Phase II planar pixel sensors:
Simulation study of interpixel isolation and surface passivation by a thin-film ALD-layer

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OUTLINE

- **Motivation**
- **Non-irradiated/irradiated 25x100 pixels:**
    - Interpixel resistance, $R_{int}(N_{ps},d_{ps},Q_f)$
    - Charge sharing(N_{ps},Q_f)
  - **p-stop/p-spray isolation vs ALD-layers with negative oxide charge**
    - Breakdown voltage, V_{bd}
- **Summary**

Motivation: Finer granularity pixels for Phase II

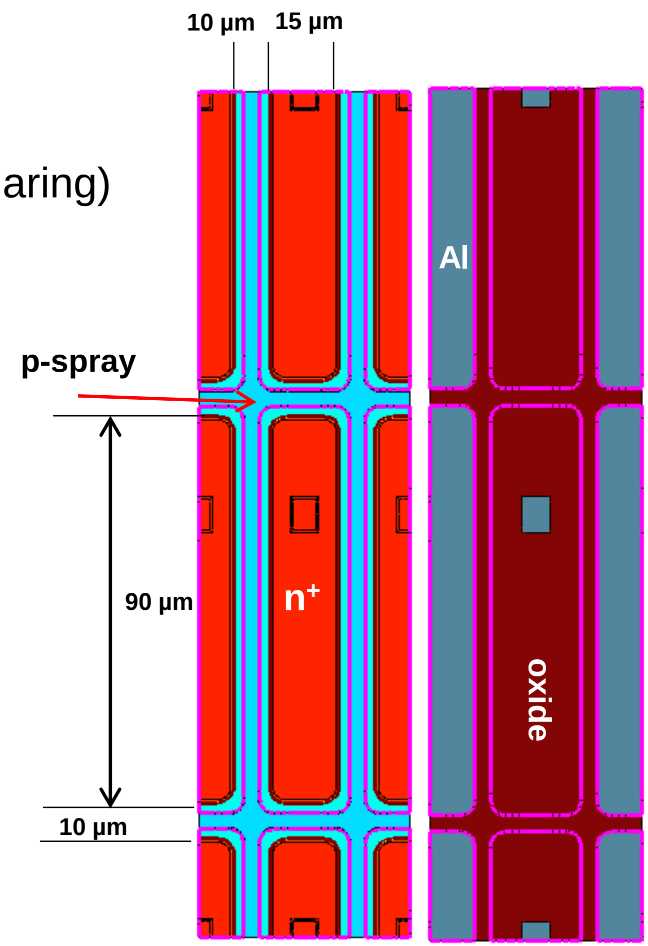
Thin n-on-p Phase II planar pixel sensors:

- Finer granularity increases local electric fields → lower V_{bd}
- More implants → higher capacitances (= noise, lower rise time of signal)

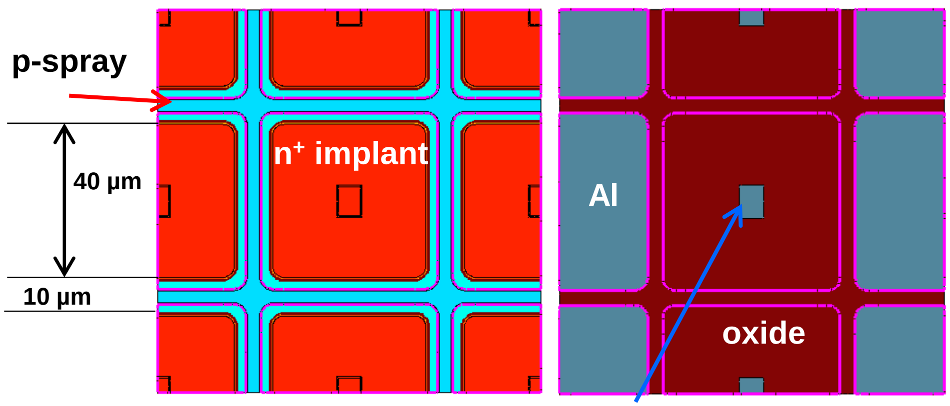
→ **optimize:**

- Isolation doping levels & depths (V_{bd}, charge sharing)
- Mask levels (=price)
- Number of high T processing steps

25x100: Wide design w/ p-spray



50x50: Wide design w/ p-spray



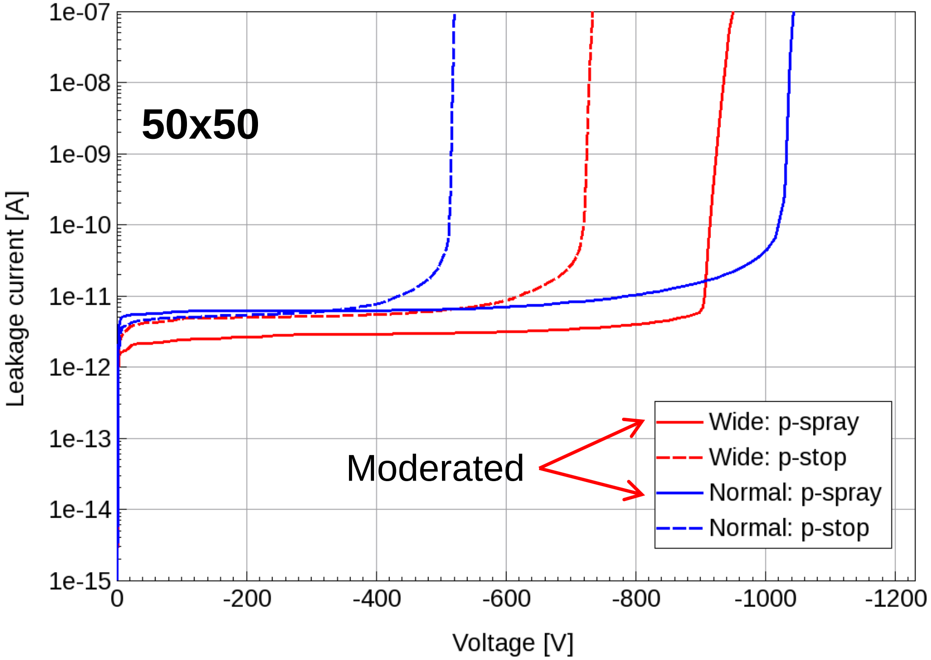
6x8 µm² DC-coupling vias with tapered edges

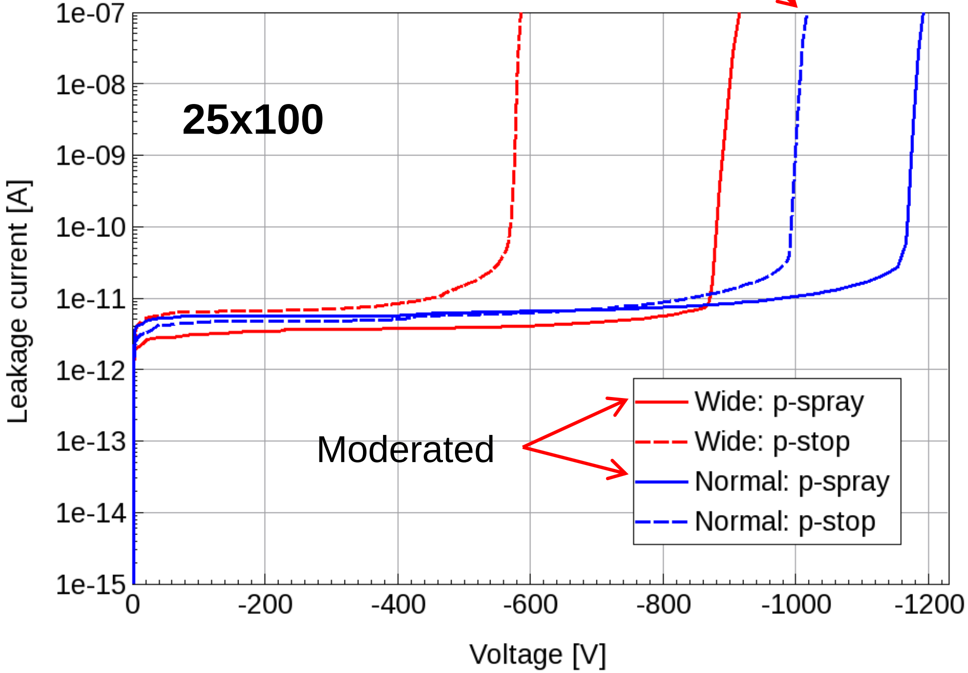
Normal vs Wide design: Breakdown voltages

