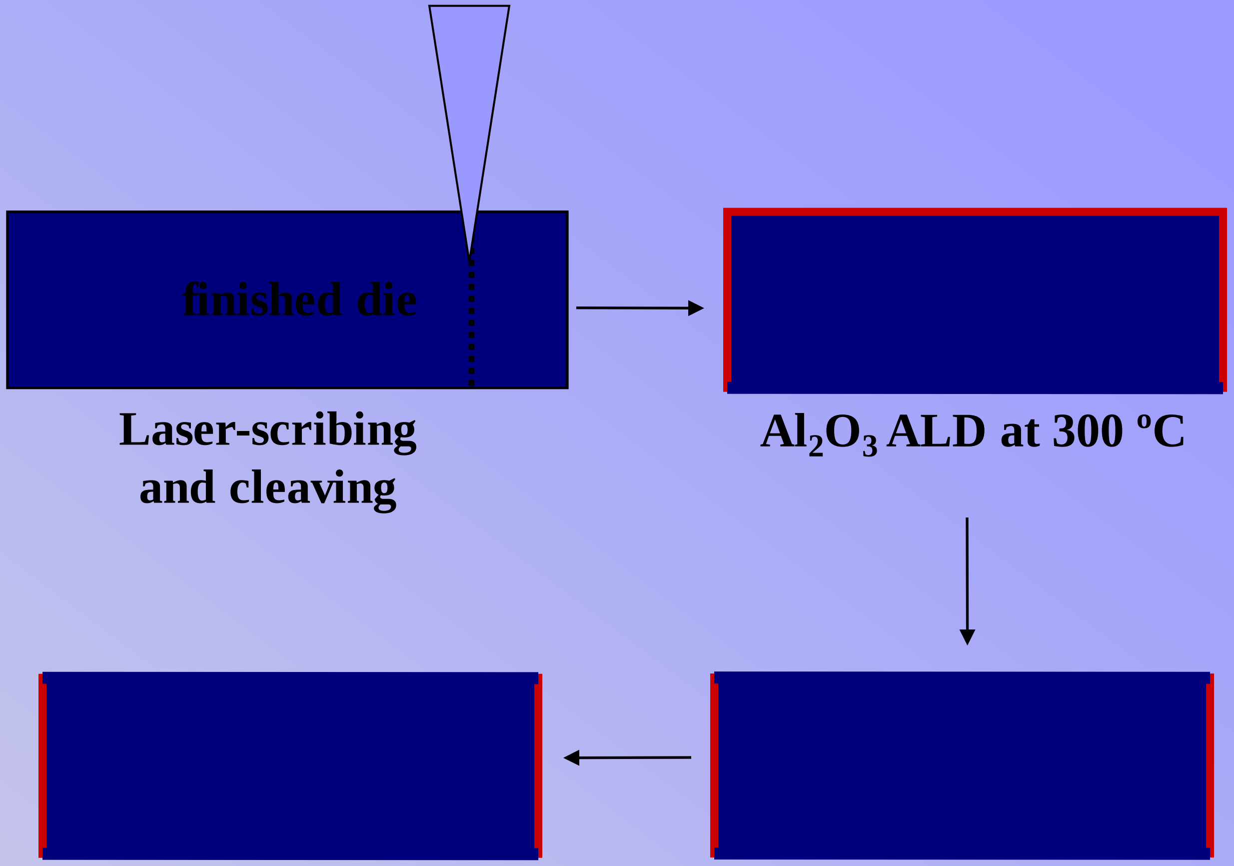
There are three key steps of the process:

1) Scibing on front-side

2) Cleaving, which leaves the surface with low defect density

3) Surface passivation to make the sidewall resistive. N- and p-type devices require different passivation technologies.

- For n-type devices one needs a passivation with positive interface charge. SiO2 layer works well.
- For p-type material a passivation with negative interface charge is necessary. We found that Al_2O_3 works in this case.



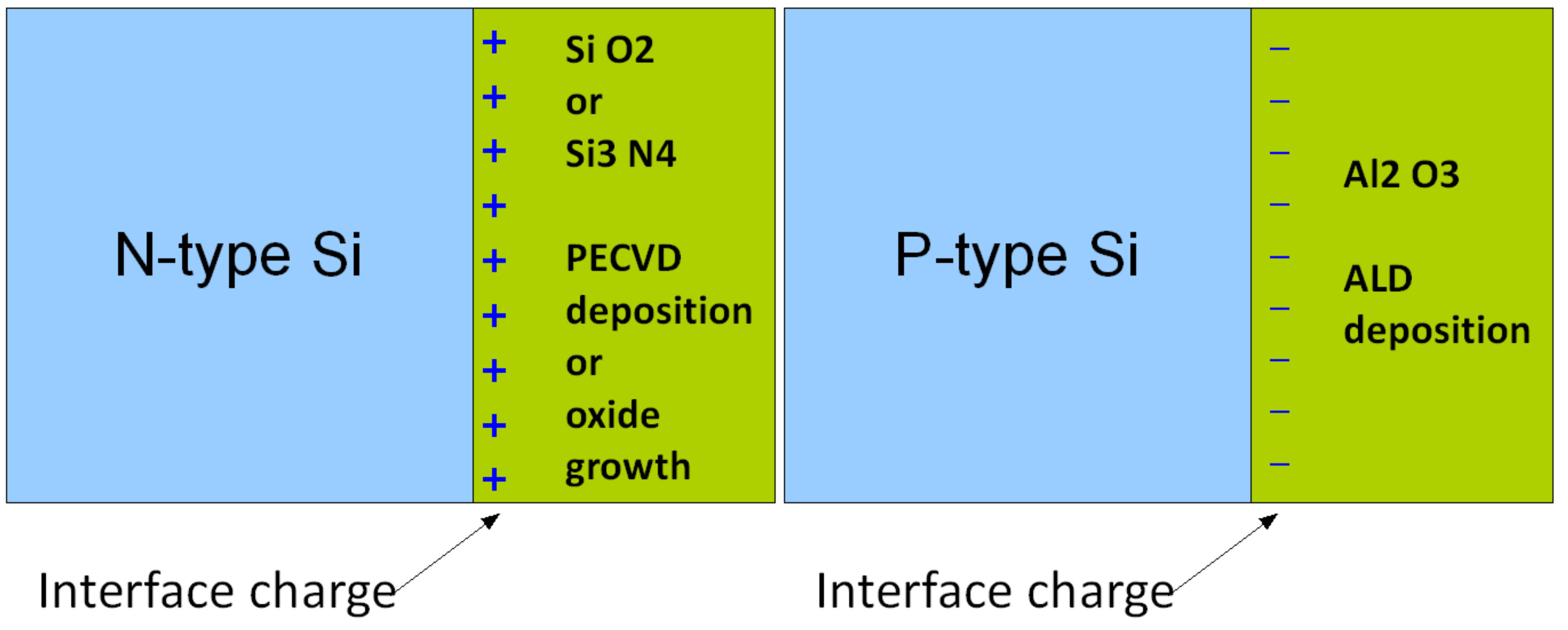
Laser-scribing and cleaving

Al_2O_3 ALD at 300 °C

RIE with hard mask

annealing at 400 °C

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.

Scribing and Cleaving

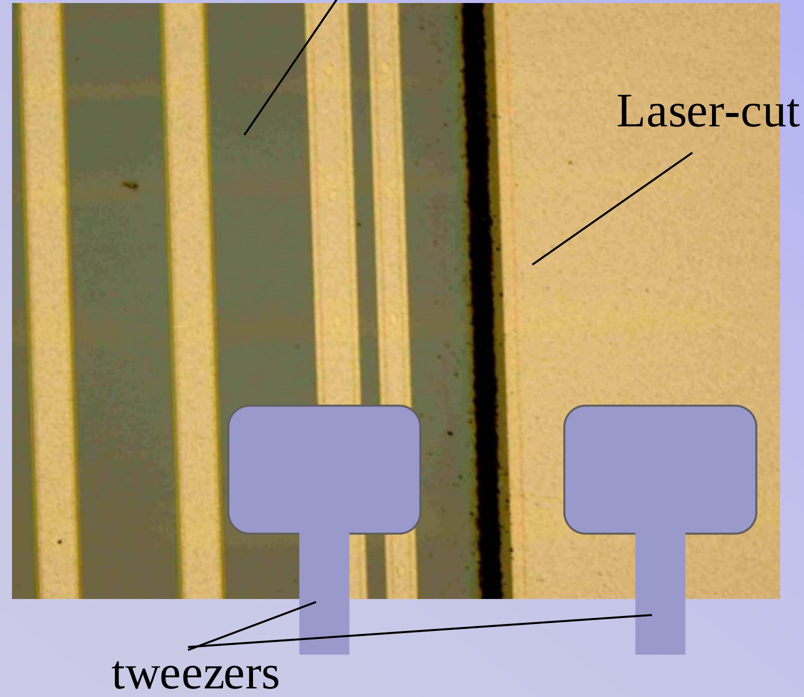
Key components:

=> Scribing the surface seeds the location of the break under stress.

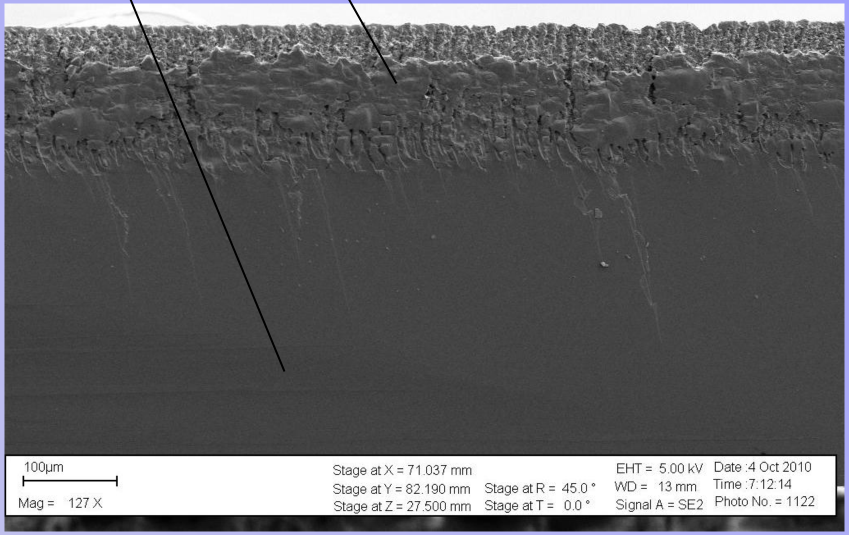
=> Cleaved surface has low defect density (except for scribe region).

