Applications of Atomic Layer Deposition (ALD) on ultra-fine pitch pixel detectors

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http://research.hip.fi/hwp/cmsupg/

http://www.aldcoe.fi/

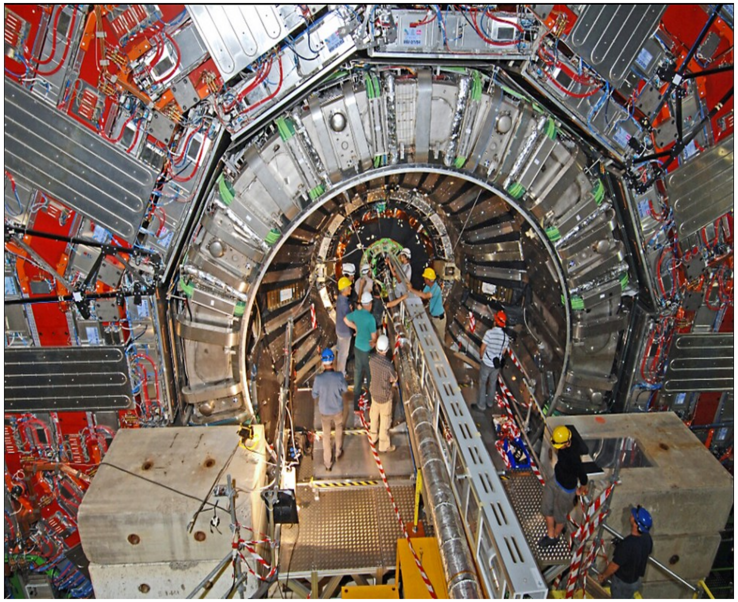
Outline

Who are we ?

Our activities – CMS experiment upgrade and detector R&D

What ALD is good for radiation detectors ?

- Particle and nuclear physics
- Photon science
- Medical and industrial imaging
- Space applications



The pixel detector contains 65 million pixels, allowing it to track the paths of particles emerging from the collision with extreme accuracy. It is also the closest detector to the beam pipe, with cylindrical layers at 4cm, 7cm and 11cm and disks at either end, and so will be vital in reconstructing the tracks of very short-lived particles. Thus, extreme radiation hardness is required. In coming few years the pixel Detector will be upgraded 65M pixels > 120M pixels.
http://cms.web.cern.ch/news/silicon-pixels

HIP CMS Upgrade Project
http://research.hip.fi/hwp/cmsupg/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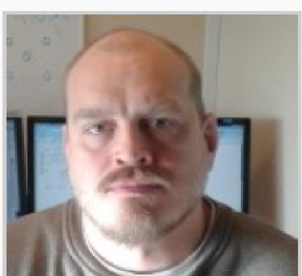
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ALD CoE

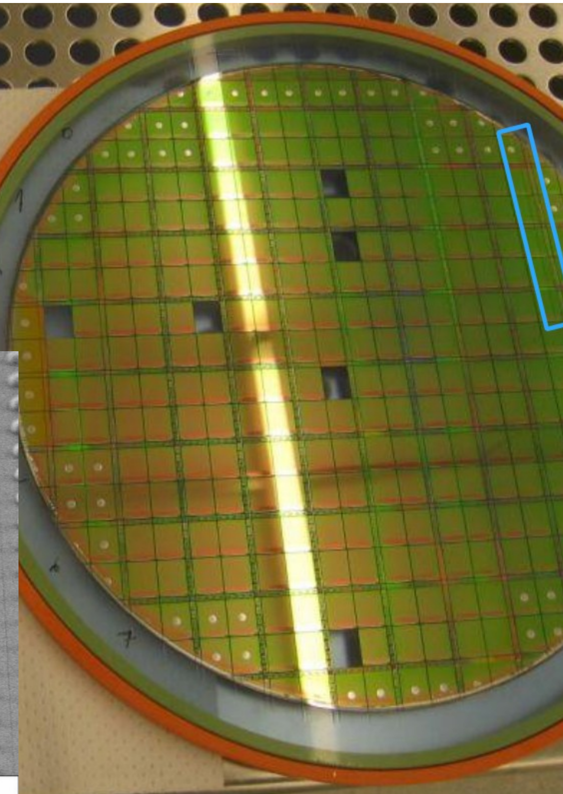
FINNISH CENTRE OF EXCELLENCE IN ATOMIC LAYER DEPOSITION

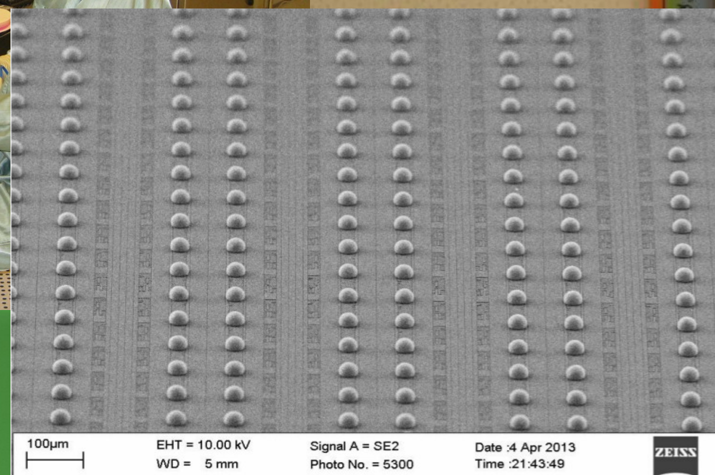
1. ALD precursors and processes
2. Micro- and nanostructures
3. Materials for electronics
4. Materials for energy technologies

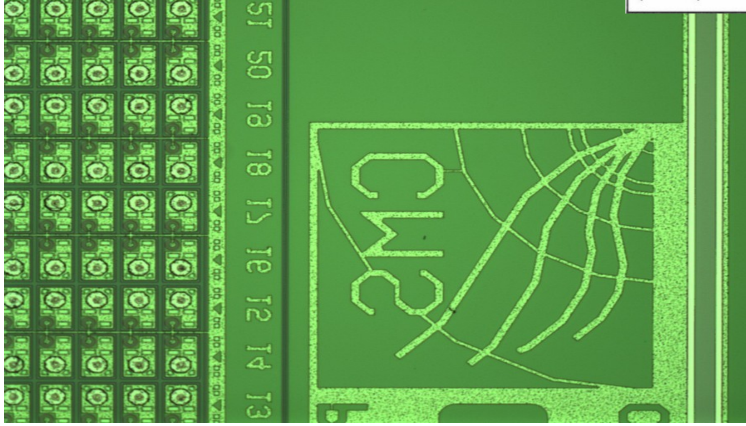
The centre of excellence consists of three groups:

1. Laboratory of Inorganic Chemistry (University of Helsinki)
2. Materials Physics Division (University of Helsinki)
3. VTT Microsystems and Nanoelectronics group