- **Si/SiO$_2$ interface charge density Q_f = 3e10 cm^{-2}**
- **Tuned e/h lifetimes for p-bulk** (high purity)**:**

τ_e = 1e-2 s, τ_h = 1e-2 s (see back-up for 3D-structure designs [1])

common p-stop





- **50x50:**

V_{bd} ≥ 1 kV: Normal design with p-spray

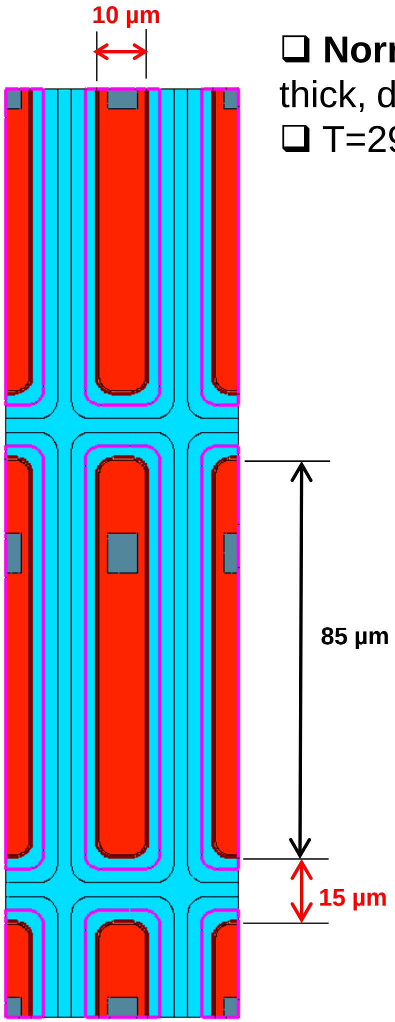
- **25x100:**

V_{bd} ≥ 1 kV: Normal design with both isolations

Further investigation of interpixel isolation & charge sharing

[1] A. Dierlamm, A. Junkes, C. Scharf, D. Schell, Pixel Phase II Sensors, 10.12.2014

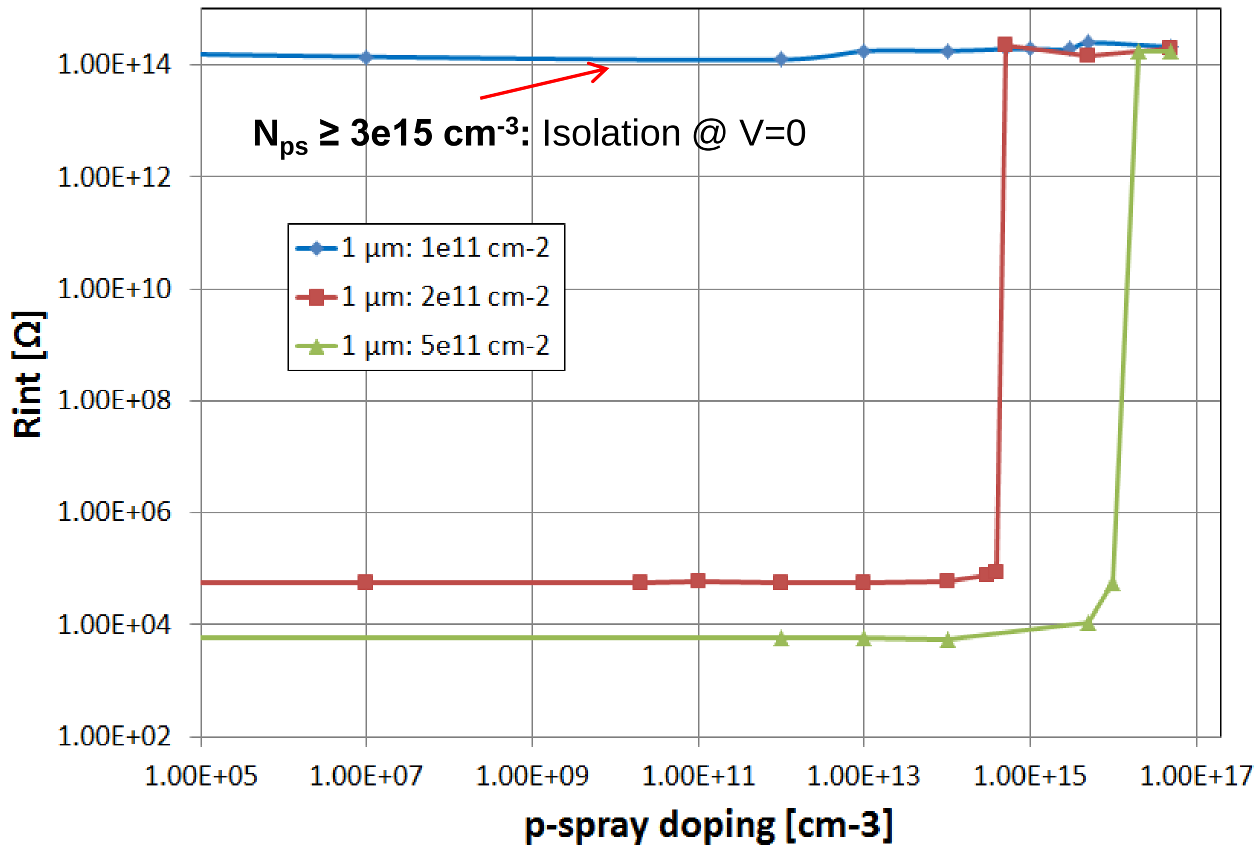
Non-irradiated 25x100 pixel: R_{int}



❑ **Normal 2D-design with (uniform) p-spray:** Interpixel gap = 15 µm, 200 µm thick, d_{ps} = 1.0 µm

❑ T=293 K, **V=-500 V**

P-spray doping (N_{ps}) scan for varied Q_f



Q_f = 1e11 cm^{-2} (expected for non-irr. device): pixels isolated at all values of N_{ps}

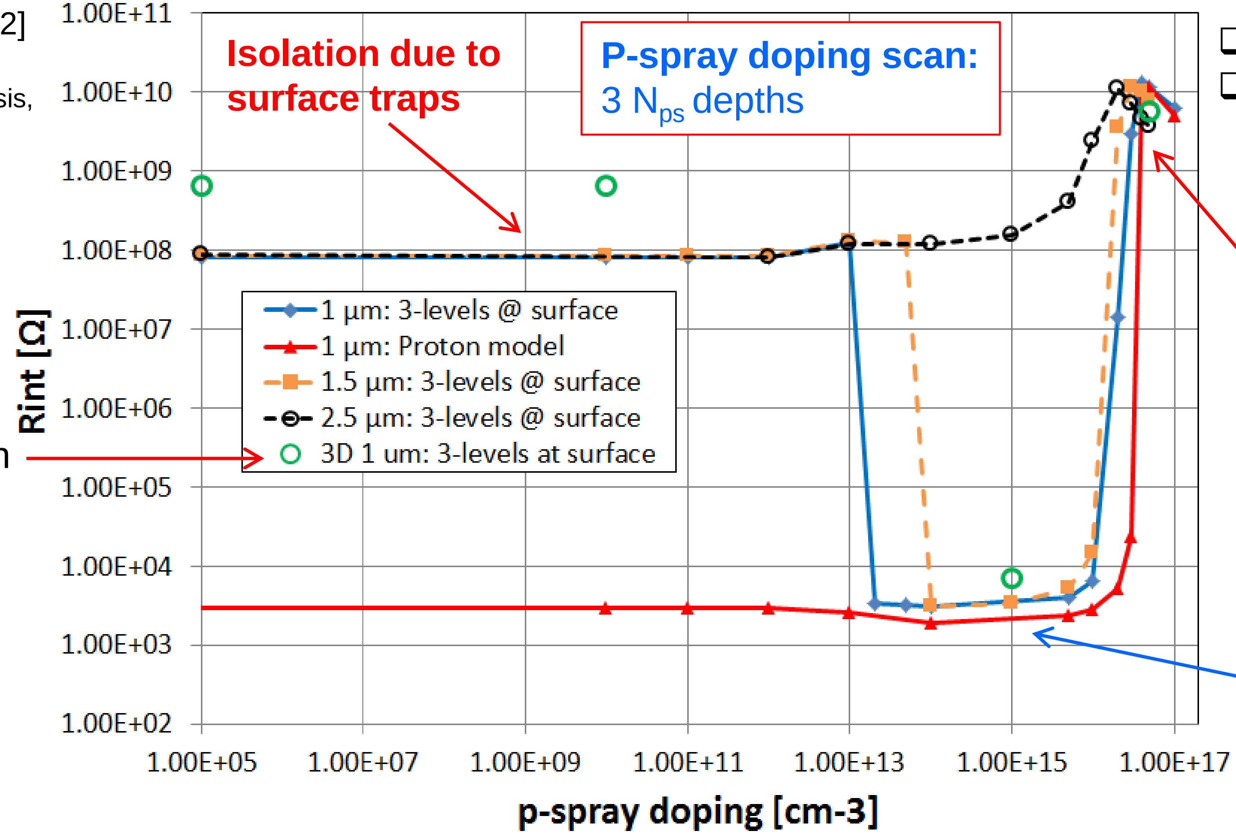
Irradiated 25x100 p-spray pixel: R_{int}