- used finished dies (post-processing)
- laser scribing → laser-damage
- cleaving → no damage

Optical micrograph, top-view



SEM micrograph, cross-section

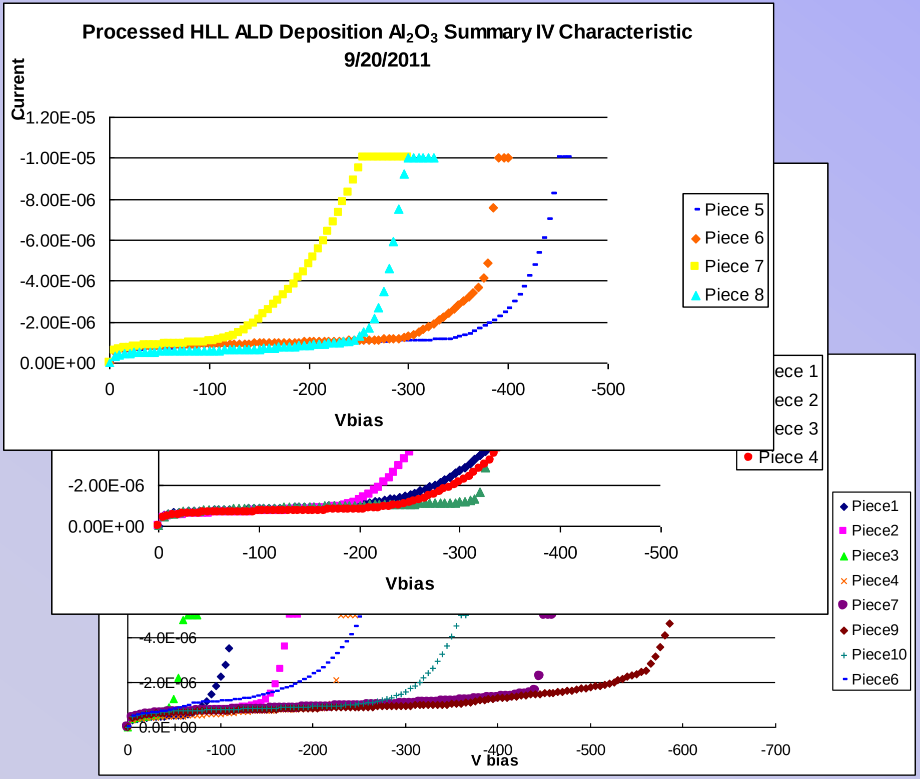


Lattice orientation crucial

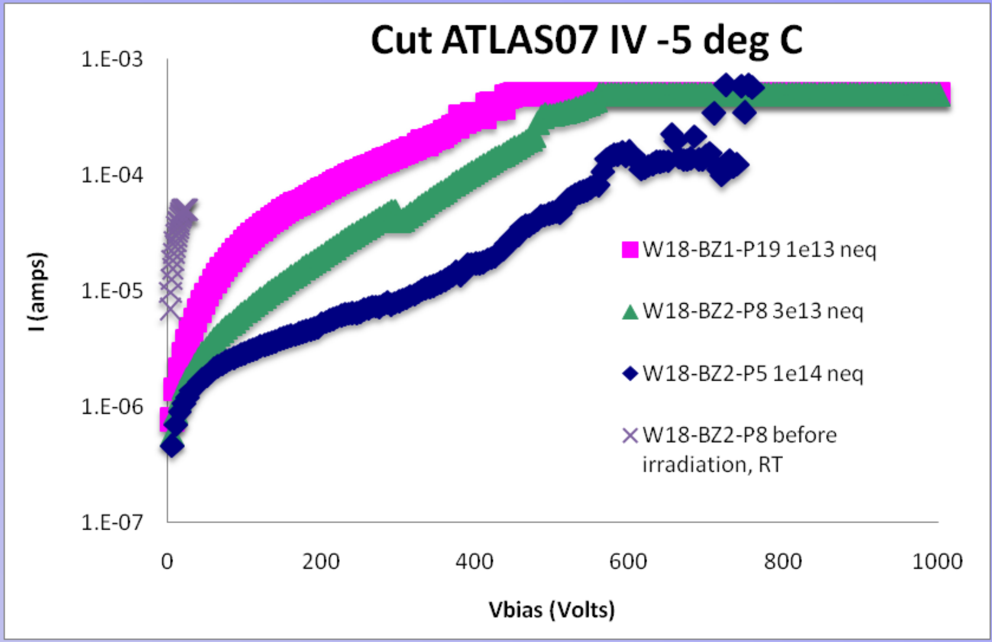
Only limited Irradiation Studies: need more!

One of the key questions is a performance of the new sidewall technology under irradiation. Work is on-going:

- We have prepared a set of processed strip devices (CIS from MPI curtesy A. Macchiolo) for a irradiation test.
- We took available cleaved HPK devices (ATLAS07) from prior trials and irradiated them in LANL proton beam. They do not have Al_2O_3 deposition => did NOT work before the irradiation. They are starting to work after 10^{13}-10^{14} neq/cm^2. This observation lends hope that the irradiated devices with alumina will work as well.



Characterization of CIS sensors before irradiation
(total of 21 sensors processsed)

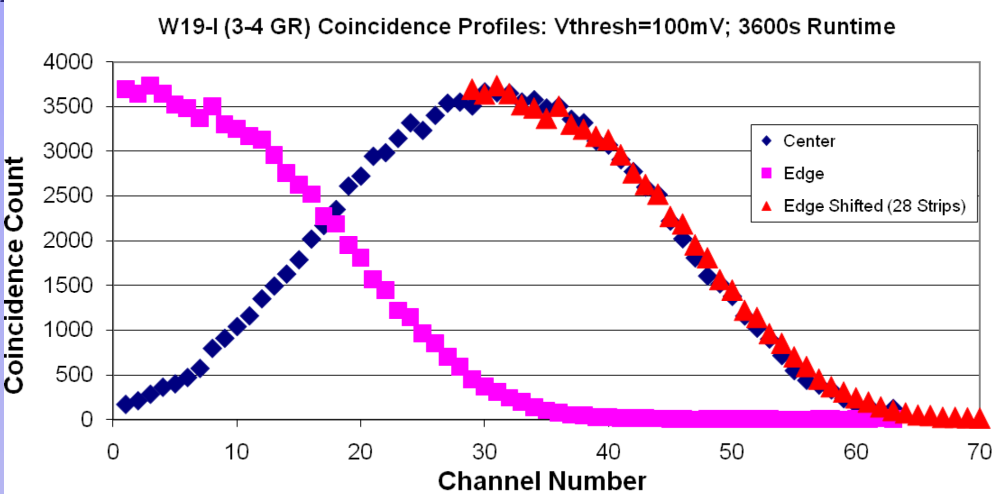


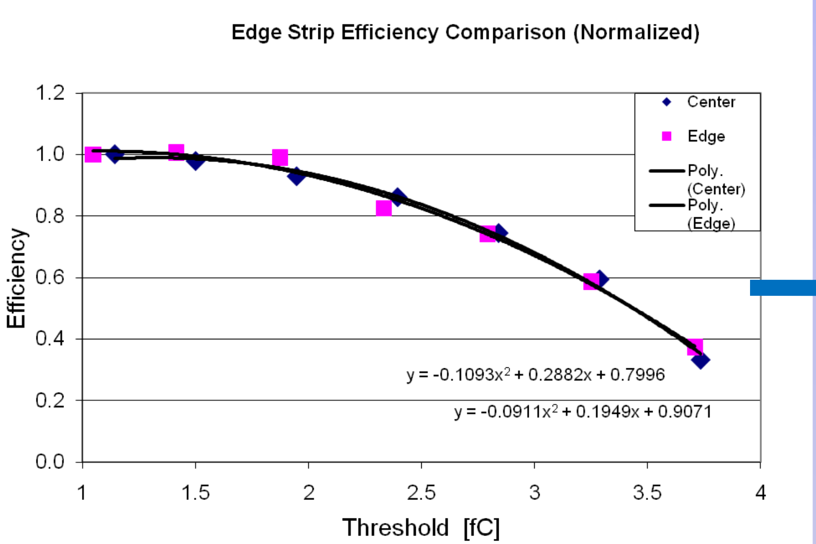
Irradiation	1.00E+13	3.00E+13	1.00E+14
I_expect (200V)	7.50E-07	2.25E-06	7.50E-06
I_observe(200V)	7.39E-05	2.02E-05	5.16E-06
Observe / expect (for bulk current)	98.57	8.99	0.69

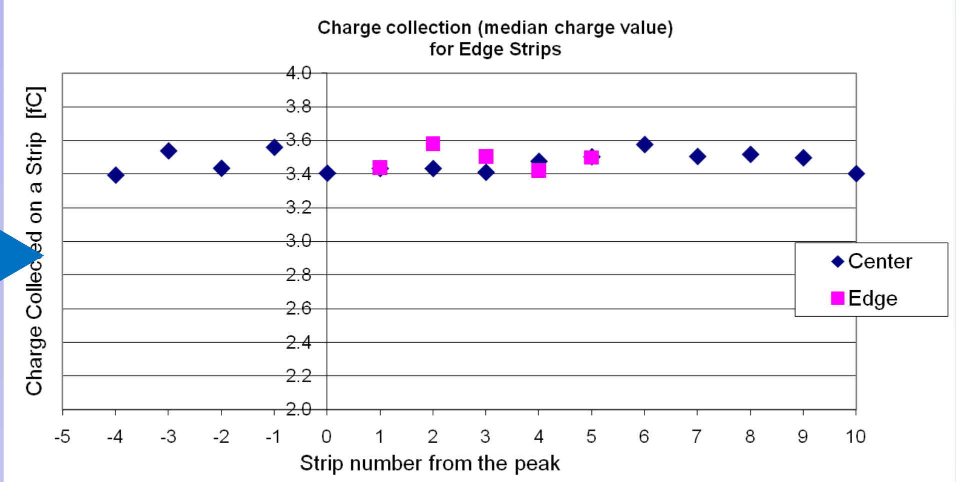
Charge Collection With Binary Readout System

Even though the i-V might be ok, we want to make sure that the charge collection near the edge does not suffer because of the slimming.

- **Consistent beam profiles taken at different positions is an indication of high efficiency at the edge.**
- **By scanning the thresholds we can derive the collected charge on each strip.**
- **We observe the same collected charge at all locations to a few percent on a p-type sensor.**

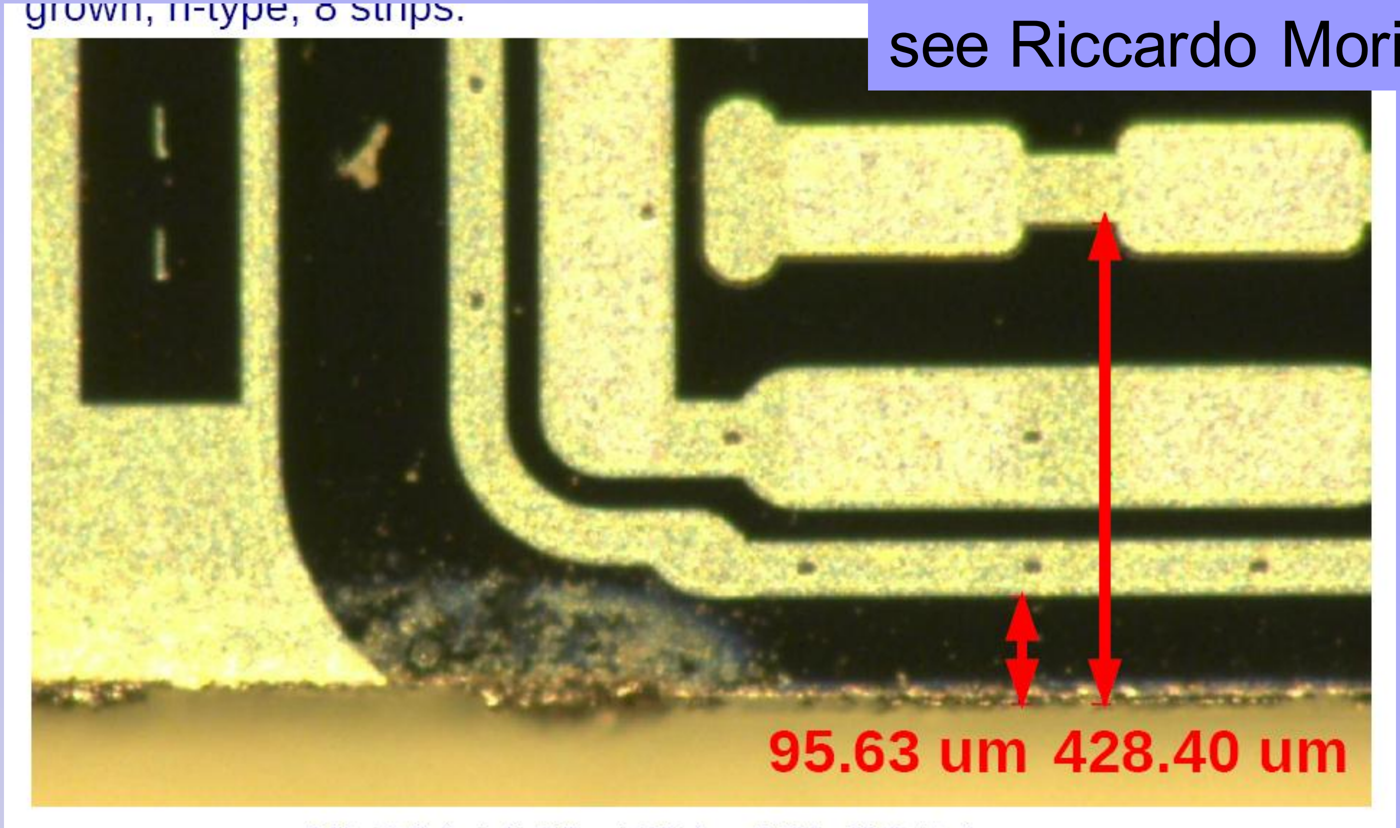






Charge Collection with AliBaVa

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



grown, n-type, 8 strips.