On-going activities of HIP CMS group -Phase I pixel upgrade





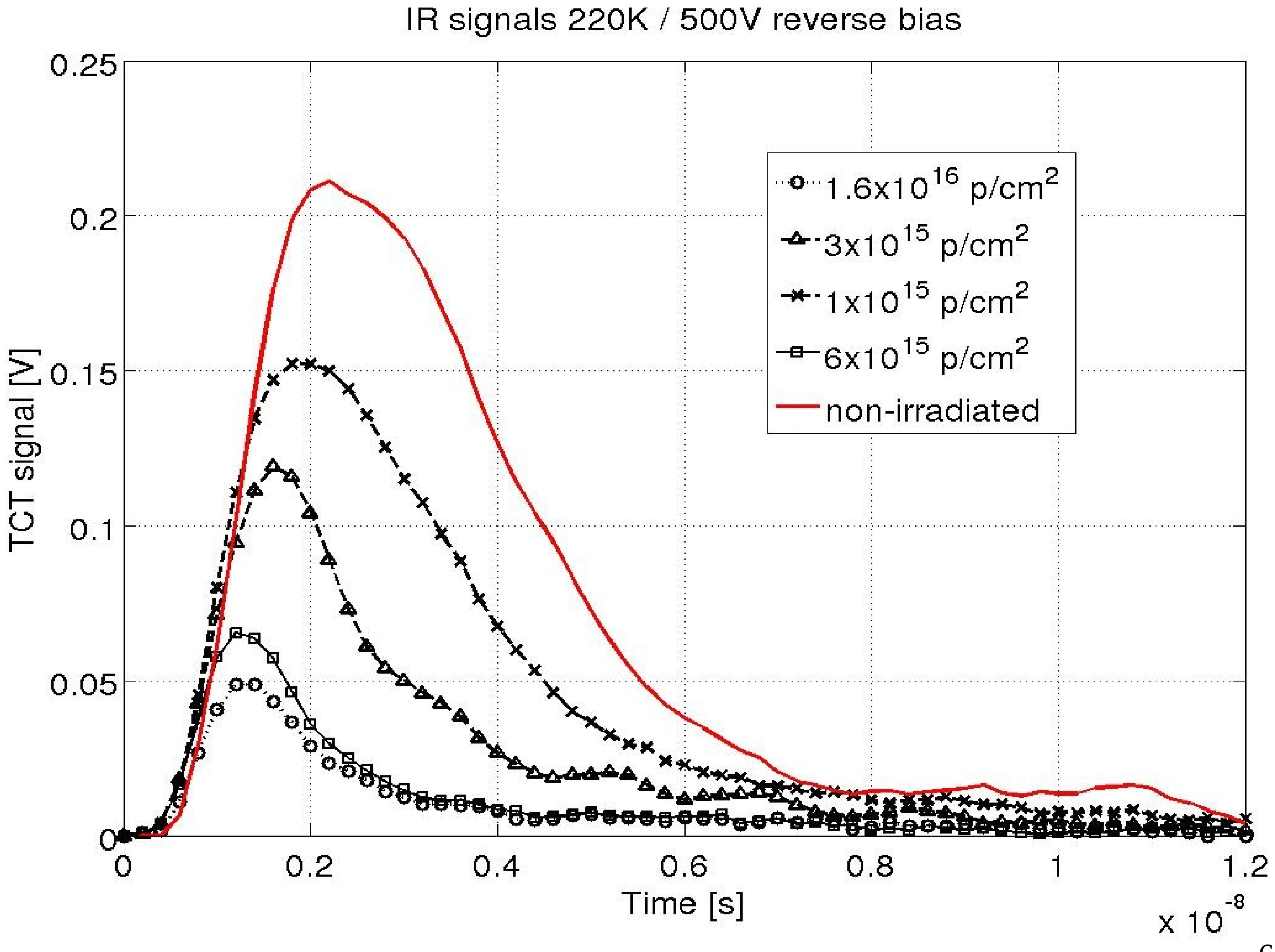


-Finland has committed to deliver in-kind 50% on pixel modules of CMS Layer3.

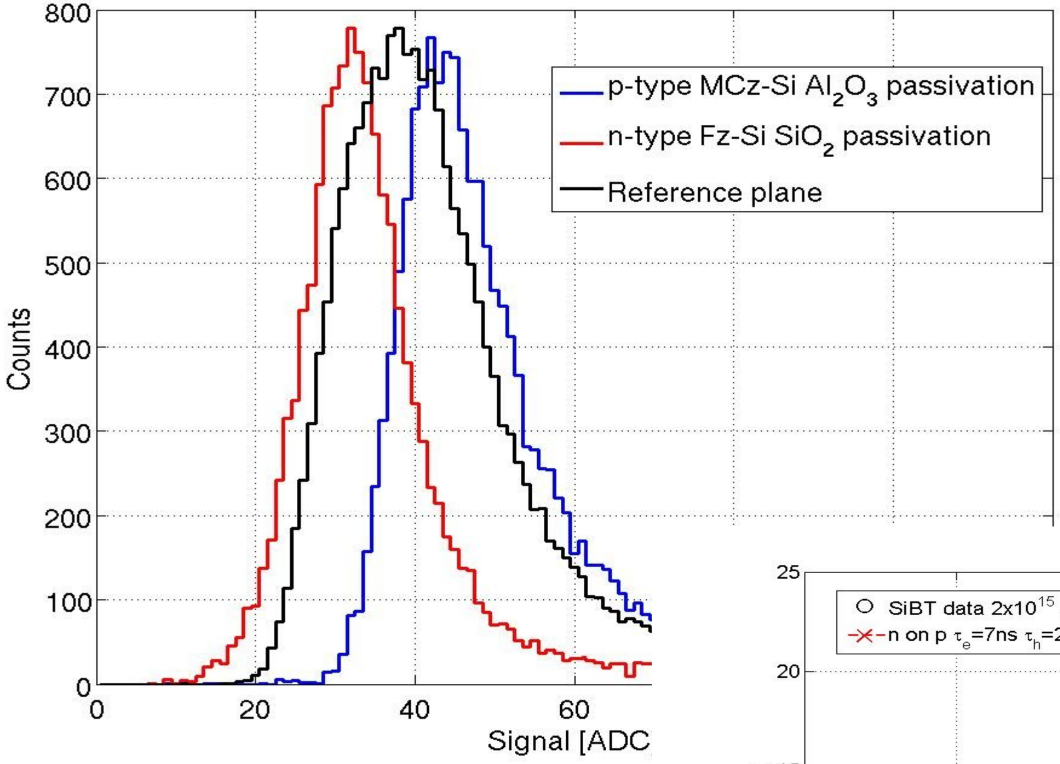
-4000 read-out ASICs will be Flip-Chip bonded in Micronova resulting in >16M channels

- Simultaneously, we have launched internal R&D for next generation pixel sensors utilizing potential of ALD technology.