- **Defect models:**
  - Non-uniform 3-level model
  - Proton model [2]

[2] R. Eber, PhD Thesis, KIT, 2013

- **Design:** as on previous slide; T=253 K, **V=-1 kV**
- **$\Phi = 1.4e15\ n_{eq}cm^{-2}$, $Q_f = 1.6e12\ cm^{-2}$**

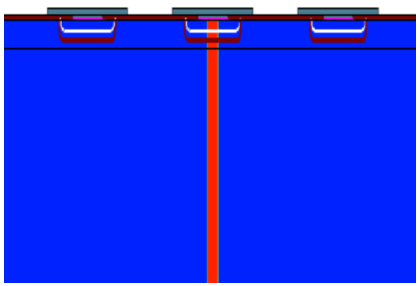
- **n^+ depth = 1.5 µm**
- **$R_{bias} = 1\ \Omega$**

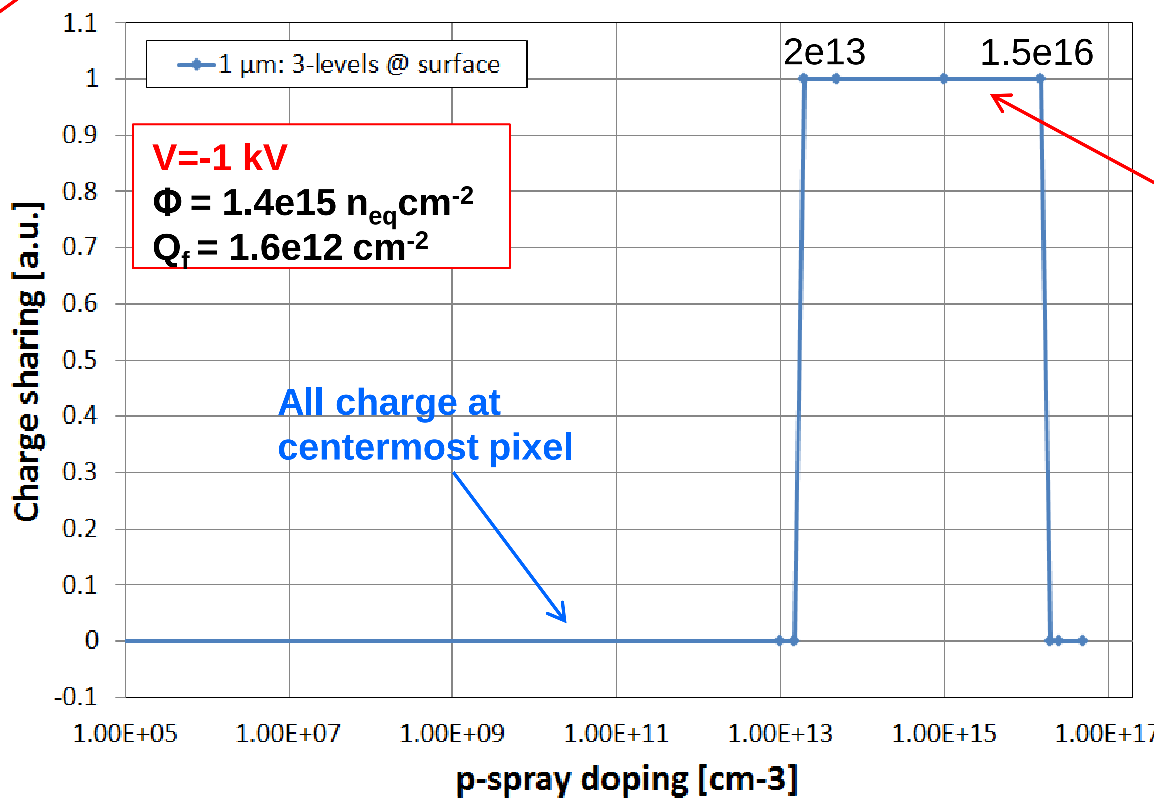


- **3-levels close to surface:**
  - **$d_{ps} \leq 1.5$ µm:** Local R_{int} minimum for 1e13 $cm^{-3} \leq N_{ps} \leq$ 1e16 cm^{-3} → surface traps compensated by p-spray acceptors (role of Q_f?)
  - **d_{ps} = 2.5 µm:** No local R_{int} minimum, breakdown @ N_{ps} = 1e17 cm^{-3} (also for d_{ps} = 1.5 µm)

Irradiated 25x100 p-spray pixel: Charge sharing

- ❑ Charge sharing corresponding to R_{int} plot on previous slide
- ❑ **Charge injection:** middle of centermost pixel