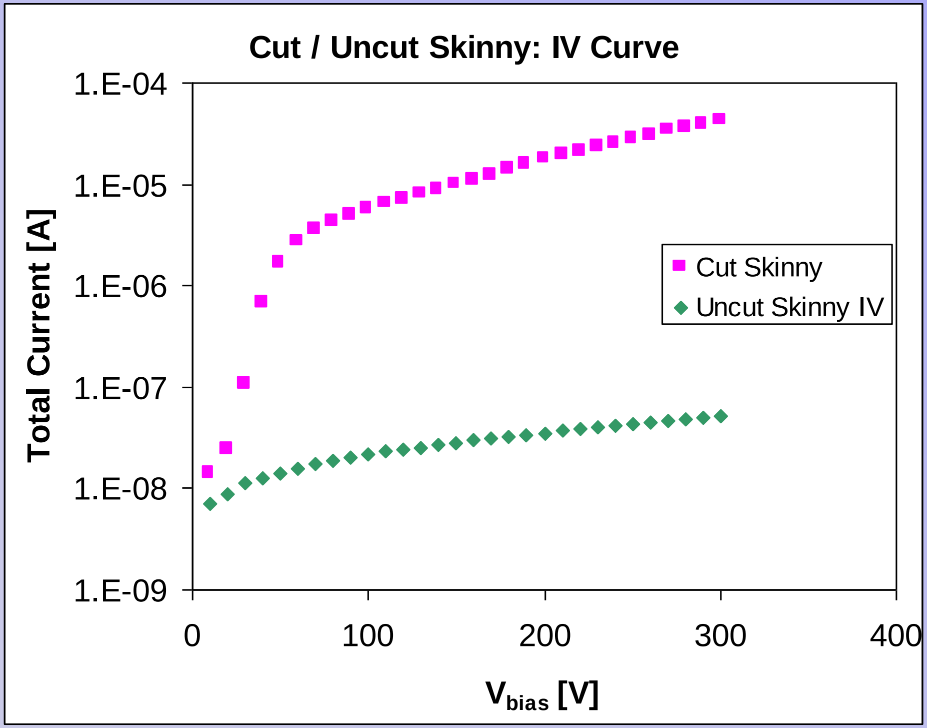
R. Mori,H. Sadrozinski, M. Bruzzi, V. Fadeyev, P. Phlips, M. Christophersen

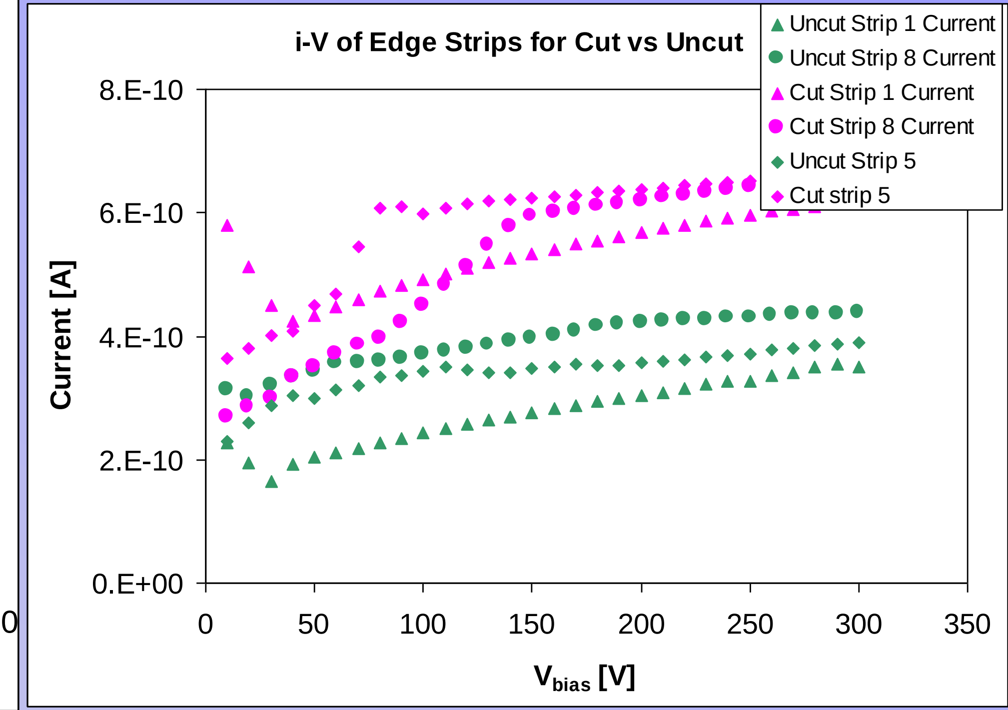
see Riccardo Mori's talk

- **A comparison of the data from two n-type Fermi detectors from HPK, one after slim edge processing, another without. The cut is 90 um from the GR.**
- **The pulse height distribution for "inner" strips show a high degree of similarity in both cases, as expected.**
- **The pulse height for the "outer" strip (closest to the edge) might be less by up to 5%.**

Currents on Individual Strips

We measured the currents on the cut sensor and see an 1000x increase wrt un-cut. We also measured i-V on the strip currents of the same 8-channel devices through the bias resistor voltage measurements. They are generally consistent for both cut and un-cut devices. We do not see an abnormal behavior for the edge strips.





Device i-V uncut-cut

Strip i-V uncut-cut

P-on-n HPK (GLAST), laser scribed, PECVD Oxygen, 96μm from guard

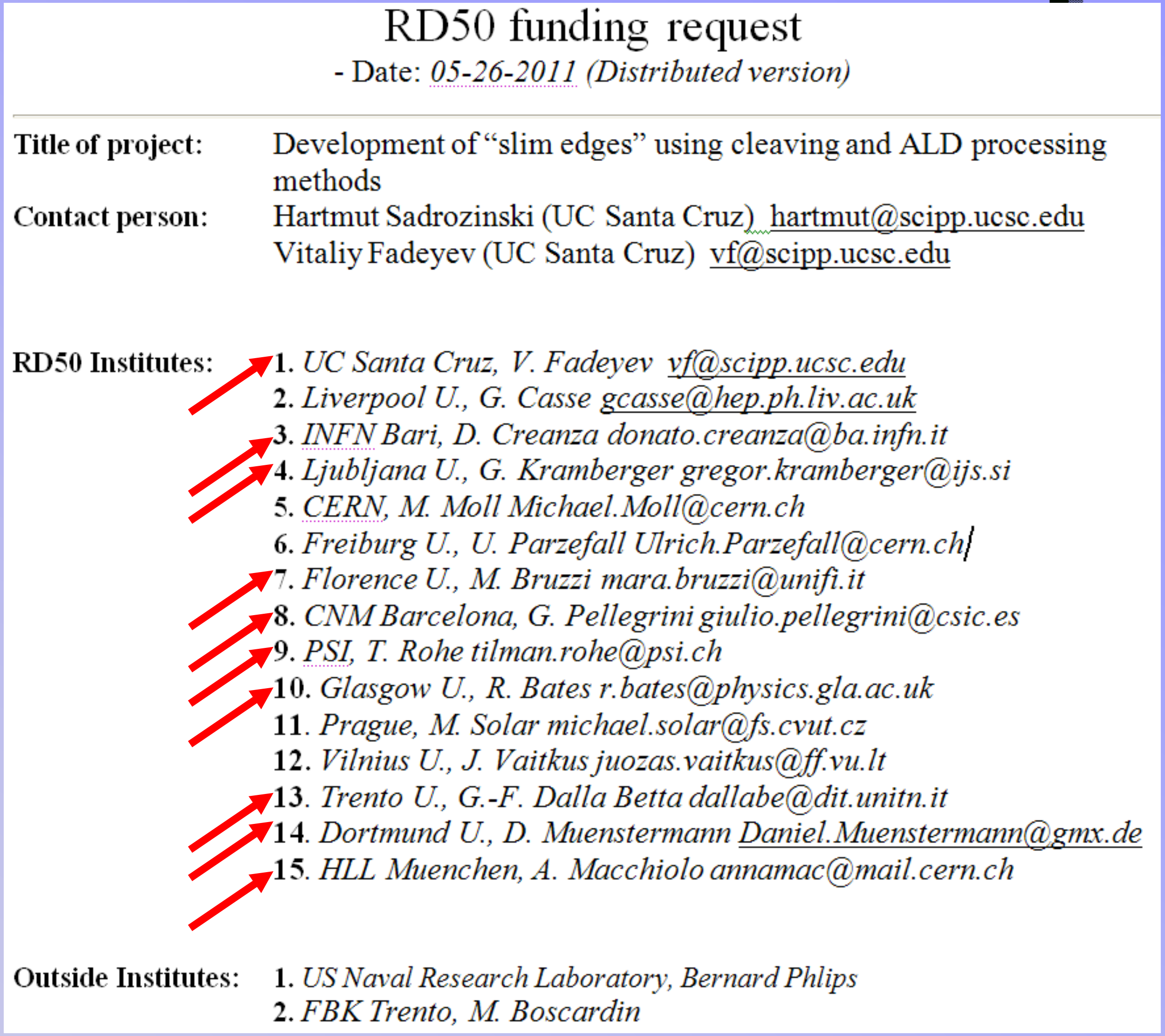
RD 50 Common Project

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

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

Last summer, the scribe-and-cleave technology of fabricating slim edge sensors has also been approved as RD50 project.

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



RD50 funding request

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

Title of project: Development of "slim edges" using cleaving and ALD processing methods

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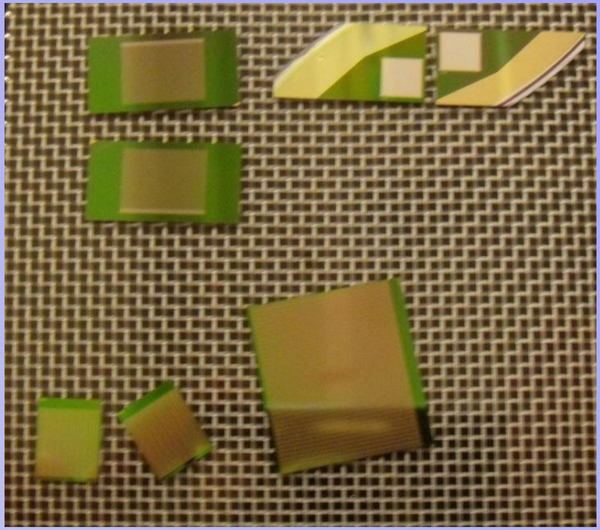
15. *HLL Muenchen, A. Macchiolo annamac@mail.cern.ch*

Outside Institutes:
1. *US Naval Research Laboratory, Bernard Phlips*
2. *FBK Trento, M. Boscardin*

On-going Projects with RD50

- The trials of n-on-p pixel sensors from CIS is in progress.
- Processing 3D devices from CNM is in progress (next slide). This includes pixel, strip, and diode configurations.
- Processing 3D devices from FBK is in the pipeline.
- There are plans for testing the method with n-on-n sensors from IBL <100> wafers in ~January.
- We are anticipating more requests.
- CCE (Glasgow, Firenze) and Edge-TCT (Ljubljana) measurements are underway/planned

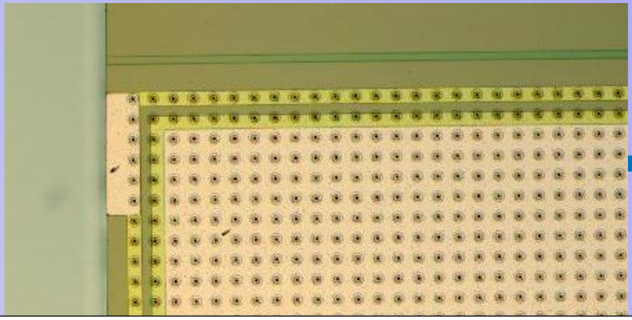
CIS pixel devices from MPI (A.Macchiolo)