Radiation hardness -Trapping of signal into radiation defects

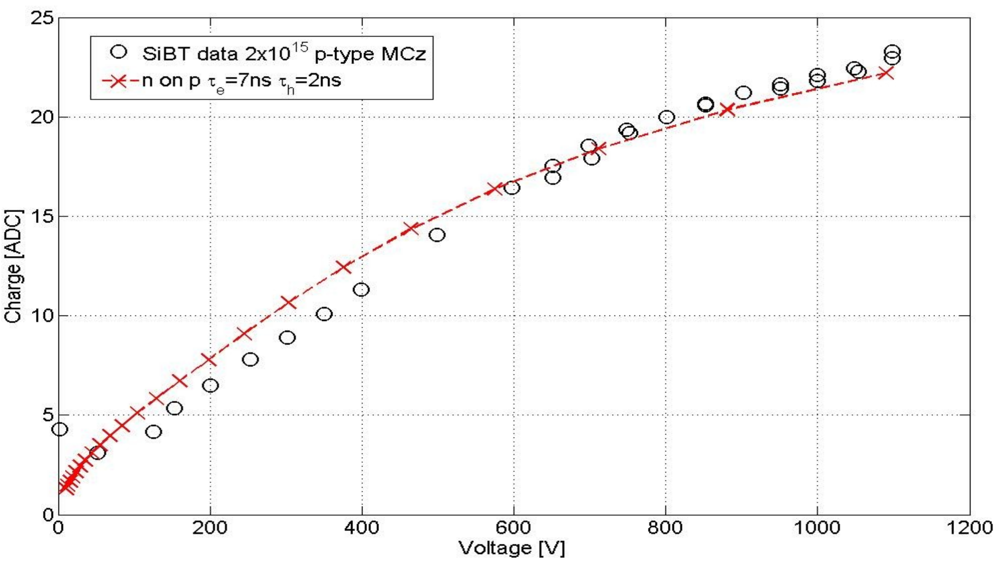


Earlier work -Helsinki SiBT results – 2×10^{15} irradiation



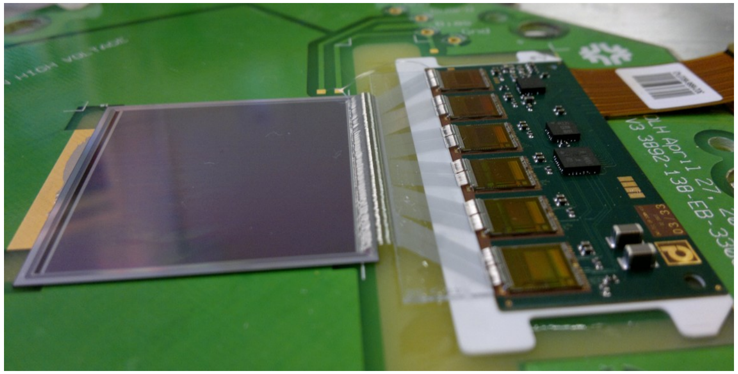
P-type MCz-Si sensor
Processed in Micronova 2007
No p-spray or p-stop
Measured in 2008
CCE @600V > 40%

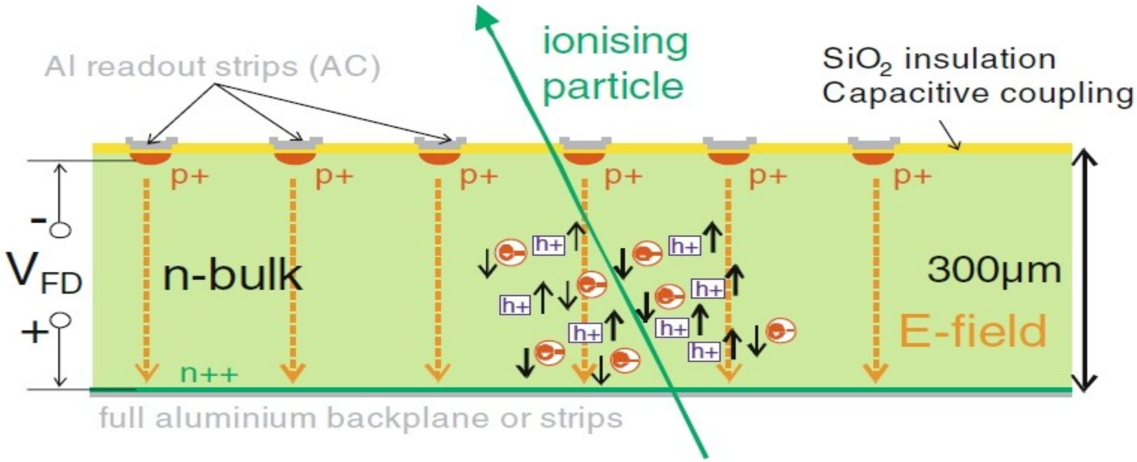
Full charge ≈ 40 ADC
(average of 8 reference planes
,HPK made n-type Fz-Si sensors
made for FNAL D0 experiment)



Capacitive (AC) coupling of signal

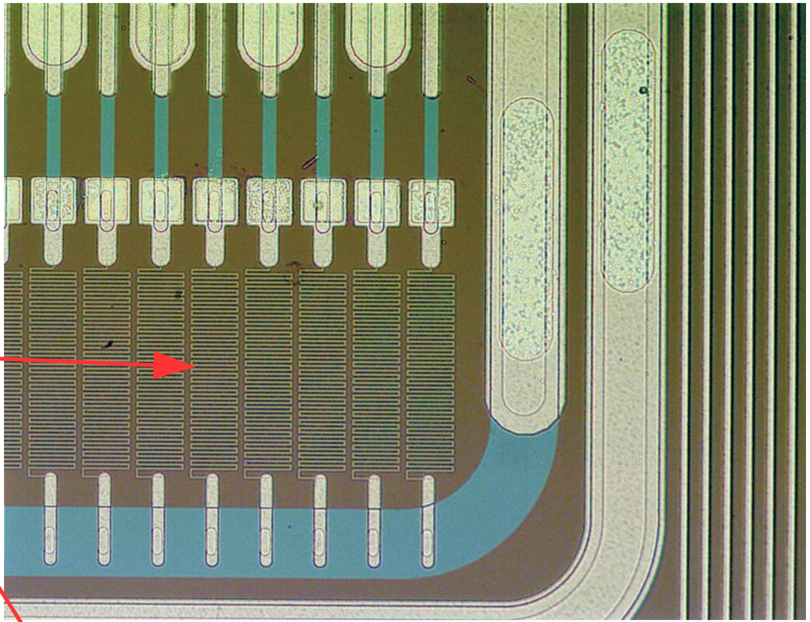
- Modern particle detectors are AC-coupled, i.e. strips (segmented electrodes) are capacitors
- AC-coupling is needed to isolate leakage current (DC-current) from input of read-out amplifier
- Coupling capacitance $C_{coup} >> C_{backplane} = \varepsilon \times \text{Area} / \text{thickness}$
- → ***high capacitance density*** is needed for effective signal coupling

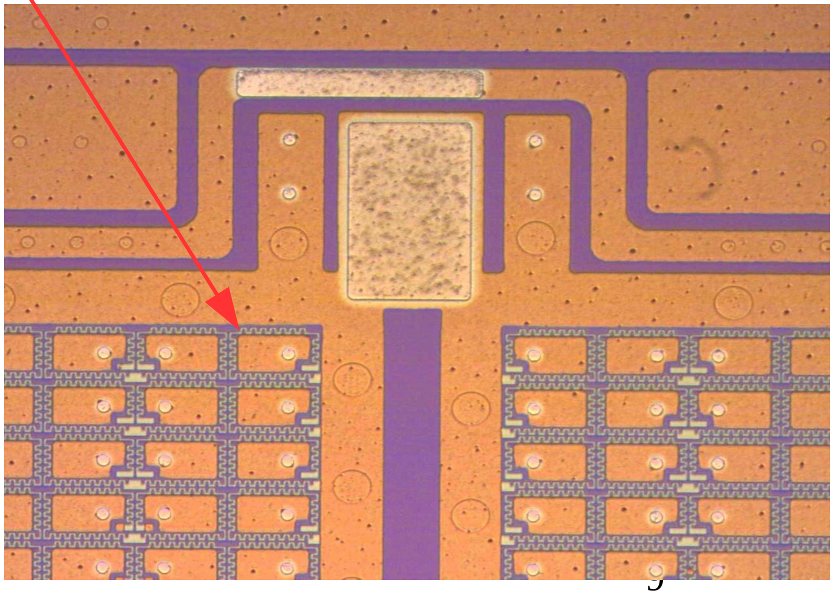




AC-coupling requires resistor for biasing

- Otherwise segmented implants (pixels or strips) would be at same potential resulting in no spatial resolution
- Bias resistors need to be ~1M Ω
- High resistance is difficult to integrate in small space
- Bias resistors are traditionally made by poly-Si process
- Why not a thin-film metal resistor deposited by ALD ?
    - No additional mask levels
    - More radiation hard (amorphous material)
    - No chlorine plasma etching
    - Low temperature processing
    - No ion implantation (for resistance trim)