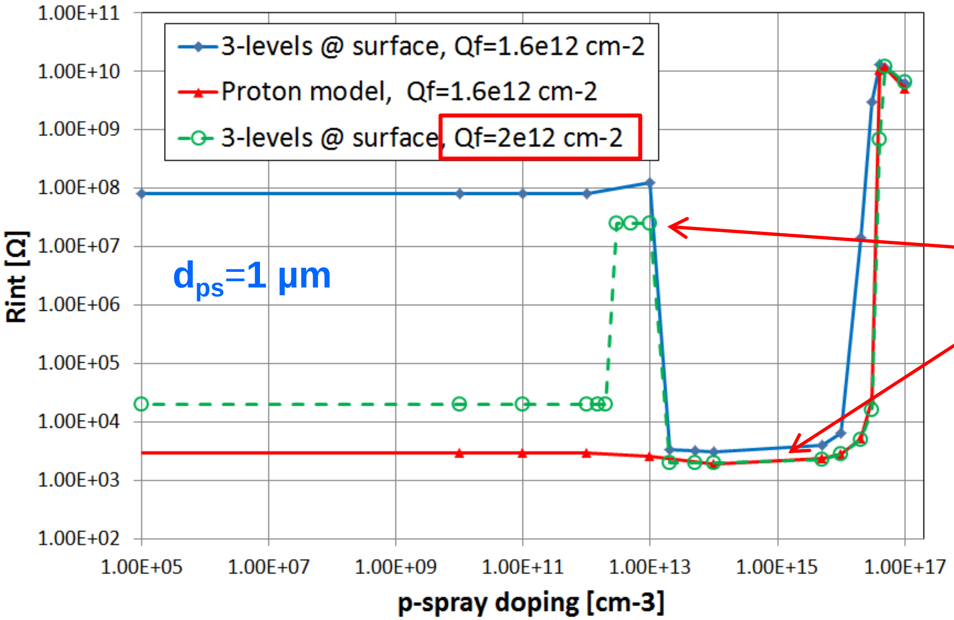


- ❑ R_{bias} = 1 MΩ

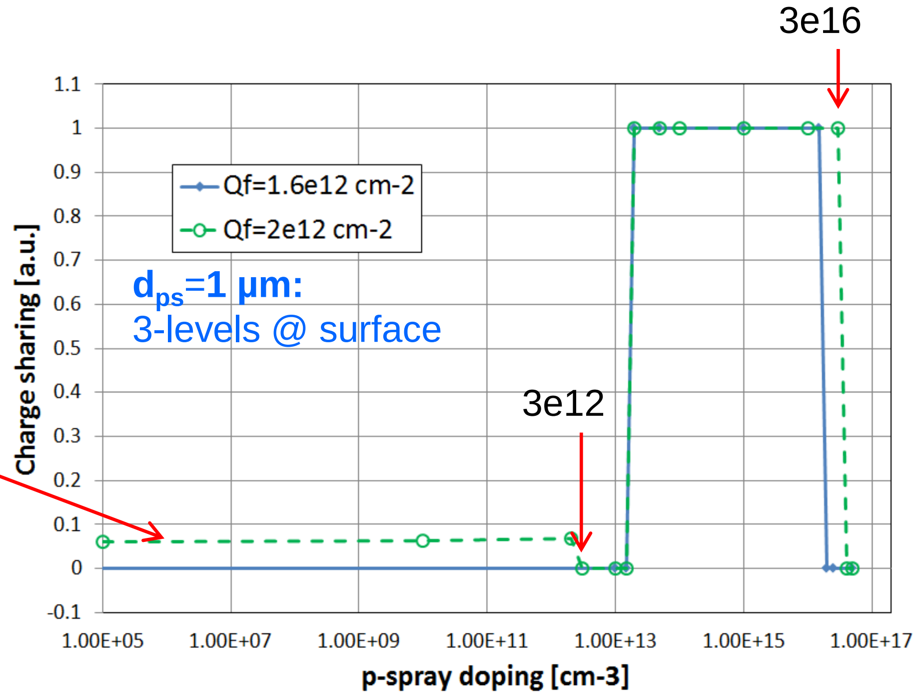
Charge evenly distributed to all electrodes

- ❑ **Charge sharing changes as step-function:** no intermediate values
- ❑ **R_{int} ~ 5 kΩ:** pixels shorted

Irradiated 25x100 p-spray pixel: Very high Q_f



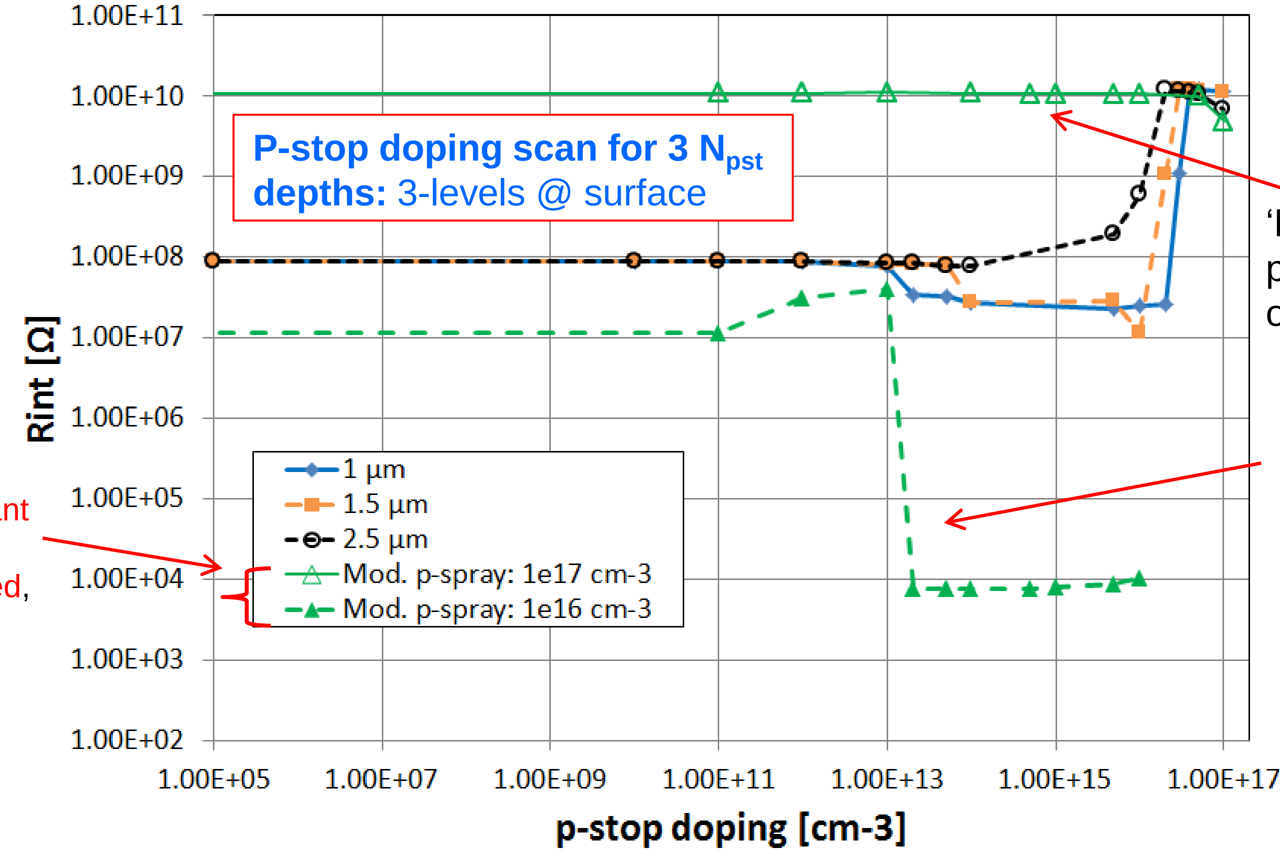
- **V=-1 kV, $\Phi = 1.4e15\ n_{eq}cm^{-2}$**
- **R_{int} @ Q_f = 2e12 cm^{-2}:**
  - Significant local max. & min.
  - No effect on threshold N_{ps} → local R_{int} min. due to interaction of traps & p-spray acceptors



- **Charge sharing @ Q_f = 2e12 cm^{-2}:**
  - 6% charge sharing @ lower values of N_{ps}
  - Charge sharing →0 @ R_{int} local max

Irradiated 25x100 pixel: R_{int} of p-stop & moderated p-spray

- **Normal design with (common) p-stop:** Interpixel gap = 15 µm, p-stop width = 5 µm
- **Φ = 1.4e15 $n_{eq}cm^{-2}$, Q_f = 1.6e12 cm^{-2}** @ T=253 K, **V=-1 kV**



'Elsewhere p-spray' affects only V_{bd}

As in uniform p-spray when N_{center}< 2e16 cm^{-3}

Moderated p-spray:
- Center: peak=2 constant values, d=1.5 µm
- Elsewhere: peak=varied, d=1 µm

- **All d_{pst}:** pixels isolated at all values of N_{pst} → surface traps compensated only at location of p-stop

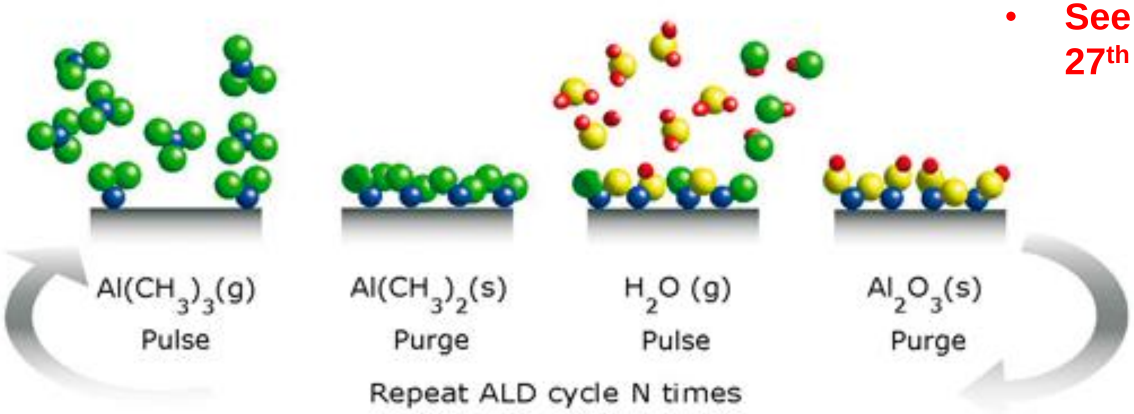
Suitable tool to study depth distribution of N_{it}: P-spray with varying N_{ps} & d_{ps}