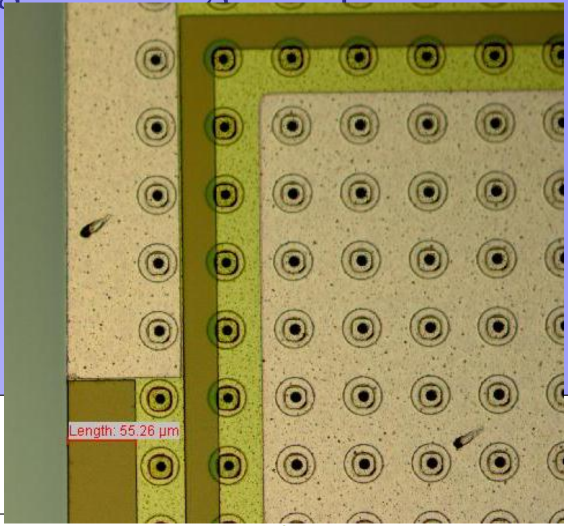
3D devices from CNM (G. Pellegrini)

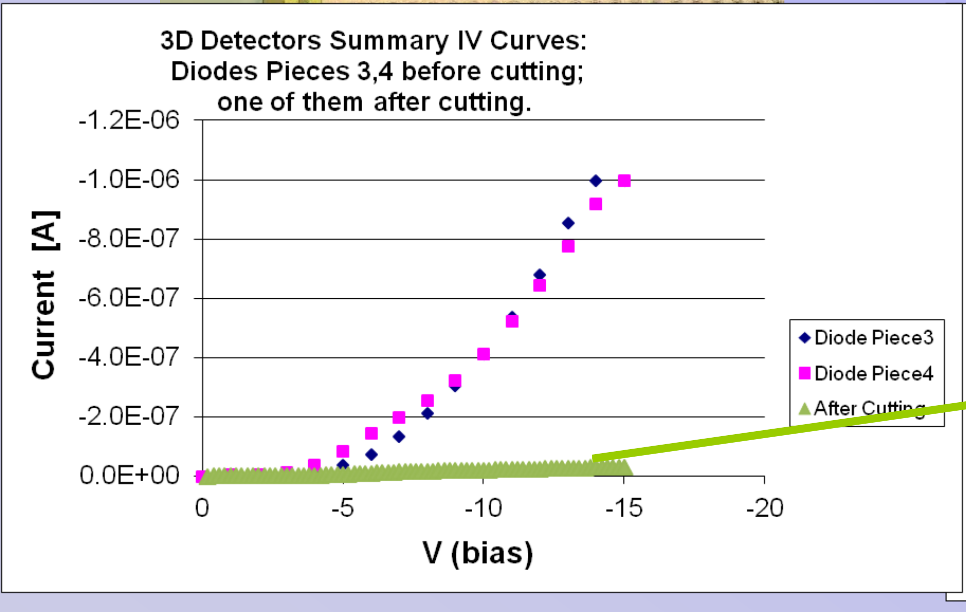
An Example of Processing: CNM 3D Device

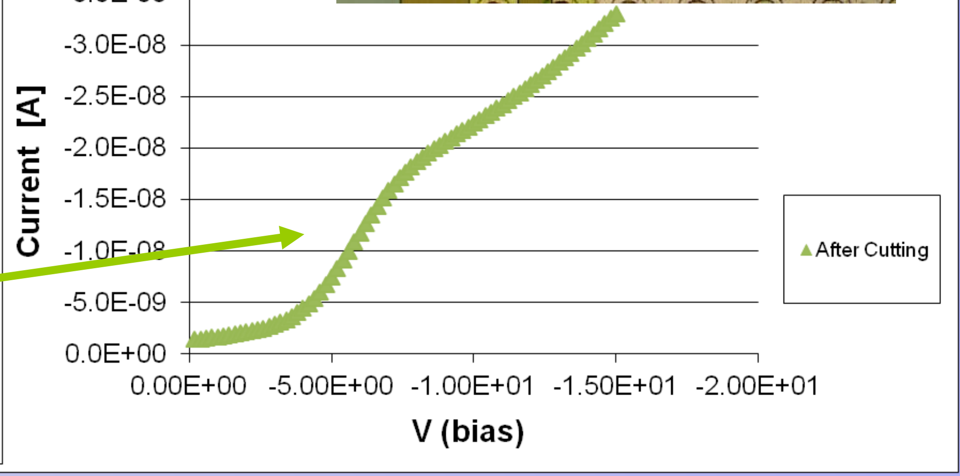
- This is 3D diode fabricated by CNM. It was cleaved at 55 um away from GR.
- As a result of the scribing, cleaving, and ALD deposition of alumina, the current seems to *improve* a lot. The exact cause is unknown. It might be a high-temperature exposure post-ALD.



Zoom in





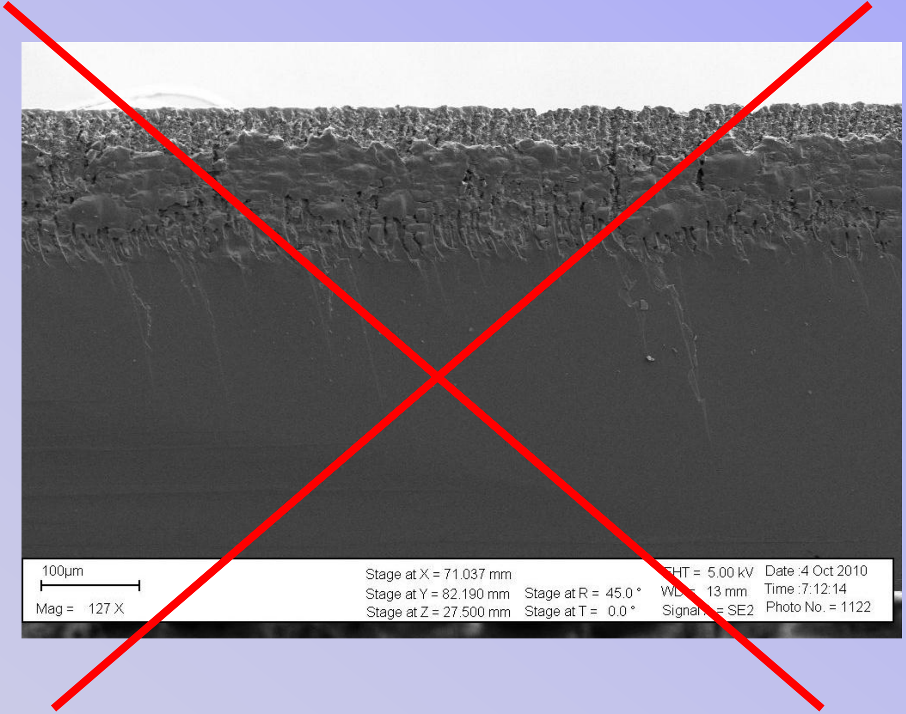


Comparison of before and after cutting

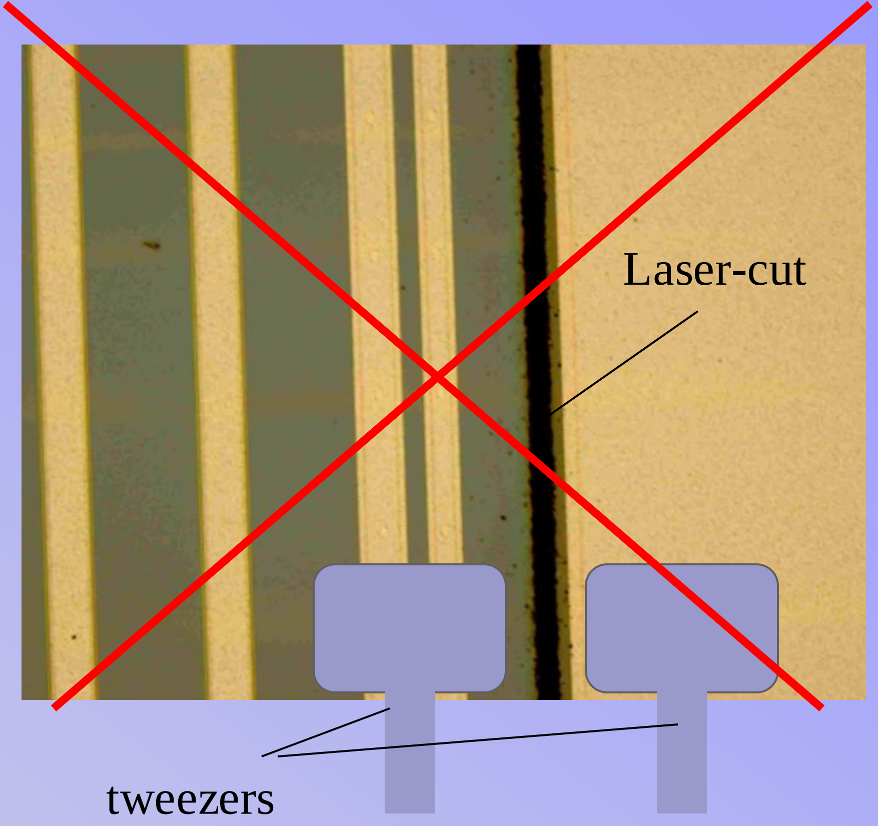
After cutting (30x less!)