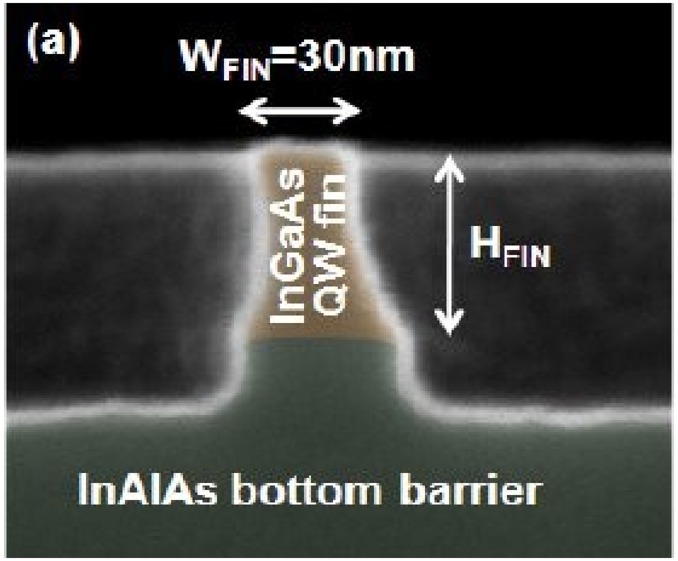


Atomic Layer Deposition (ALD)

http://www.aldcoe.fi/publications/ald_history.pdf

Originally developed and discovered by Dr. Tuomo Suntola in Finland in early 1970's.

ALD is nowadays key-technology in developments for post-Moore's Law CMOS



Possibilities of ALD for radiation hard detectors

- ALD provides many potentially interesting material systems, e.g. high ε materials HfO_2, ZrO_2 etc
- With ALD one can tailor amount and **type of oxide charge**
- ALD is pinhole free deposition
- ALD is applicable on large surfaces
- ALD is low temperature process, typically 300^0C

1. Putkonen, M., Niinistö, J., Kukli, K., Sajavaara, T., Karppinen, M., Yamauchi, H., and Niinistö, L., ZrO_2 thin films grown on silicon substrates by atomic layer deposition with $Cp_2Zr(CH_3)_2$ and water as precursors, Chemical Vapor Deposition 9 (2003) 207-212.
2. Niinistö, J., Putkonen, M., Niinistö, L., Kukli, K., Ritala, M., and Leskelä, M., Structural and dielectric properties of thin ZrO_2 films on silicon grown by atomic layer deposition from cyclopentadienyl precursor, Journal of Applied Physics 95 (2004) 84-91.
3. Niinistö, J., Rahtu, A., Putkonen, M., Ritala, M., Leskelä, M., and Niinistö, L., *In situ* quadrupole mass spectrometry study of atomic-layer deposition of ZrO_2 using $Cp_2Zr(CH_3)_2$ and water, Langmuir 21 (2005) 7321-7325.
4. Niinistö, J., Putkonen, M., Niinistö, L., Stoll, S. L., Kukli, K., Sajavaara, T., Ritala, M., and Leskelä, M., Controlled growth of HfO_2 thin films by atomic layer deposition from cyclopentadienyl-type precursor and water, Journal of Materials Chemistry 15 (2005) 2271-2275.
5. Niinistö, J., Putkonen, M., Niinistö, L., Arstila, K., Sajavaara, T., Lu, J., Kukli, K., Ritala, M., and Leskelä, M., HfO_2 films grown by ALD using cyclopentadienyl-type precursors and H_2O or O_3 as oxygen source, Journal of The Electrochemical Society 153 (2006) F39-F45.
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7. Niinistö, J., Petrova, N., Putkonen, M., Sajavaara, T., Arstila, K., and Niinistö L., Gadolinium oxide thin films by atomic layer deposition, Journal of Crystal Growth 285 (2005) 191-200.
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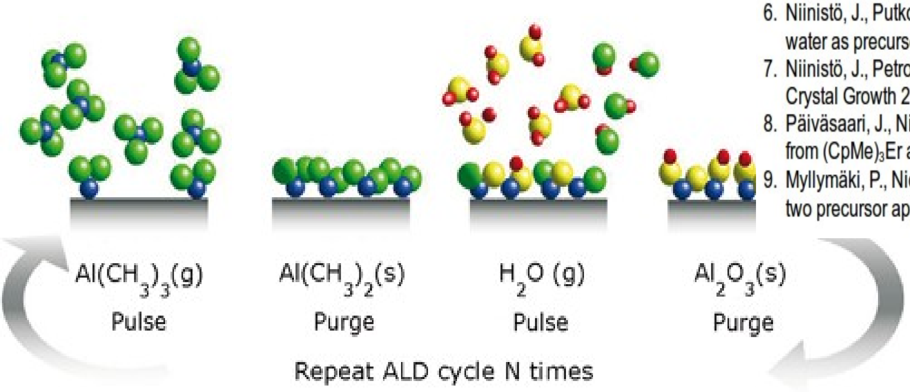
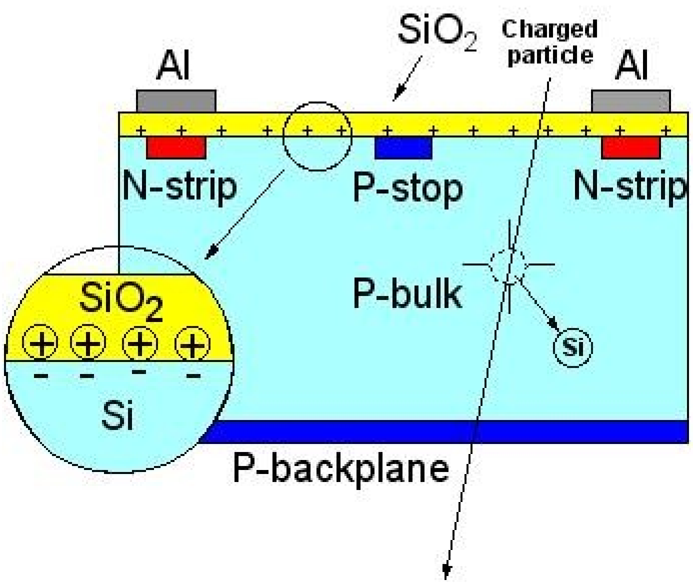
9. Myllymäki, P., Nieminen, M., Niinistö, J., Putkonen, M., Kukli, K., and Niinistö, L., High-permittivity $YScO_3$ thin films by atomic layer deposition using two precursor approaches, Journal of Materials Chemistry 16 (2006) 563-567.

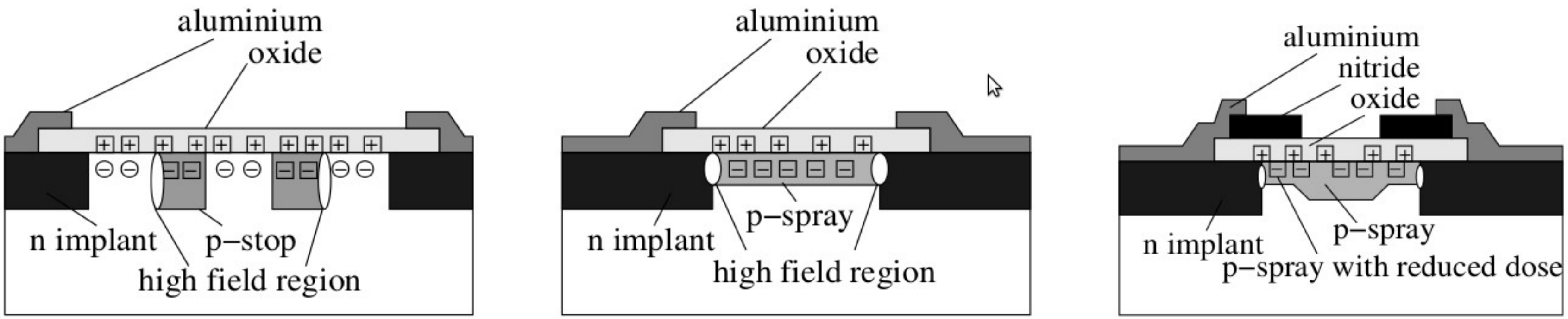


http://www.beneq.com/atomic-layer-deposition.html

What is ALD good for radiation detectors ?