Atomic Layer Deposition (ALD)

- Provides potentially interesting material systems: high-ε materials HfO_2, Ta_2O_5 etc.
- Possible to tailor amount & **type of oxide charge** → **negative charge** → **segmentations isolated without implantations**

- Pinhole free deposition → practically stress free
- Applicable on large surfaces
- Low T process, typically ~300° C

- **See also my talk from 27th RD50 Workshop**



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

ALD-passivation layers: Material dependence

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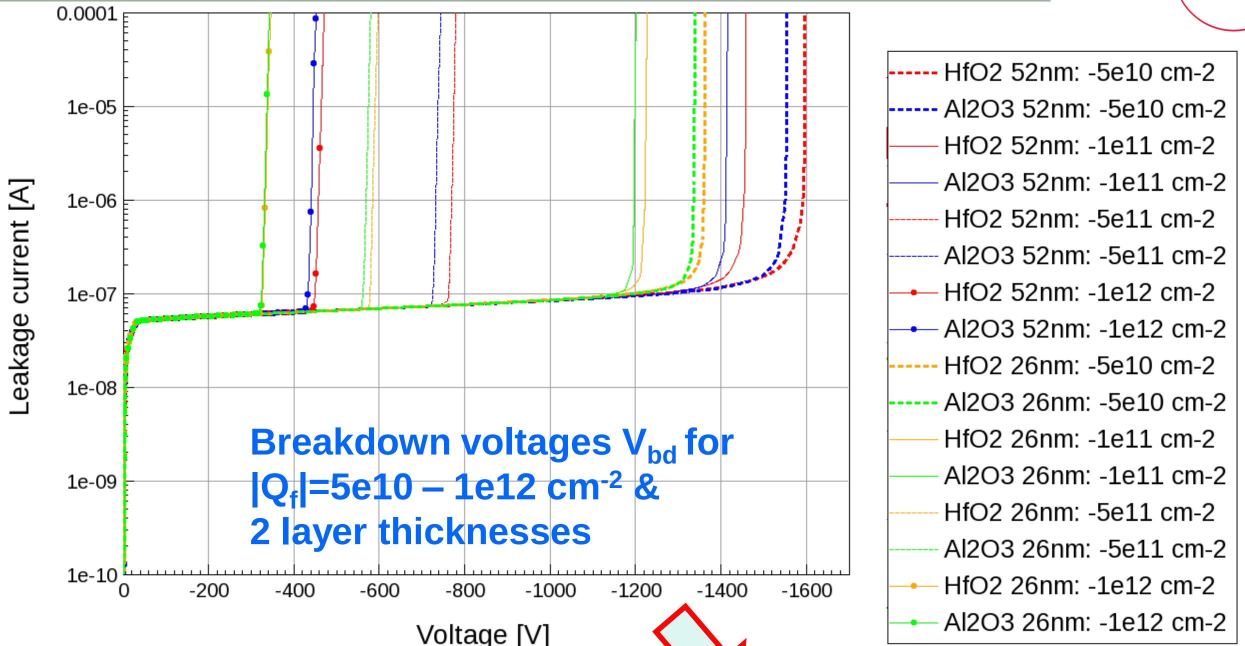
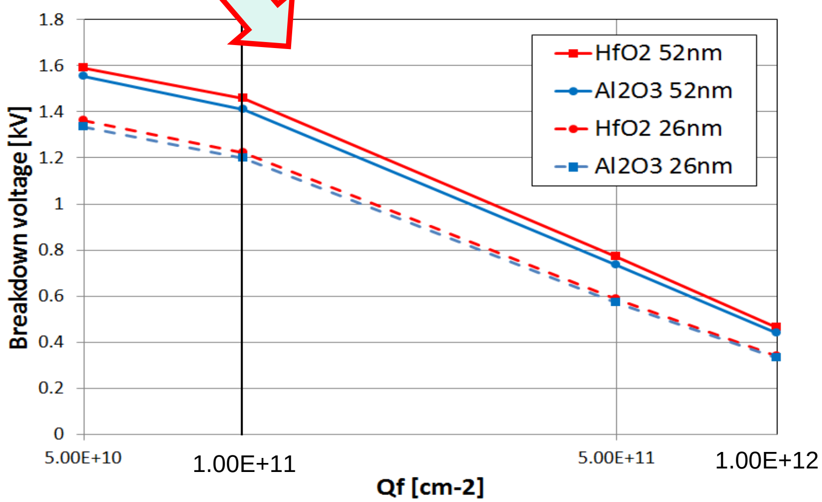
2D test structure for alumina vs hafnia study:

- ❑ 200 μm thick n-on-p (V_{fd}=30 V) 3-strip structure @ T=293 K
- ❑ Pitch=55 μm, implant width=30 μm, MO=3 μm, DC-coupled
- ❑ **ε(HfO_2)=22, ε(Al_2O_3)=9.34**



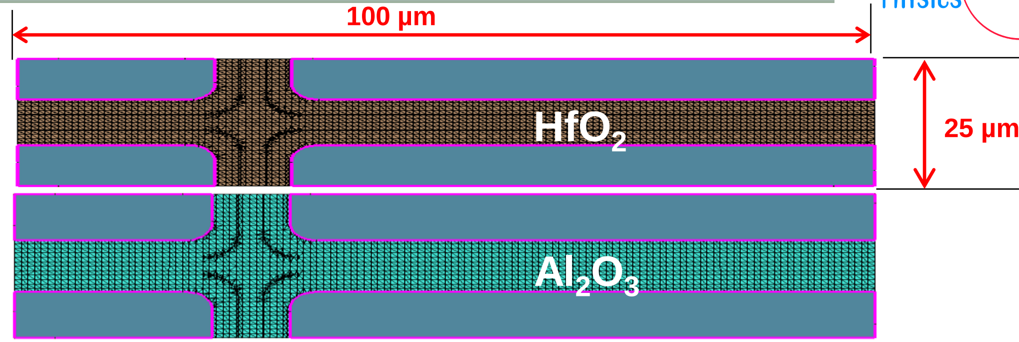
Breakdown voltages V_{bd} for $|Q_f|$=5e10 – 1e12 cm^{-2} & 2 layer thicknesses



- ❑ **Thicker high-ε layer:** more benefit to V_{bd}
- ❑ **Strip isolation:**
  - No effect from material & layer thickness → exclusive dependence on negative interface charge density Q_f
  - R_{int} ≈ 100 MΩ @ V=0, $|Q_f|$=5e10 cm^{-2}