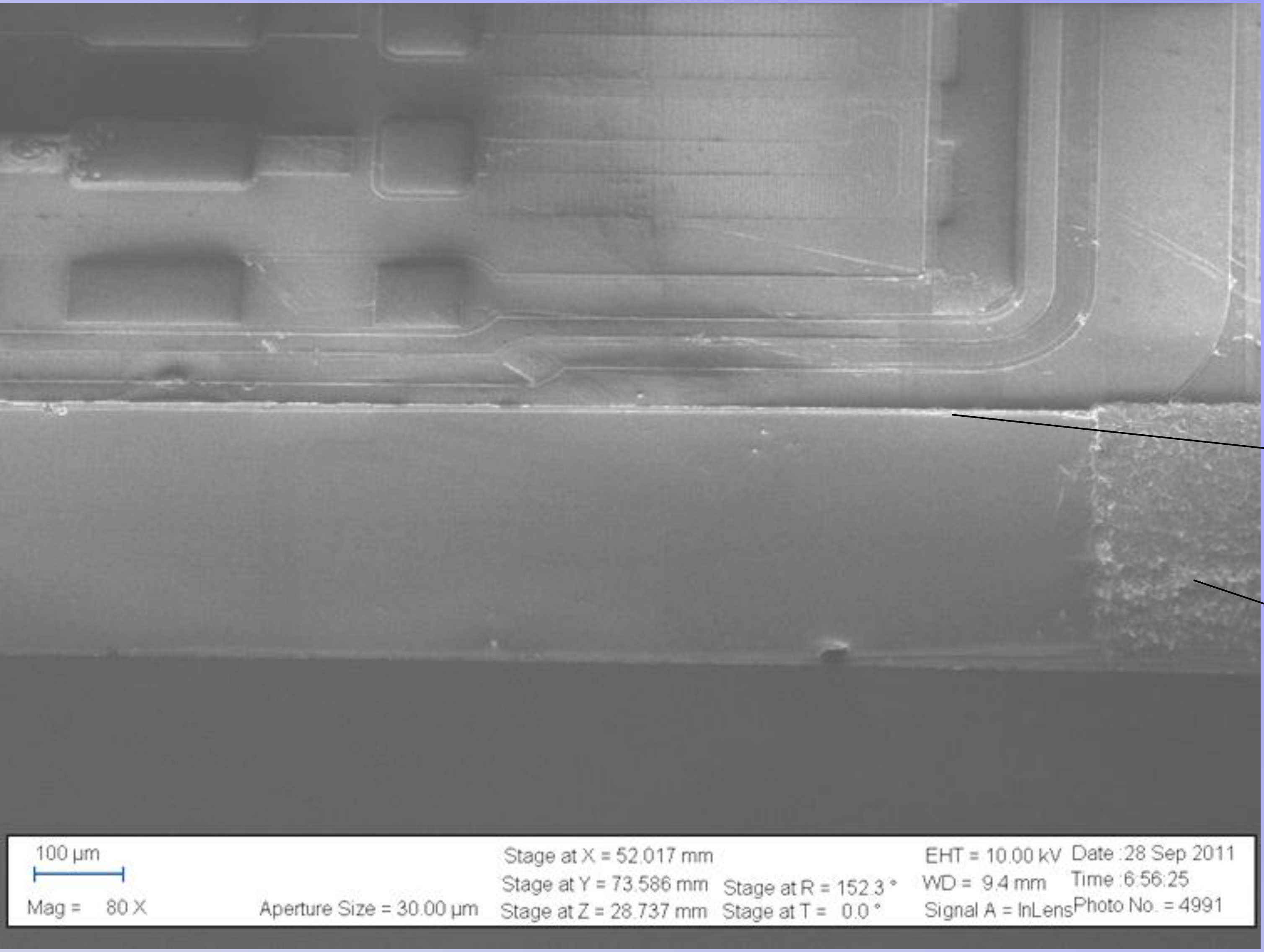
Priority: Replace marginal Technologies

Laser scribing → XeF_2 etch



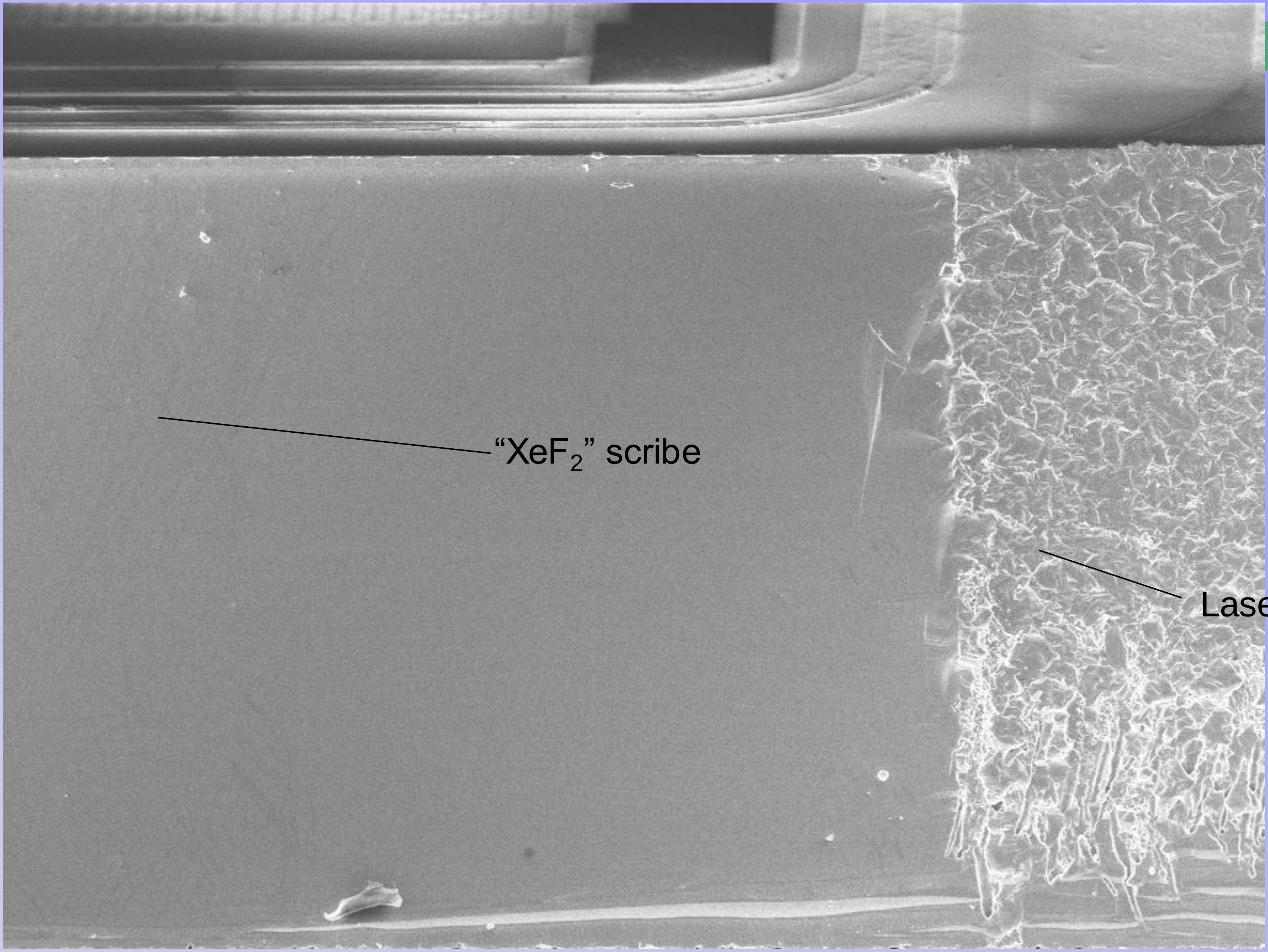
Cleaving: no tweezers!

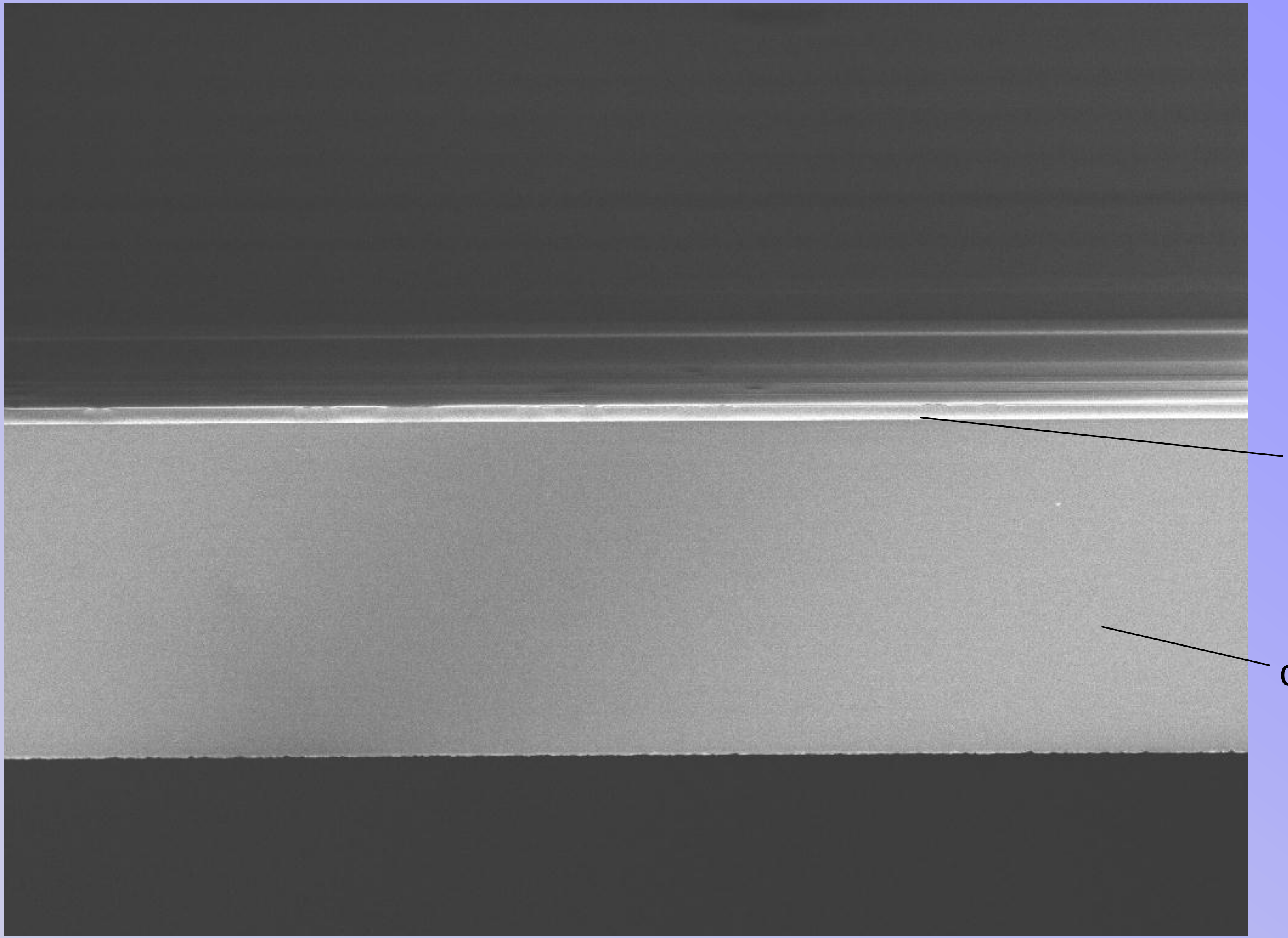




“XeF_2” scribe

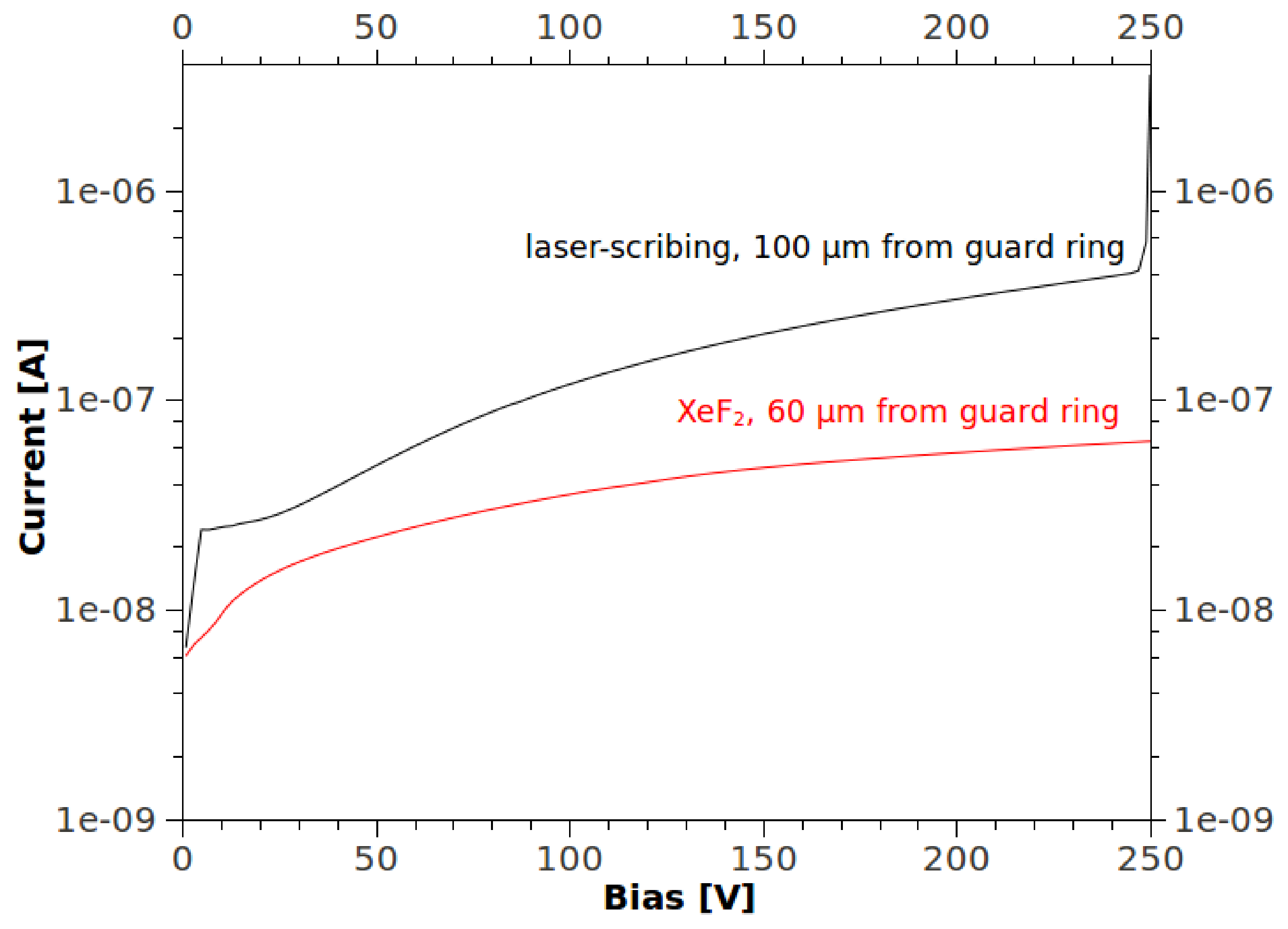
Laser scribe


“XeF$_2$” scribe
Laser scribe



no defects in cleavage plane

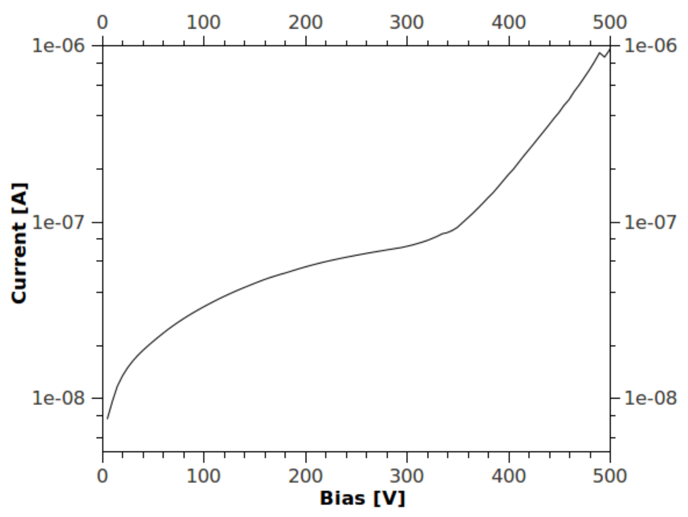
Effect of XeF2 scribing:
10x reduction in leakage current