- Trapping can significantly reduced if detector structure is $n^+/p^-/p^+$ (n on p) instead of usual p+ implants.
- This is due to 3×higher mobility of electrons
- Oxide charge is positive → electron accumulation at Si/SiO_2 interface
- Elevated surface charge can be eliminated by different p-spray (B field implantation) and p-stop (segmented B implant)





(a) *p*-Stops

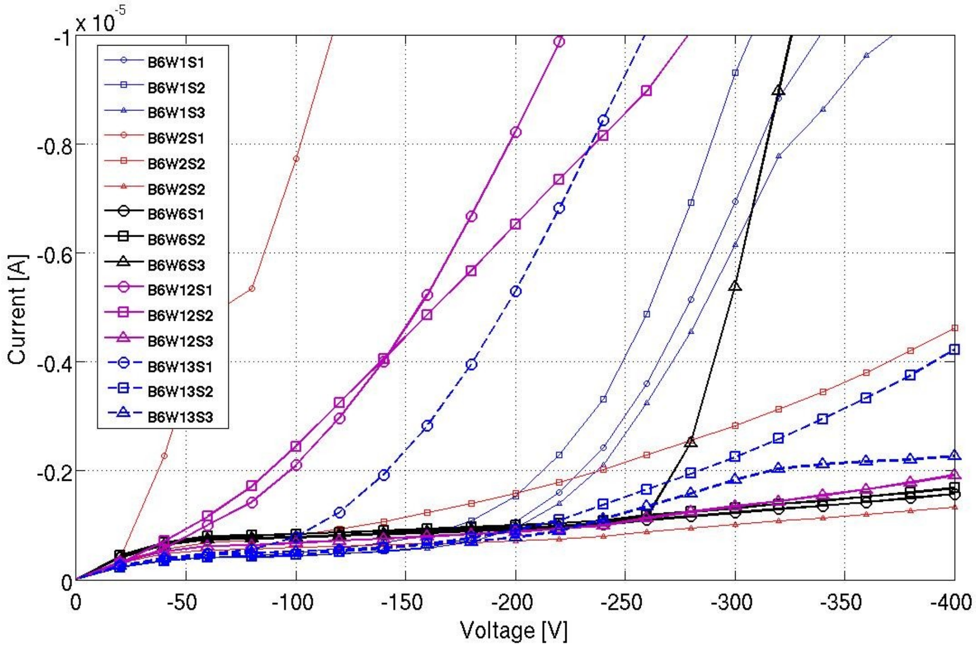
(b) *p*-Spray

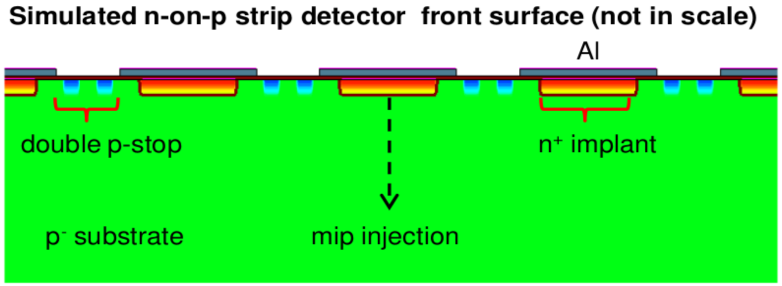
(c) moderated *p*-Spray

Figure by Tilman Rohe

Problem with p-stop implants

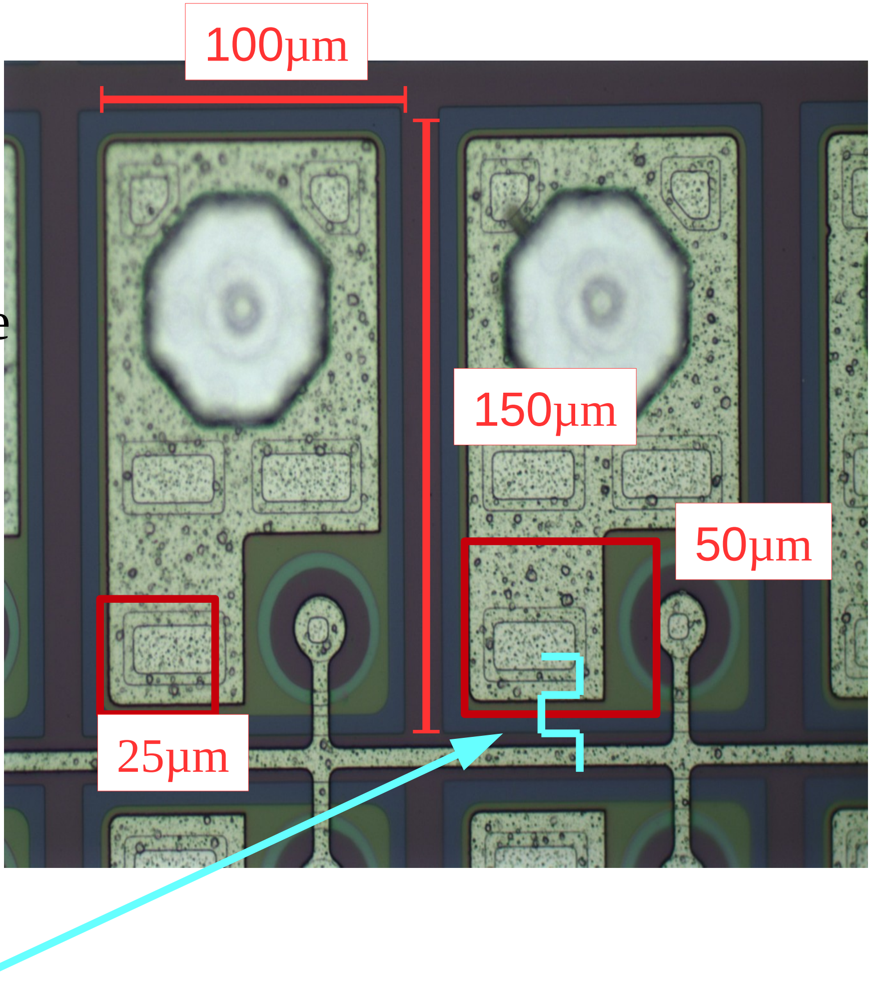
- Requires more
  - Mask levels (=price)
  - High temperature processing steps
- Finer granularity increases local electric fields → lower breakdown voltage
- More implants mean higher capacitances (=noise, lower rise time of signal)





Small pixels in the future

- Radiation damage reduces Charge Collection length $L_{CC} = V_{DRIFT} / \tau_{TRAPPING}$
- L_{CC} will be order of 30μm
- In order to maintain efficient tracking one has to increase granularity, i.e. reduce physical pixel size.
- Target is to reduce pixel size > 50μm × 50μm or even 25μm × 25μm
- Bias resistor will be significant challenge
- ALD method allows to deposit many metal-nitride thin films
- E.g TiN *d≈20nm* might allow 100kΩ/μm with 2-4μm linewidth (compatible with standard contact mask aligner and wet etching)



Earlier work: n on p MCz-Si strip sensors with ALD coupling insulator and surface termination

- Activity ongoing since 2006
- It is well-know that ALD grown Al_2O_3 can have negative fixed oxide charge
- Negative Q_{ox} is widely applied in e.g. Si solar cells
- Strip sensors tested in SPS muon Beam with SiBT setup in 2008 and 2011