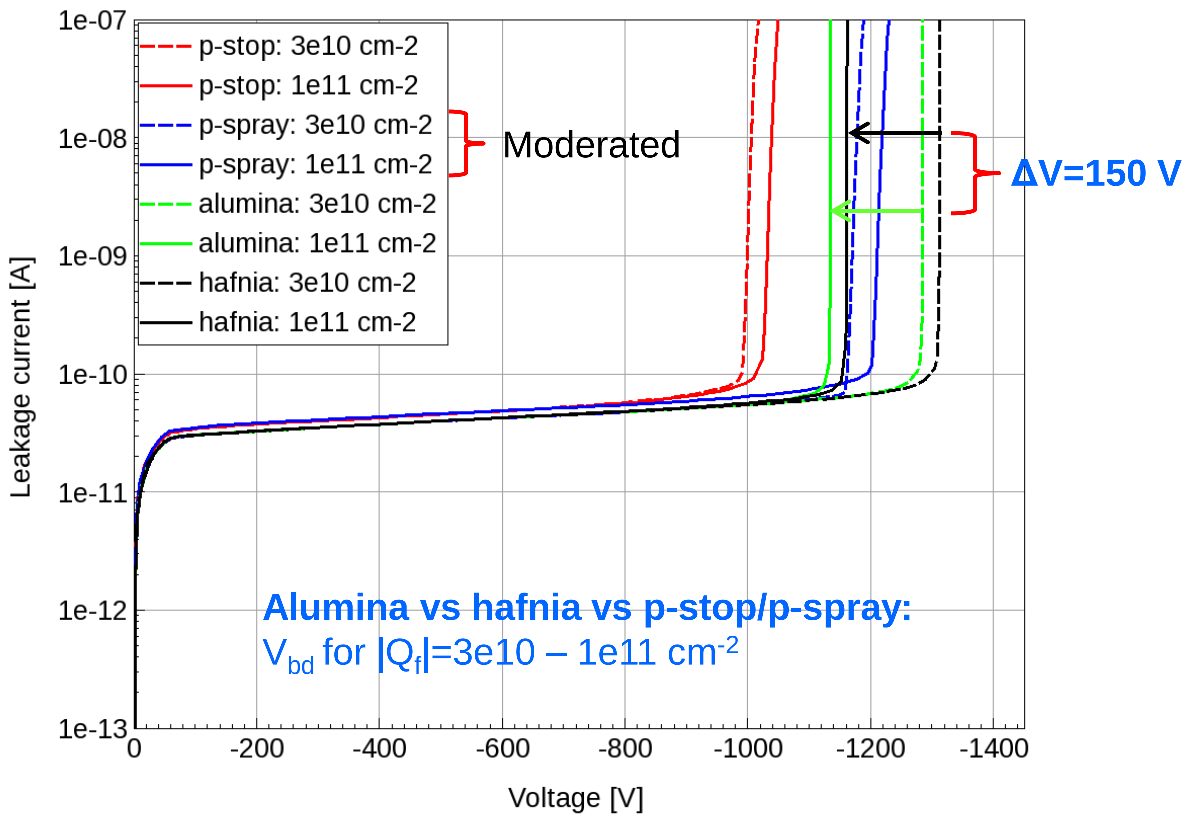
25x100 pixel: ALD-passivation layers

CMS Phase II pixel 3D-structure:
❑ 150 µm thick n-on-p 25x100 (normal design) pixel corner region
❑ 52 nm thick ALD-layers

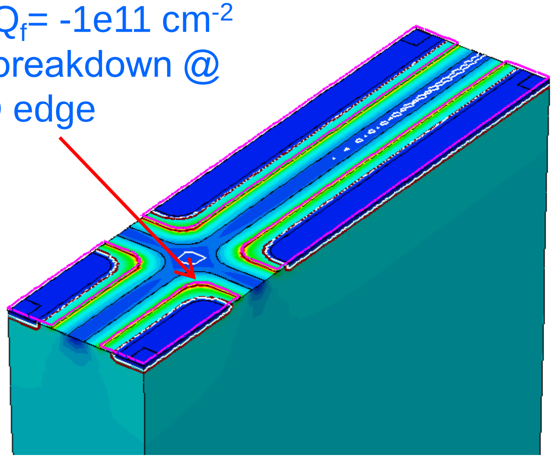


❑ **ALD-layers @ V ≈ -1 kV:**
- No breakdown for expected values of Q_f for non-irradiated device
- ~30 V higher V_{bd} for hafnia @ both values of Q_f

❑ **P-stop: Clear benefit to V_{bd} from both ALD-layers for whole Q_f range**



Alumina: E-fields @ Q_f= -1e11 cm^{-2} → breakdown @ MO edge



Summary

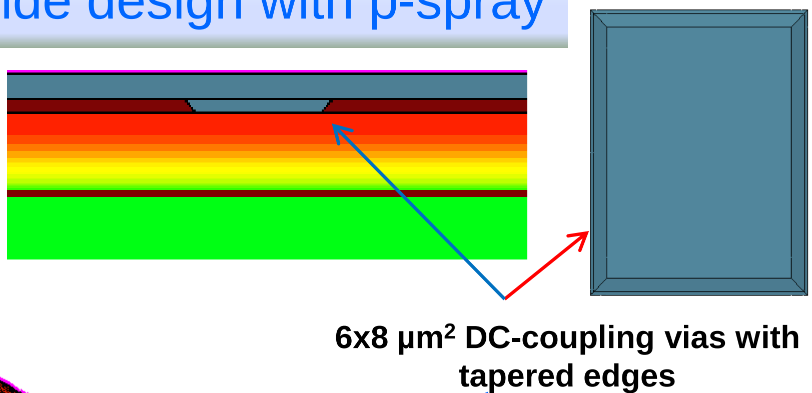
- **25x100 interpixel resistance:**
  - **Low Φ/Non-irradiated @ V=500 V:** pixels isolated without p-stop/p-spray at expected Q_f
  - **Φ=1.4e15 $n_{eq}cm^{-2}$, Q_f = 1.6e12 cm^{-2} @ V=1 kV:**
    - p-stop: pixels isolated at all values of N_{pst} & d_{pst}
    - p-spray: R_{int} has local minimum for N_{ps} when $d_{ps} \leq n^+$ depth

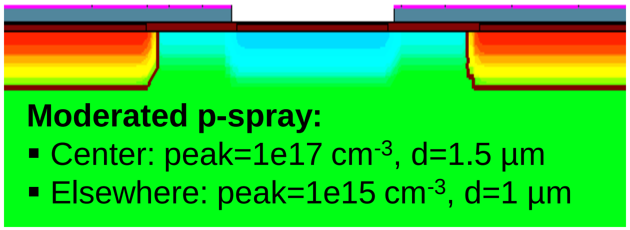
    → Could be used to study depth distribution of N_{it}: p-spray with varying N_{ps} & d_{ps}
    - Moderated p-spray: No local R_{int} minimum when $N_{center} \geq$ 2e16 cm^{-3}

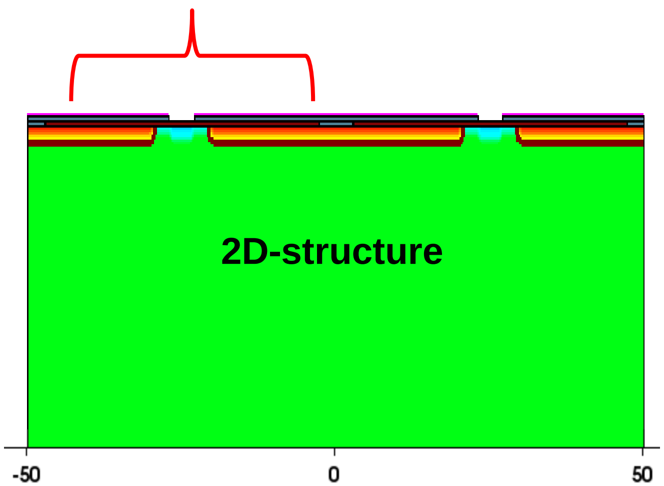
- **ALD-layer passivation:**
  - **Higher V_{bd}: Layer with high-ε (> 20) & increased thickness (> 50 nm)**
  - **25x100 pixels w/ 52 nm ALD-passivation:** No breakdown @ V=1 kV & Q_f=1e11 cm^{-2} → **clear benefit to p-stop & similar performance to moderated p-spray design**