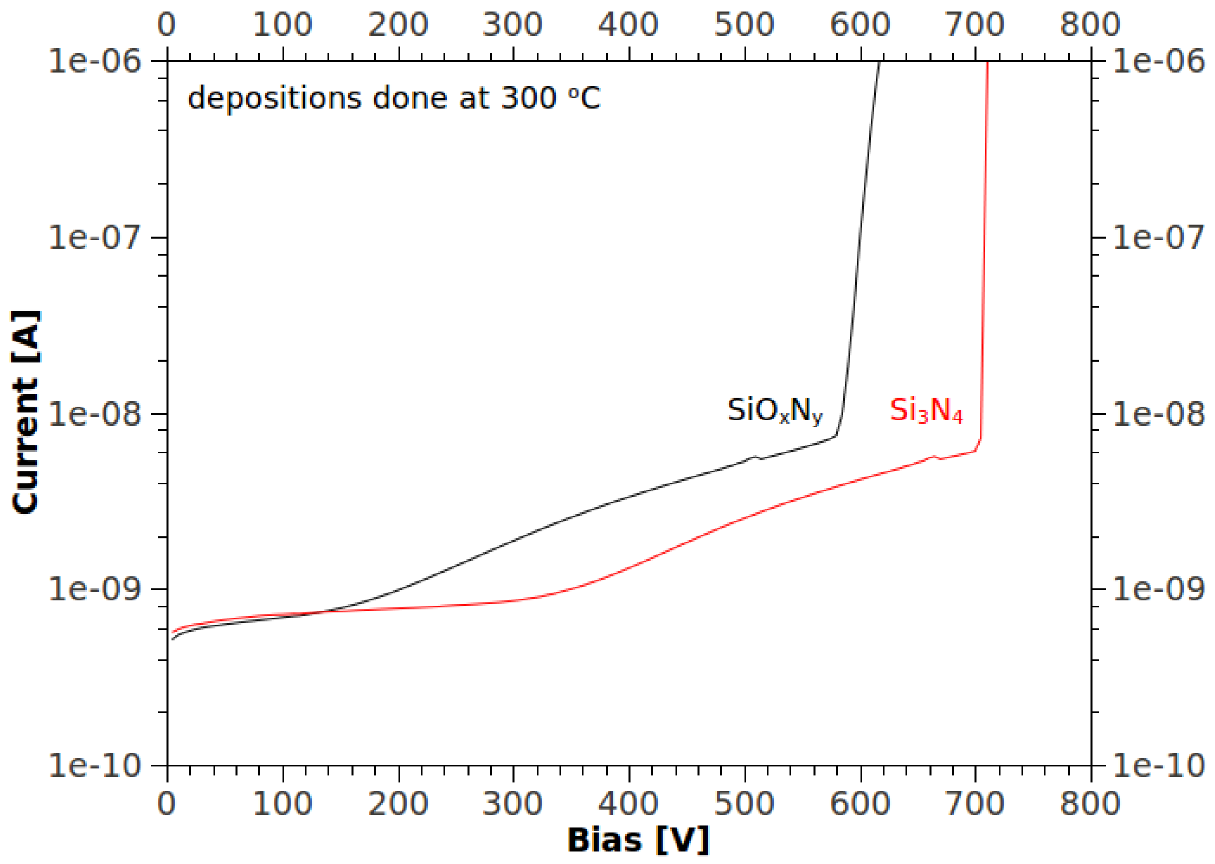


Progress with N-type Sensors

Laser scribing + Oxygen PECVD:

XeF2 scribing + Nitrite PECVD

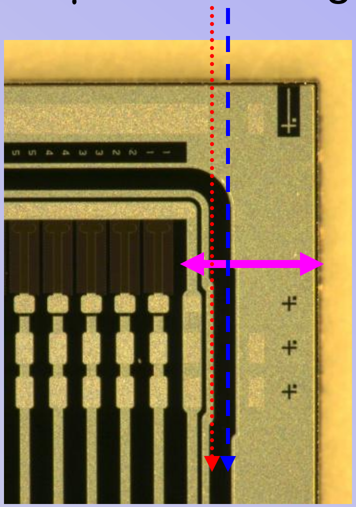




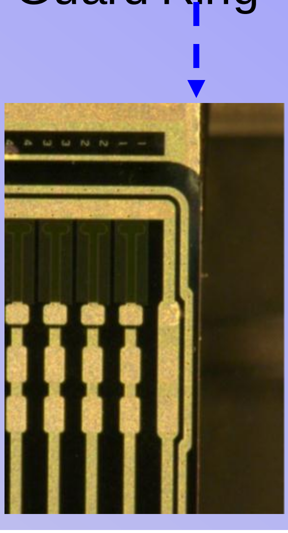
Progress with N-type Sensors

XeF2 scribing + Nitrogen PECVD

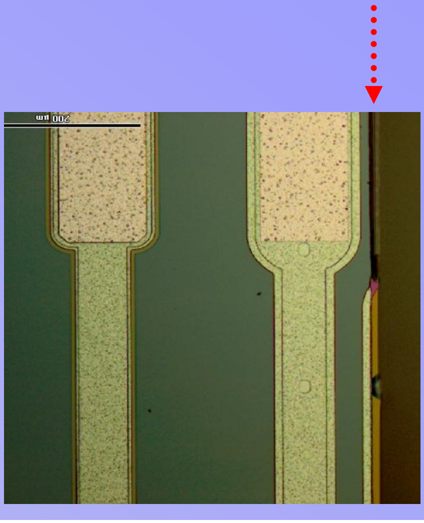
Si SSD with
900µm dead edge

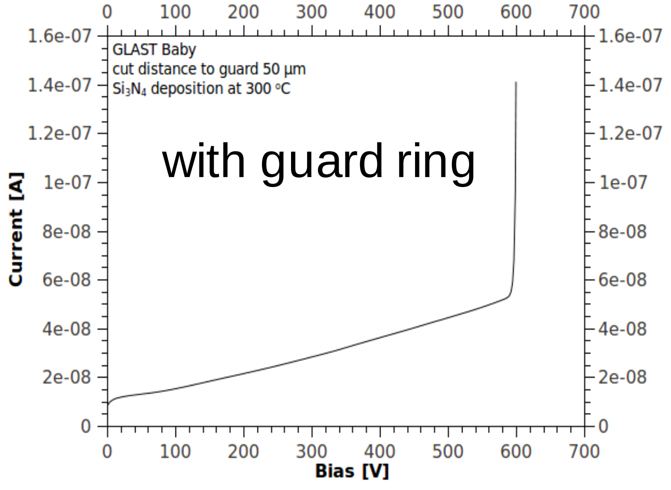


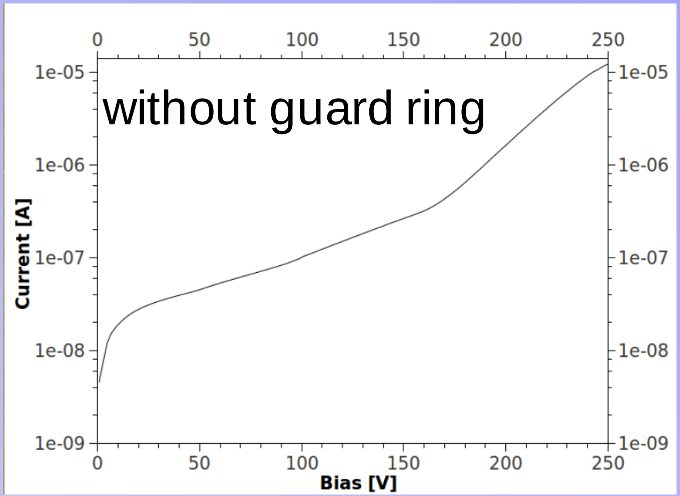
Cut within 50 µm
of Guard Ring



Guard Ring Cut (!)

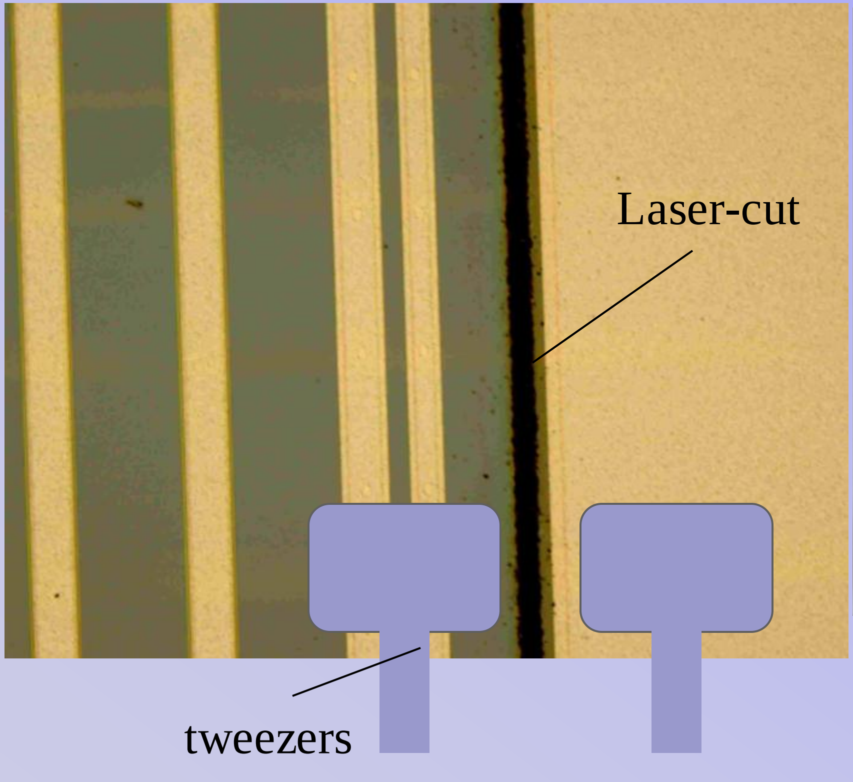




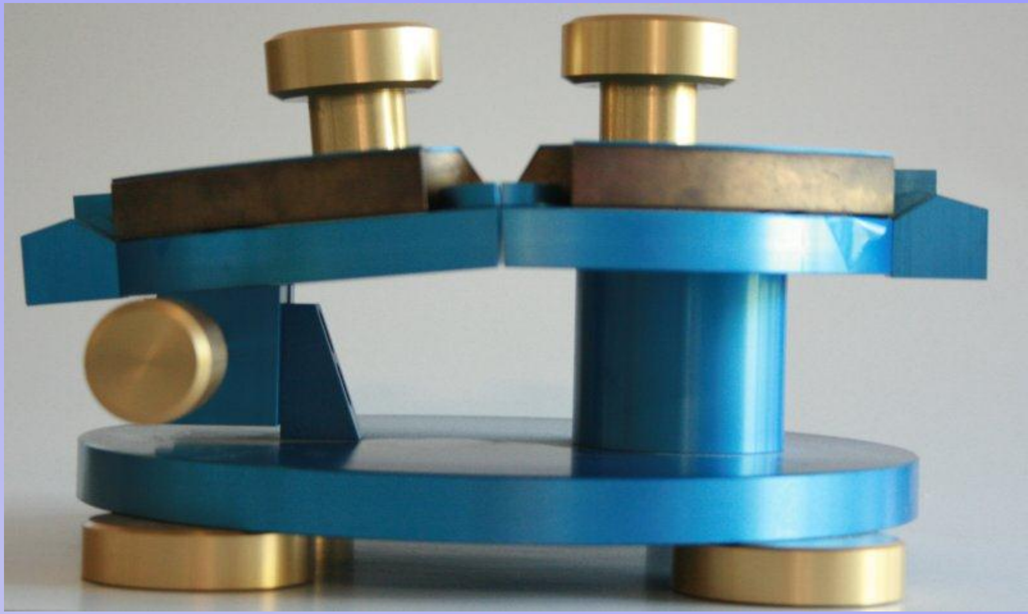


Cleaving

Optical micrograph, top-view



Wafer Brech Maschine
Courtesy PSI and Uni Bonn



If somebody has a wafer breaking machine,
that could be shared or loaned, we are interested!