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Energy Procedia 8 (2011) 681–687

Energy Procedia

SiliconPV: 17-20 April 2011, Freiburg, Germany

Silicon Surface Passivation by Al_2O_3: Effect of ALD Reactants

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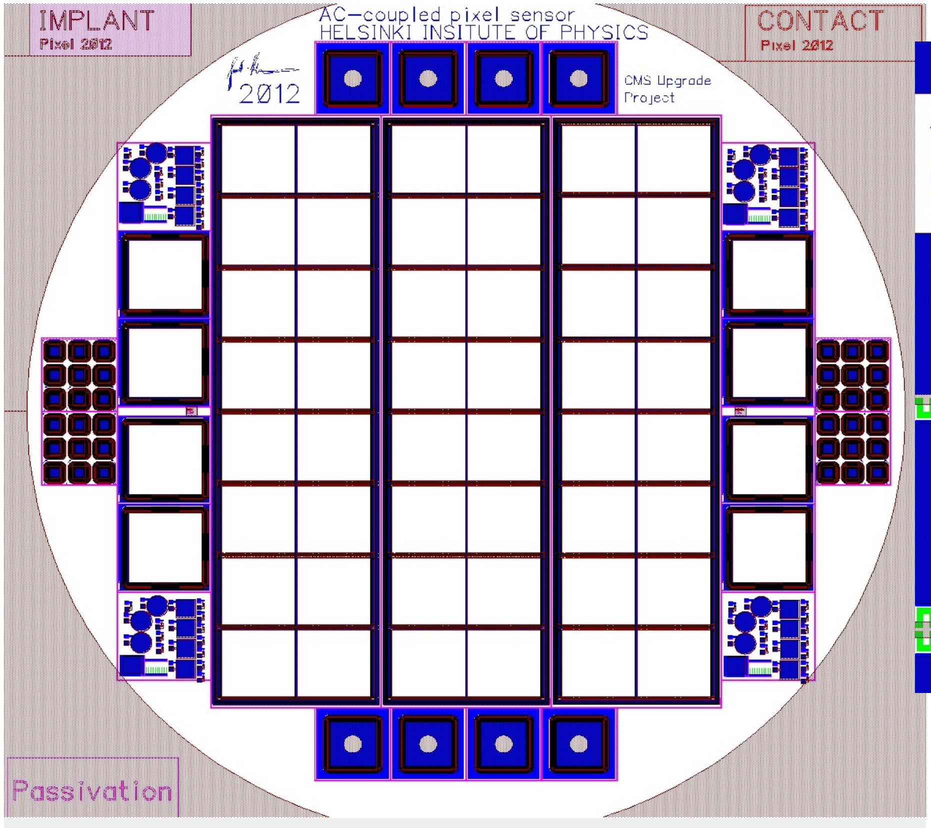
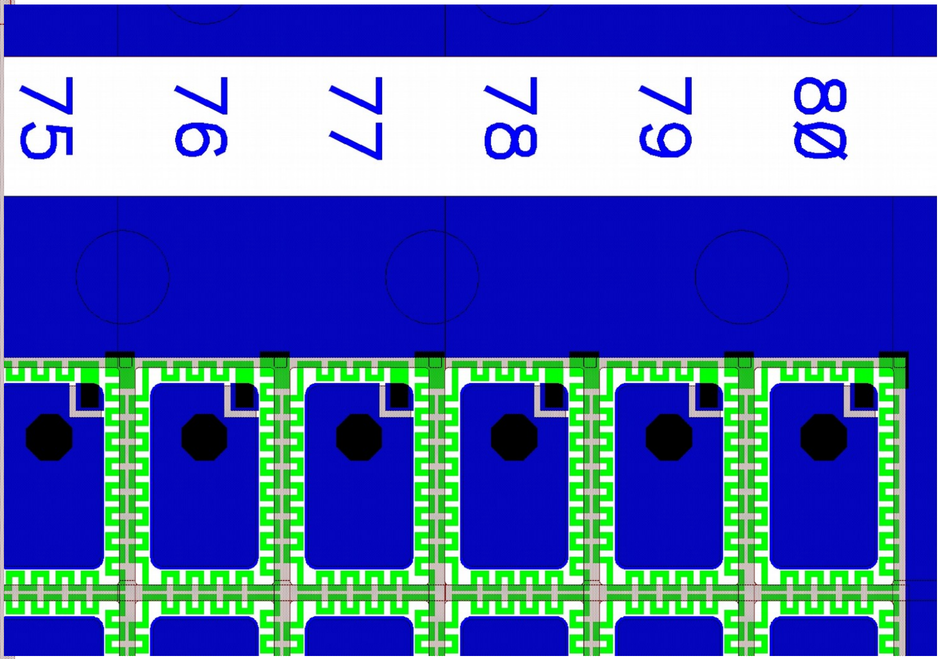
Abstract

We have studied the surface passivation of p- and n-type silicon by thermal atomic layer deposited (ALD) Al_2O_3. The main emphasis is on different ALD reactant combinations and especially on using ozone as an oxidant. Thermal stability of Al_2O_3 will also be briefly addressed. Our results show that in p-type CZ-Si Al_2O_3 leads to much higher passivation than thermal oxidation, independent of the reactants. The best minority carrier lifetimes are measured when a combination of Al_2O_3 and TiO_2 is used. In n-type CZ-Si similar results are obtained except the choice of reactants seems to be more crucial. However, the combination of Al_2O_3 and TiO_2 results again in the best passivation with measured lifetimes well above 10 ms corresponding surface recombination velocities of ~2 cm/s. Finally, we demonstrate that Al_2O_3 passivation is also applicable in high resistivity n-type FZ-Si and in ~1 Ωcm p-type multicrystalline Si.