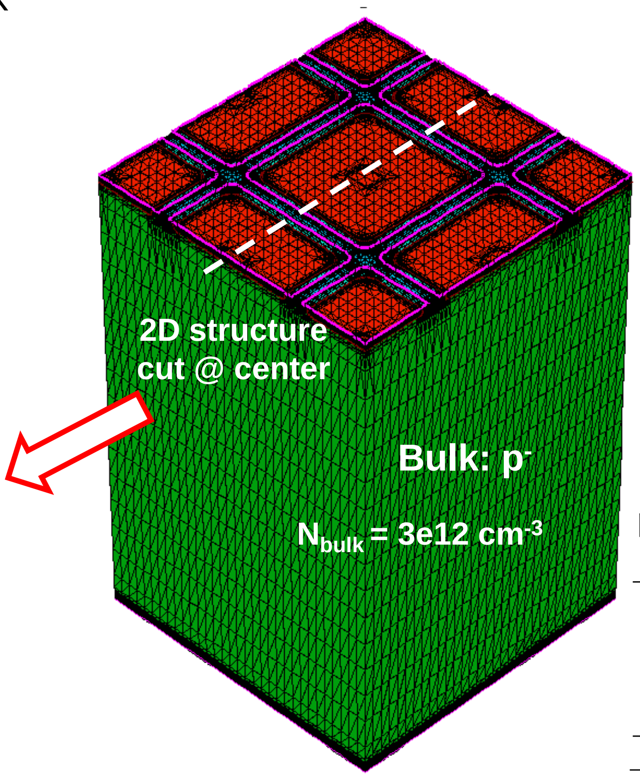
Back-up: 2D vs 3D 50x50 pixel: Wide design with p-spray

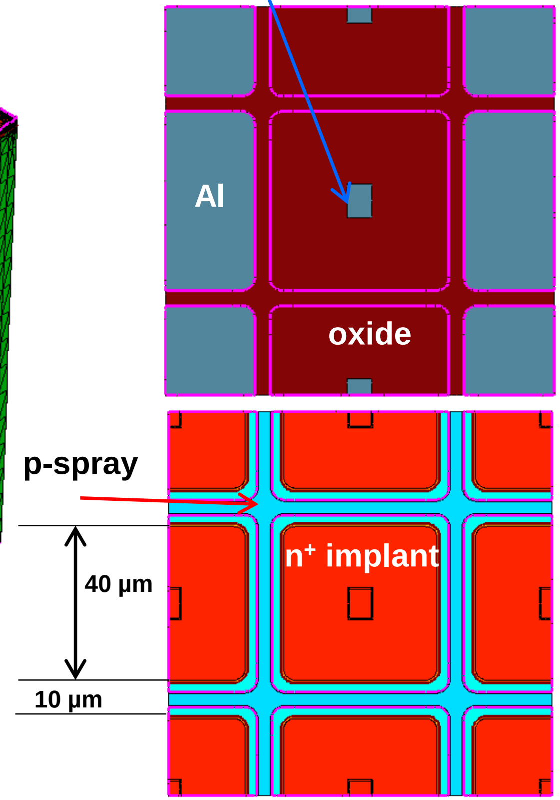
- 150 µm thick 50x50 n-on-p pixel sensor
- MO=3 µm, oxide=250 nm, center p-spray width= 3 µm
- **n^+ implant**: N_n=1e19 cm^{-3}, d=1.5 µm, lateral spread=0.8*depth
- Implant & Al rounded corners: r=3 µm
- **Mesh points:** 3D = 123k, 2D = 40k





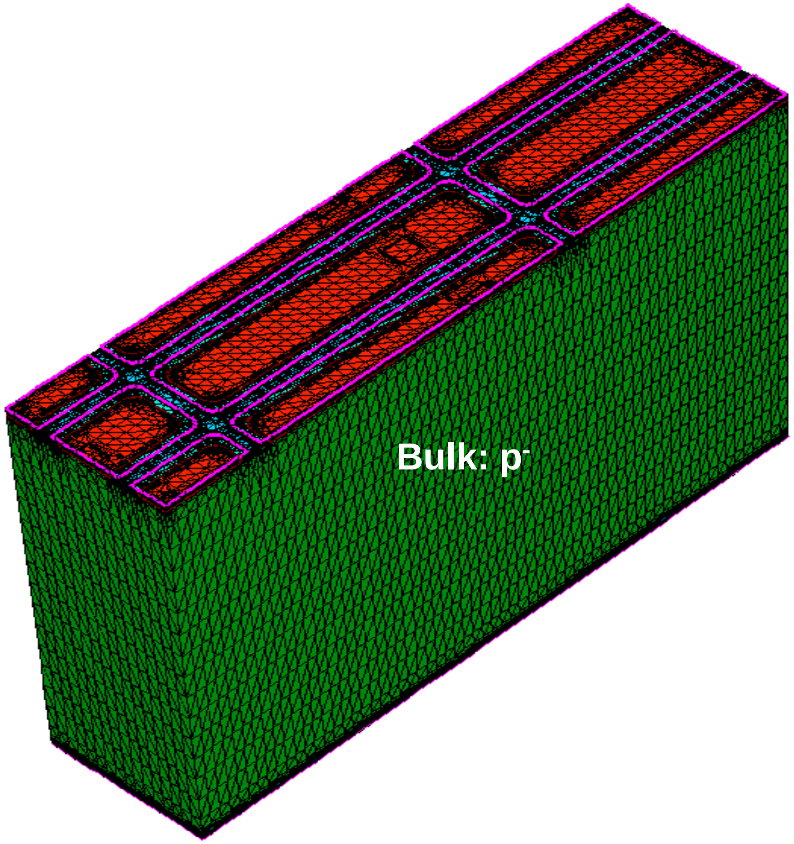


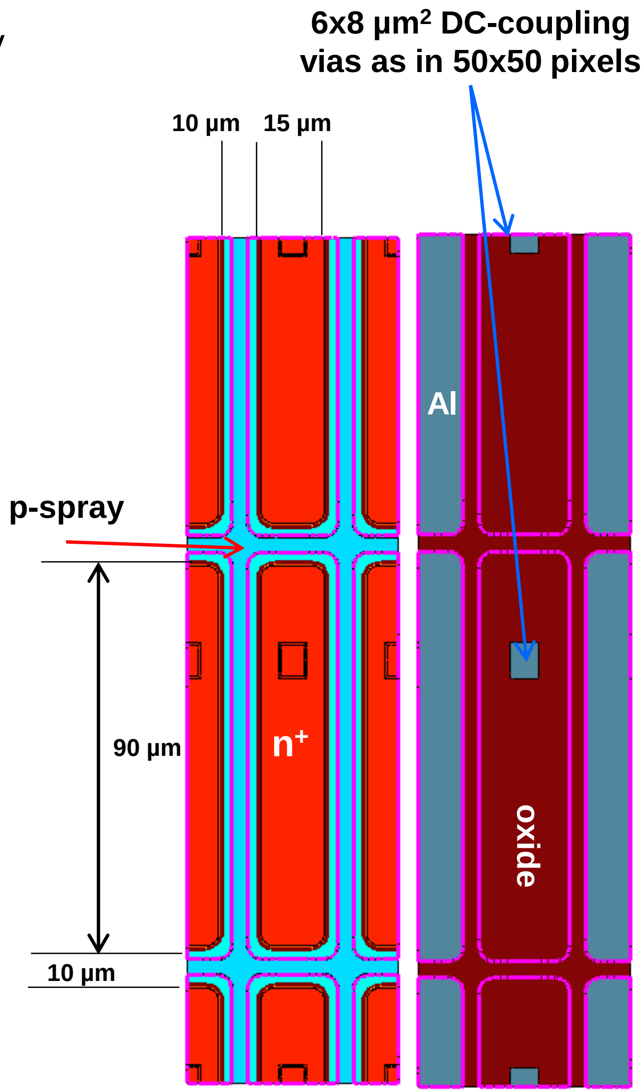




Back-up: 3D 25x100 pixel: structure

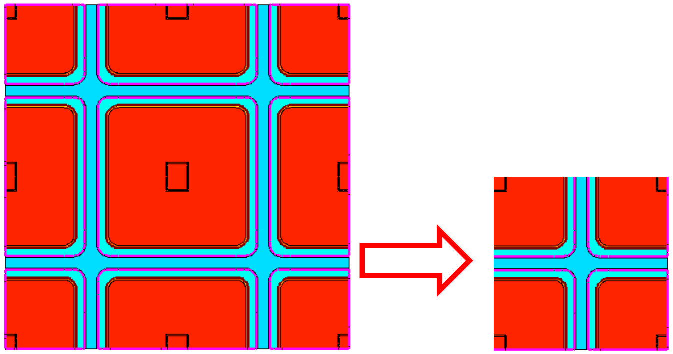
- ❑ 150 µm thick 25x100 n-on-p pixel sensor, wide with p-spray
- ❑ MO, oxide & moderated p-spray as in 50x50 pixels
- ❑ **n^+ implant & rounded corners:** as in 50x50 pixels
- ❑ **Via position:** 90 µm/4=22.5 µm from implant center
- ❑ **Mesh points:** 133k