R&D for Large-Scale Application

One of the key issues in making further progress is replacement of tweezer-based cleaving with better methods.

Looking at the industrial-scale cleaving machines:

- Dynatex machines seem nice. However we have a major delay in scheduling a test run with them.
- Loomis seem to be less automated, but suitable. Could do a test run soon.

LOOMIS Industries LSD-150

Evolution of Slim Edge Treatment

Laser

↓

XeF2 Etch

Tweezers

↓

??

Native Oxide
+ Radiation

N-type ↙ ↘ P-type

PECVD
Oxygen

↓

PECVD
Nitrogen

ALD
Alumina

**All Treatment is
post-processing
low-temp**

Conclusions and Future Work

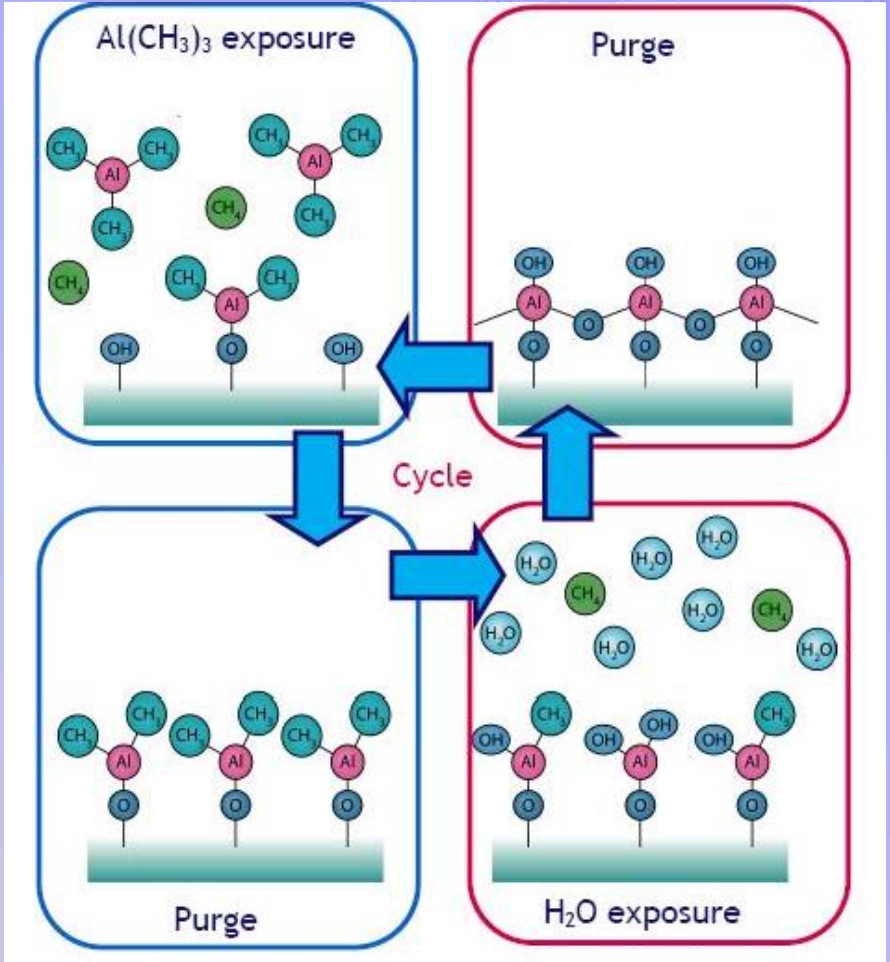
- Scribe-and-cleave method of making a slim edge device followed up by the sidewall passivation holds a lot of promise.
- Work goes on in the framework of PPS and RD50 collaboration.
- The method development continues:
  - Etch-based scribing looks promising
  - For N-type devices, PECVD deposition of nitride/oxide works well
  - Next return to P-type sensors with etch-scribing and ALD
- We have ongoing studies of:
  - Radiation tolerance
  - Charge collection near the edge
  - Industrialization of this technology
- We are performing dedicated studies with the community:
  - MPI P-type pixel devices
  - CNM 3D devices
  - FBK 3D devices
  - (yesterday:) Dortmund n-on-n devices, look good
  - HPK n-type and p-type devices

Back-Up Slides

Introduction - ALD

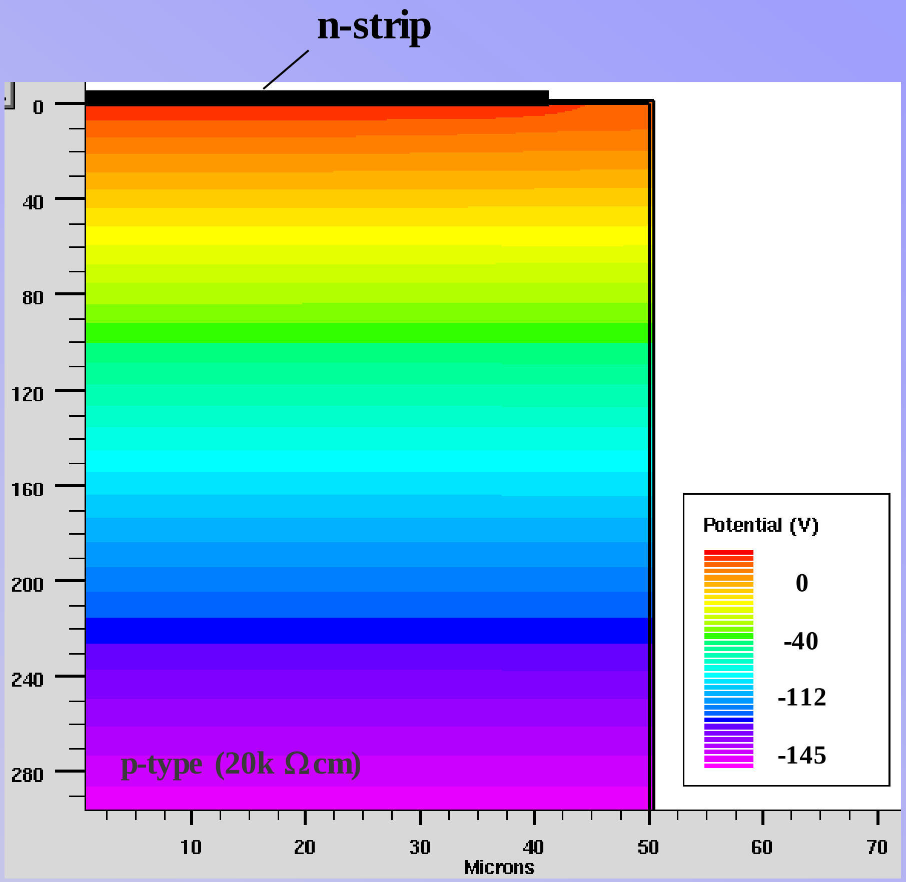
- Similar in chemistry to CVD (chemical vapor deposition), except that the ALD (**atomic layer deposition**) reaction breaks the CVD reaction into two half-reactions, keeping the precursor materials separate during the reaction.
- ALD film growth is **self-limited and based on surface reactions**, which makes achieving atomic scale deposition control possible.
- Perfect 3-D conformality, 100% step coverage: uniform coatings on flat, inside porous and around particle samples.
- **Origin of negative interface charge**: Functional surface groups on the silicon wafer are not optimal for an adsorption of the TMA (trimethylaluminium) precursor molecules, which leads to an incomplete reaction of the TMA and, consequently, an increased relative oxygen concentration at the interface (F. Werner et al., 25th European Photovoltaic Solar Energy Conference, Valencia, Spain, 6-10 September 2010).

Alumina ALD Deposition Cycle



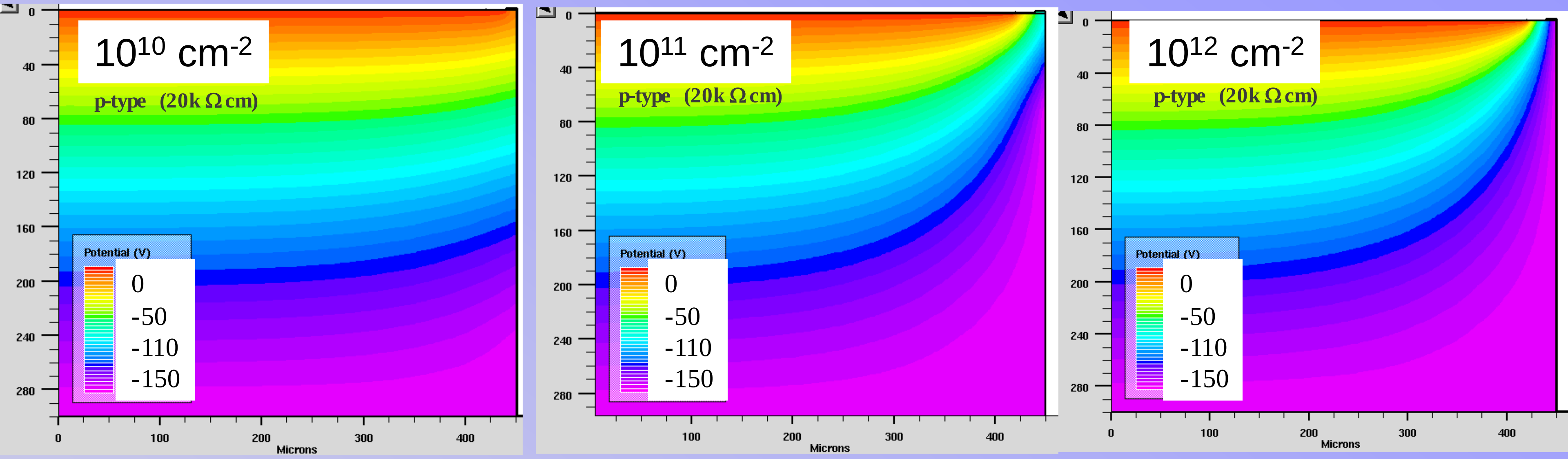
ALD Growth of Al_2O_3 from $Al(CH_3)_3$ and H_2O

Potential Distribution Without Surface Charge



Not considering surface charges leads to *wrong* potential distribution at sidewall.

Influence of Surface Charge Concentration: P-Si/Al_2O_3



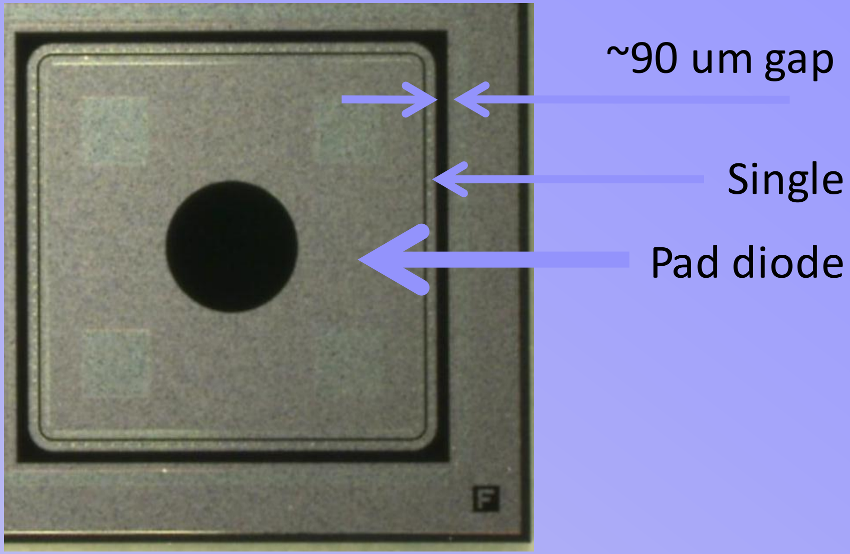
increasing negative surface charge

Typical literature values for alumina are ~ 10^{11} – 10^{13} cm^{-2} depending on deposition conditions. BUT most research is focused on increasing (*not decreasing*) surface charge.