Keywords: Al_2O_3 ; Silicon ; Passivation ; ALD ; Reactant ; Ozone

HIP AC-coupled pixel sensor

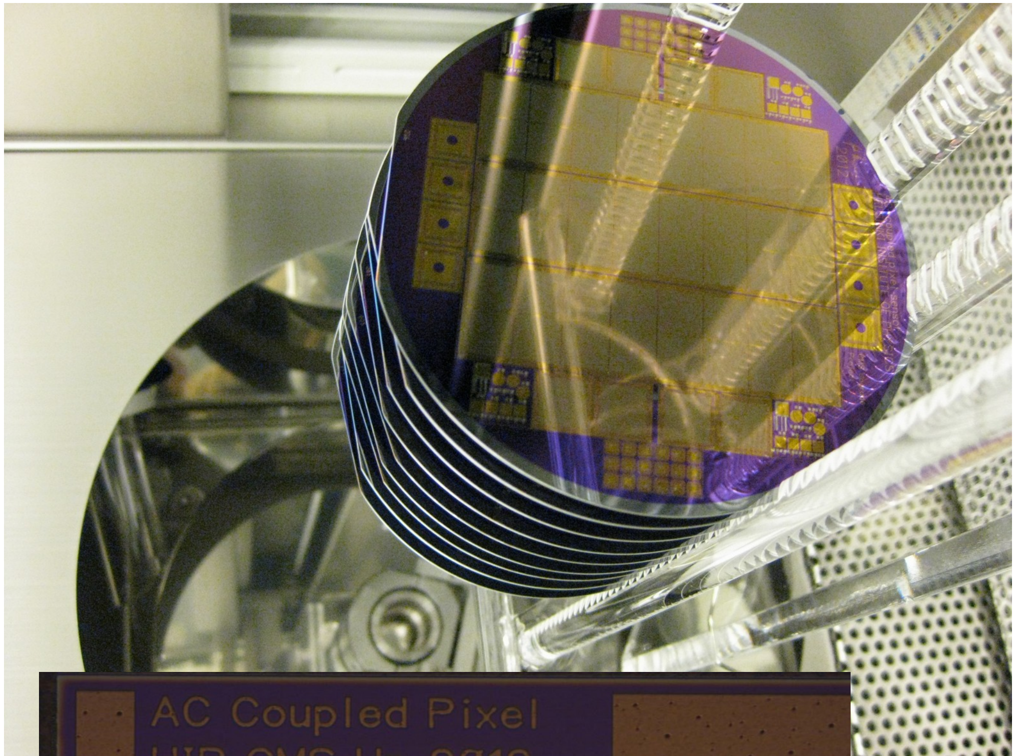




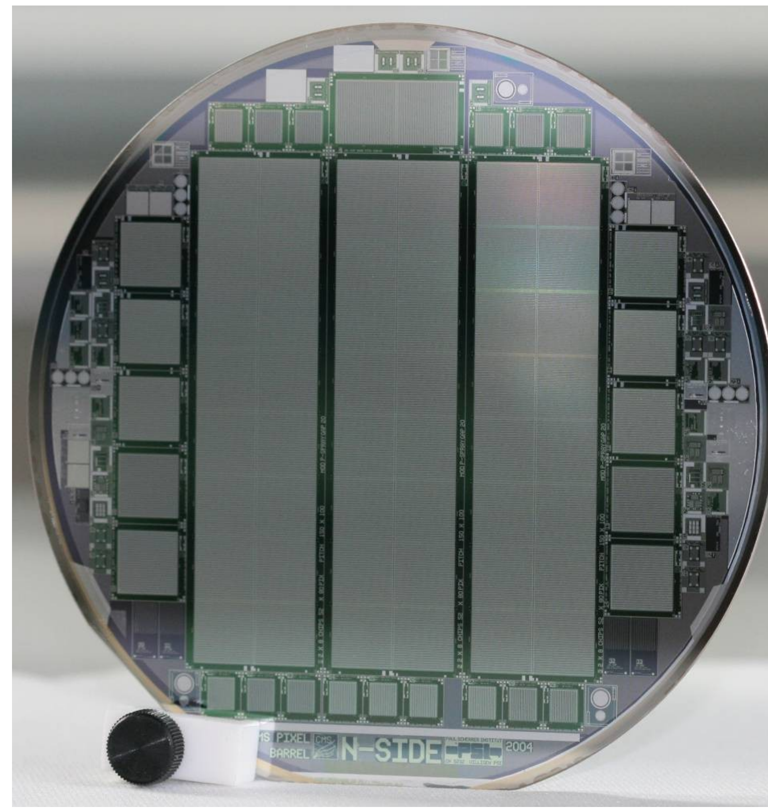
Basic wafer layout similar as current CMS pixel:
Three large (2x8 ROC) sensors + 8 single chip sensors

-Biasing via WNx thin film resistors
- Easy process: room temperature sputter deposition + RT wet/plasma etching
- Poly-Si resistor = 2 implants + high temp poly CVD + high temp activation
-Coupling insulator ALD Al_2O_3
-No p-spray or p-stop

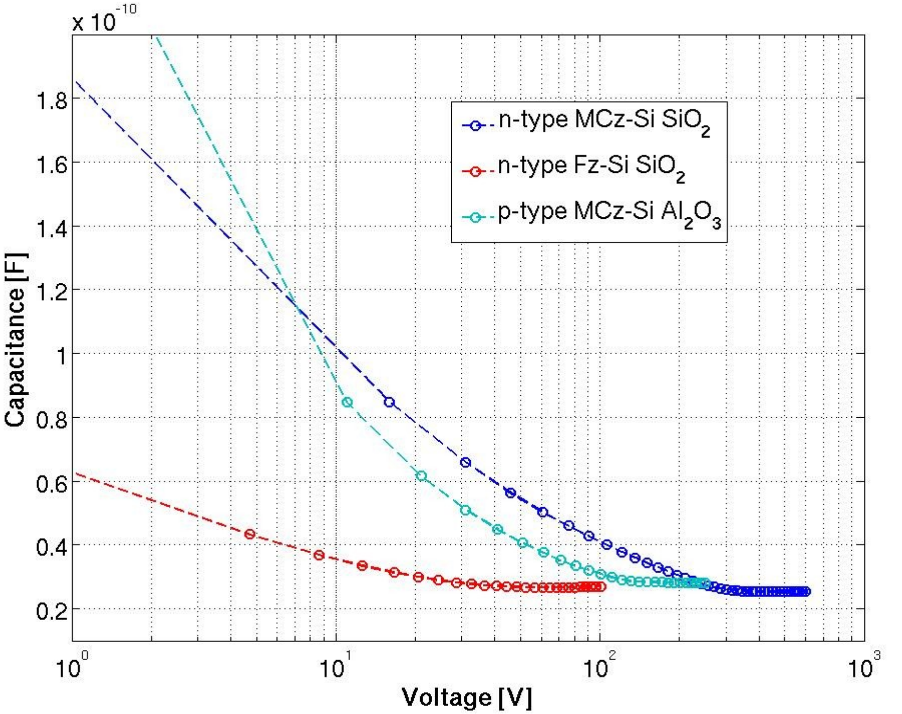
HIP AC-coupled pixel sensor II

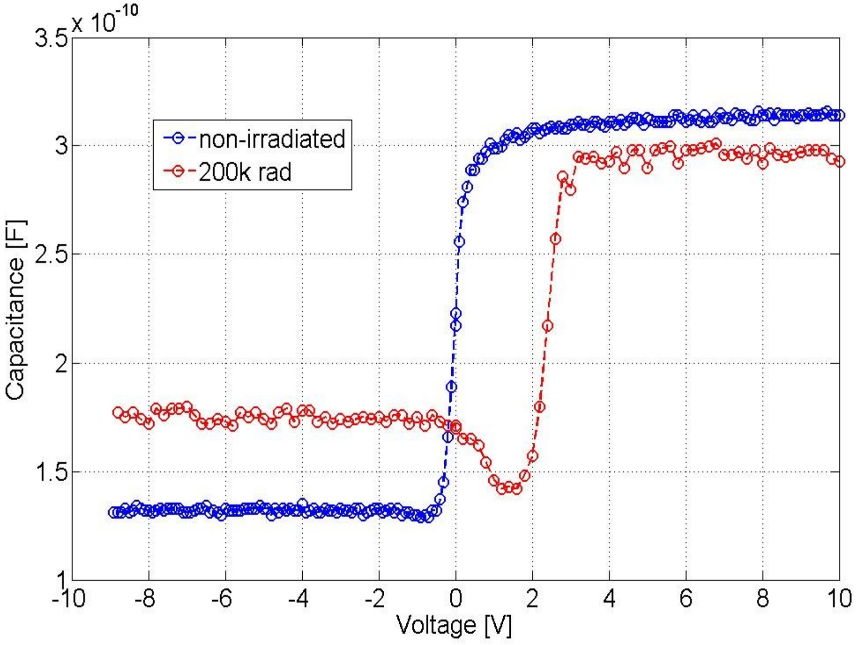


First batch processed in 2013



AC-coupled pixel sensors III



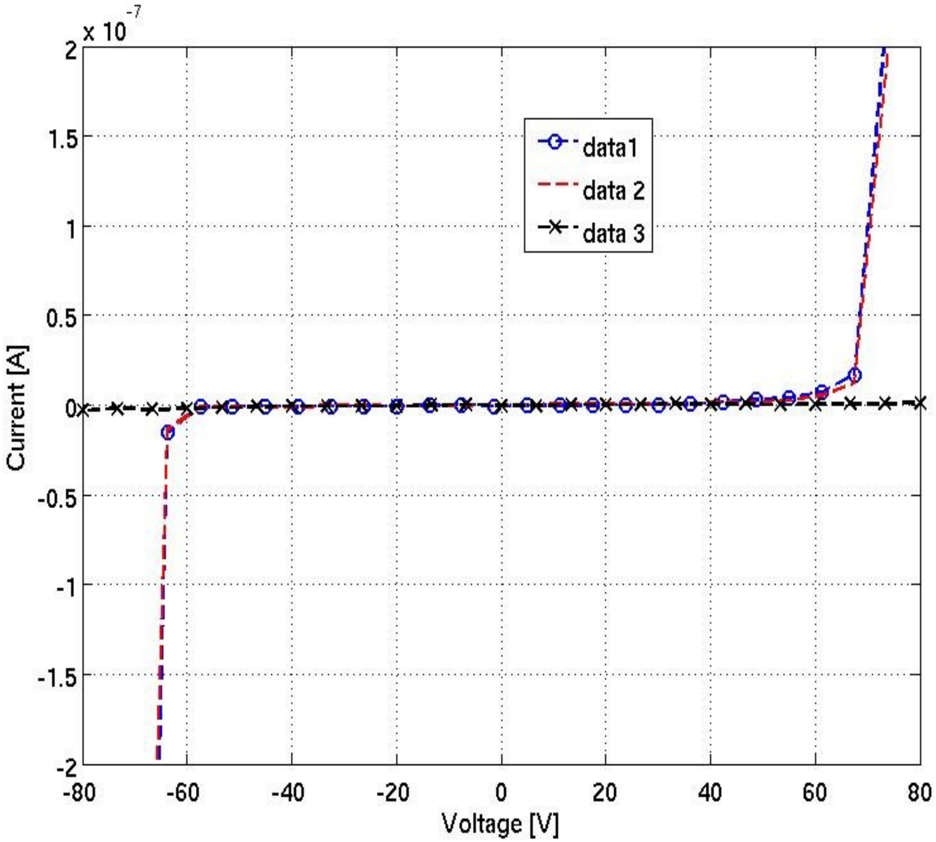


CV of AC-coupled pixel p-MCz detector with Al_2O_3 field insulator. V_{fd} is about 120V

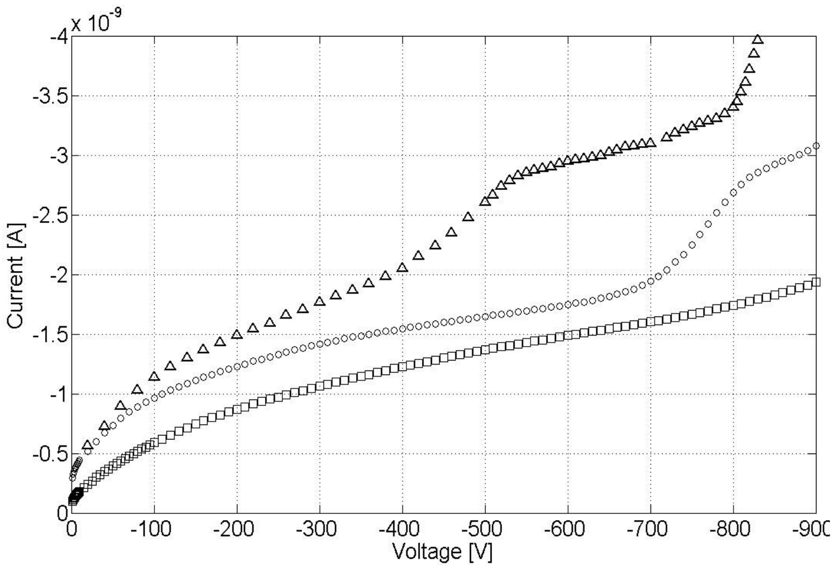
Co60 gamma irradiated Al_2O_3 capacitor. Flat band voltage shift towards to right indicates accumulation of negative oxide charge

AC-coupled pixel sensors IV

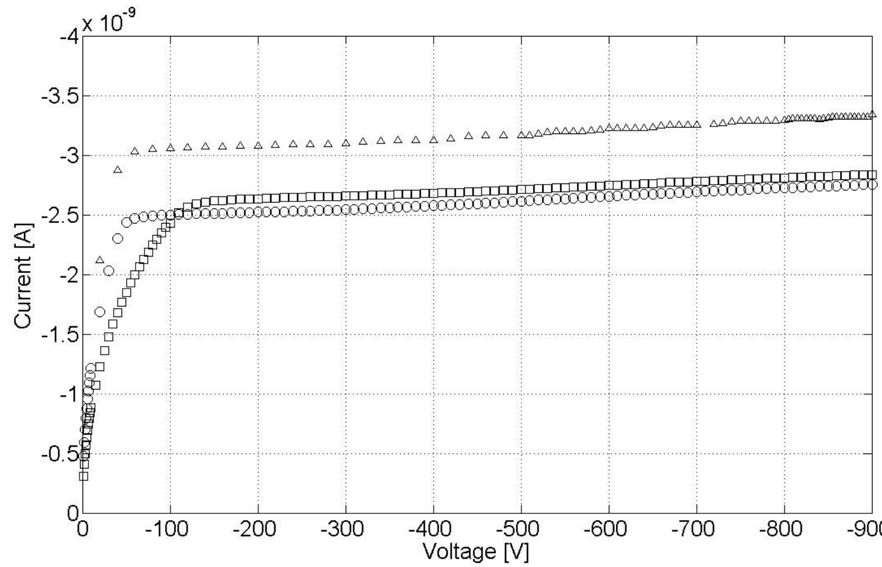
IV curves of capacitors. The test structure has dimensions of W=20μm and L=250μm. The thicknesses of Al_2O_3 insulator is 40nm.



Long term stability of negative oxide charge in Al_2O_3



Guard ring current



Center contact current

IV curves of diodes processed in 2012. Measurements were done in 2015

Comparison of relevant properties for high-κ candidates.

TABLE I. Comparison of relevant properties for high-κ candidates.

Material	Dielectric constant (κ)	Band gap E_G (eV)	ΔE_C (eV) to Si	Crystal structure(s)
SiO_2	3.9	8.9	3.2	Amorphous
Si_3N_4	7	5.1	2	Amorphous
Al_2O_3	9	8.7	2.8[a]	Amorphous
Y_2O_3	15	5.6	2.3[a]	Cubic
La_2O_3	30	4.3	2.3[a]	Hexagonal, cubic
Ta_2O_5	26	4.5	1–1.5	Orthorhombic
TiO_2	80	3.5	1.2	Tetrag.[c] (rutile, anatase)
HfO_2	25	5.7	1.5[a]	Mono.[b], tetrag.[c], cubic
ZrO_2	25	7.8	1.4[a]	Mono.[b], tetrag.[c], cubic

High- gate dielectrics: Current status and materials properties considerations
G. D. Wilk, R. M. Wallace, and J. M. Anthony
Journal of Applied Physics 89, 5243 (2001); doi: 10.1063/1.1361065

Summary

With ALD

- Pinhole free thin films (very important for AC-coupled particle detectors)
- Thin films with very good dielectric strength
- Almost perfect step coverage
- Low temperature process, deposition typically <400^{0}C
- It is possible to adjust type of oxide charge negative ↔ positive
- Negative oxide charge accumulates during the irradiation
- Strip sensors show comparable signal and noise with HPK commercial detectors = good capacitive coupling
- Thin films with very high κ → potentially interesting for AC coupling of pixel sensors.
- n on p detector made by simply one field insulator significantly reduces the complexity and price of sensor processing

- Pixels could be AC coupled via Tungsten nitride thin film resistors >

  = very simple process

  = metal (amorphous material) resistor is very robust against radiation damage (unlike poly-Si

  resistors or punch-through structures)