The potential drop at edge depends strongly on surface charge density.

Devices I-IV: HPK Samples

- 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. Vdepl ~ 180 V. Thickness 320 um.



(*) ATLAS07 strip sensors have been developed for ATLAS tracker upgrade for higher luminosity. They served as test vehicle for inter-strip isolation, punch-through protection, and other studies.

References:

Y. Unno et al., "Development of n-on-p silicon sensors for very high radiation environments", NIM A, doi:10.1016/j.nima.2010.04.080 .

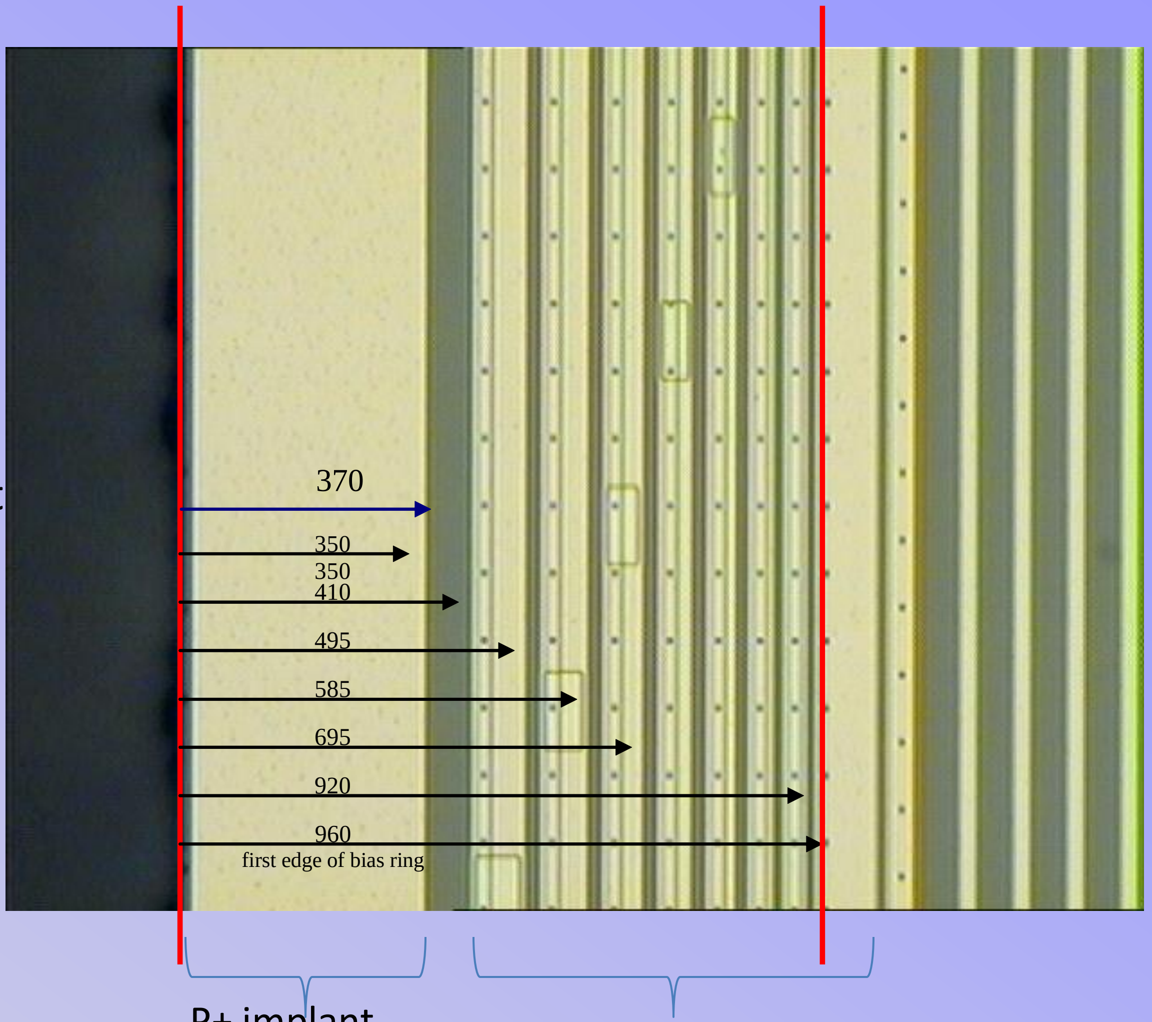
S. Lindgren et al., "Testing of surface properties pre-rad and post-rad of n-in-p silicon sensors for very high radiation environment", NIM A, doi:10.1016/j.nima.2010.04.094 .

J. Bohm et al., "Evaluation of the bulk and strip characteristics of large area *n*-in-*p* silicon sensors intended for a very high radiation environment ", NIM A, doi:10.1016/j.nima.2010.04.093 .

Device IV: CIS Sensor

- These strip test structures were part of ATLAS Planar Pixel submission to CIS foundry.
- The basic design is the same that Liverpool group used in Micron submissions (*).
- 8 guard ring structures. N-on-p sensor type. Vdepl ~50 V.
- The usual p+ implant structure at the periphery was specifically removed to facilitate the edge studies.

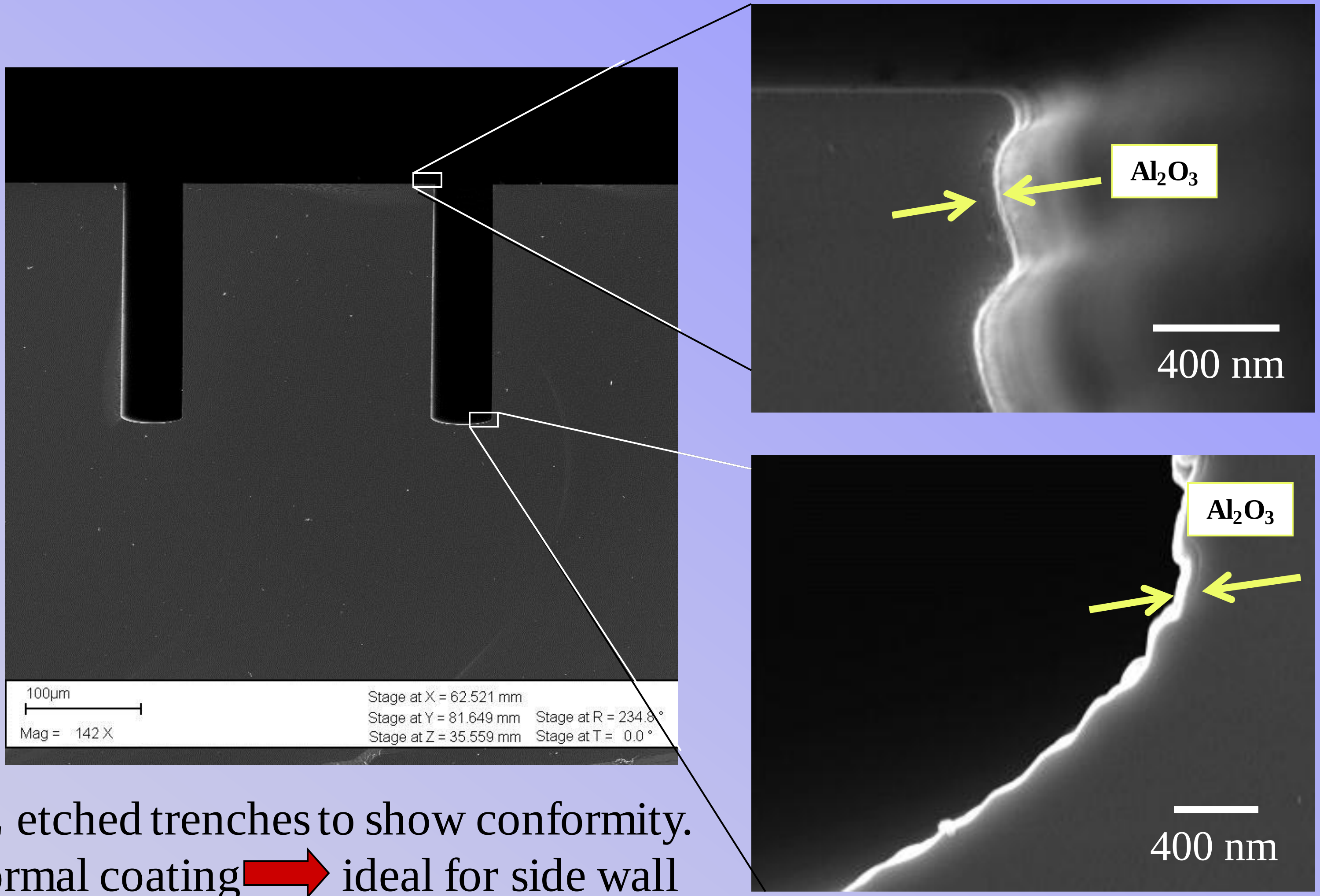
(*) G. Casse, P.P. Allport, A. Greenall, "Response to minimum ionising particles of p-type substrate silicon microstrip detectors irradiated with neutrons to LHC upgrade doses", NIM A 581 (2007) p. 318.



P+ implant is *absent* in CIS sensors

8 guard rings

ALD – Step Coverage



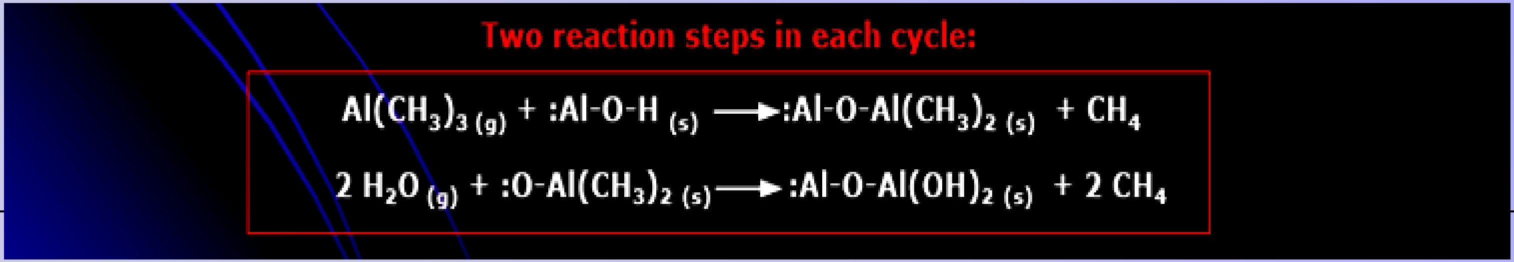
- DRIE etched trenches to show conformity.
- conformal coating → ideal for side wall passivation.

Alumina ALD Reactions

- Releases sequential precursor gas pulses to deposit a film one layer at a time.

  Two fundamental mechanisms:
  - ☐ *Chemisorption saturation process*
  - ☐ *Sequential surface chemical reaction process*

- Since each pair of gas pulses (one cycle) produces exactly one monolayer of film, the thickness of the resulting film may be precisely controlled by the number of deposition cycles.
- One TMA (trimethylaluminium) and H_2O vapor pulse per cycle, ~ 1 Å per cycle, pumping ~ 3 sec per cycle.



Two reaction steps in each cycle:

$$Al(CH_3)_{3\,(g)} + :Al\text{-}O\text{-}H_{\,(s)} \longrightarrow :Al\text{-}O\text{-}Al(CH_3)_{2\,(s)} + CH_4$$

$$2\,H_2O_{\,(g)} + :O\text{-}Al(CH_3)_{2\,(s)} \longrightarrow :Al\text{-}O\text{-}Al(OH)_{2\,(s)} + 2\,CH_4$$