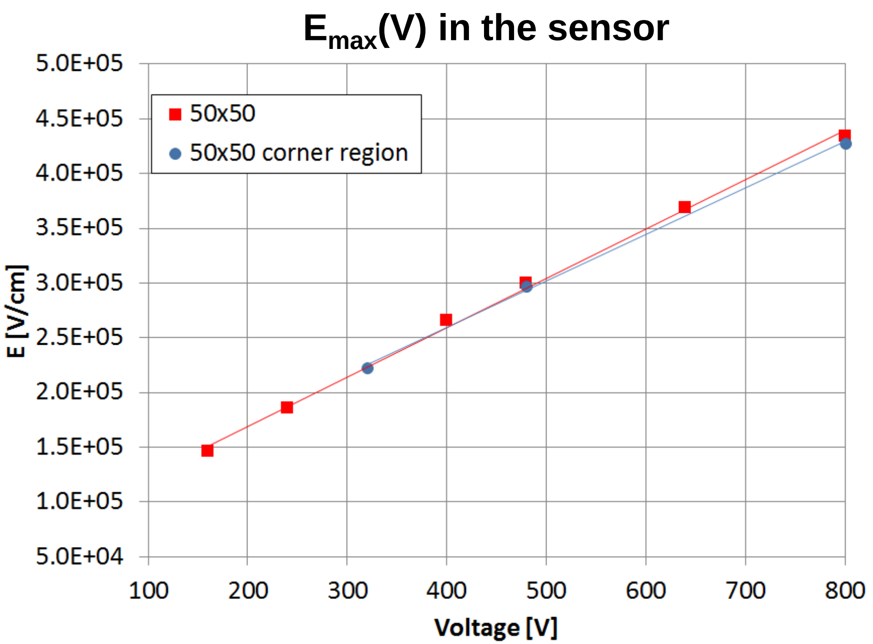


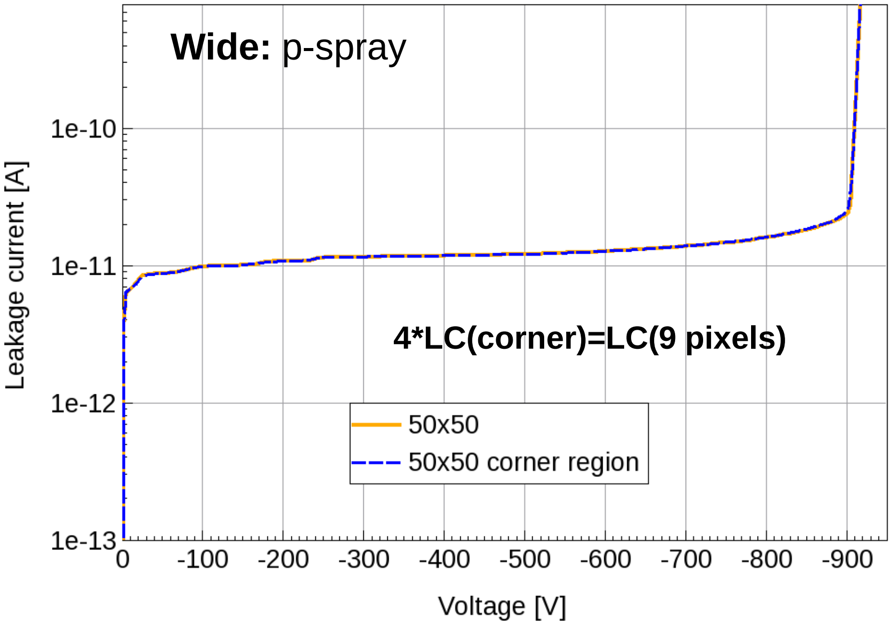


Back-up: 3D 50x50 pixel: corner region cut

- ❑ Corner region chopped from 9 pixel structure for simulation time optimization



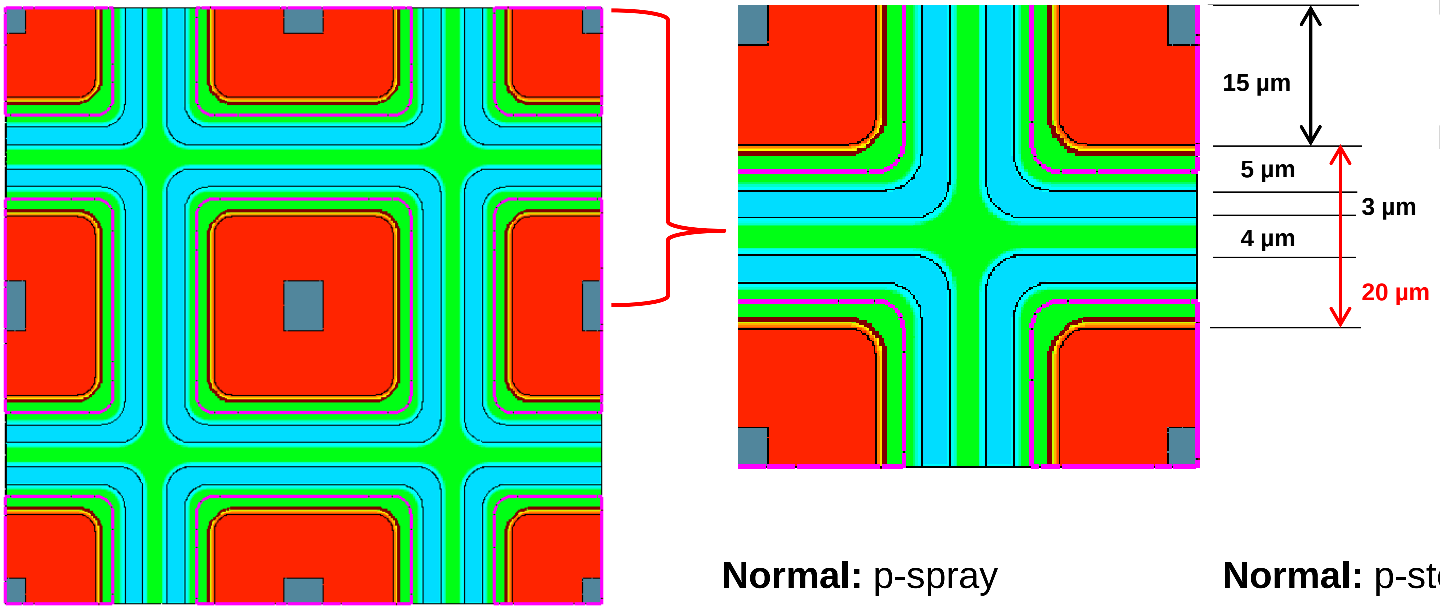




- ❑ Corner region yields identical LC, V_{bd} to 9 pixel structure → sufficient for E-field, V_{bd} simulations

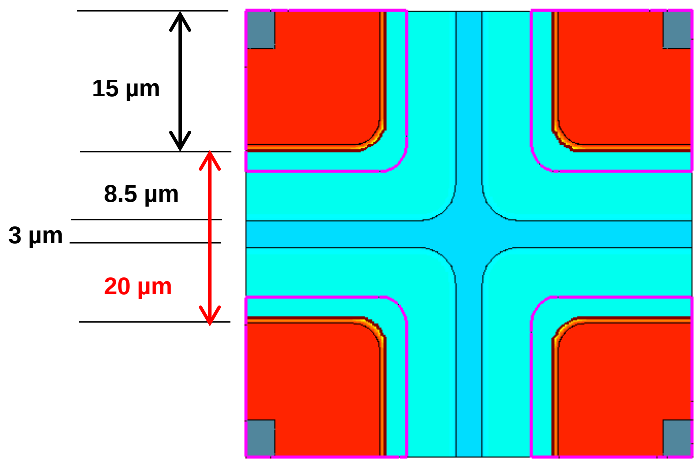
Back-up: 50x50 pixel: corner region cut, Normal vs Wide

Wide: p-stop

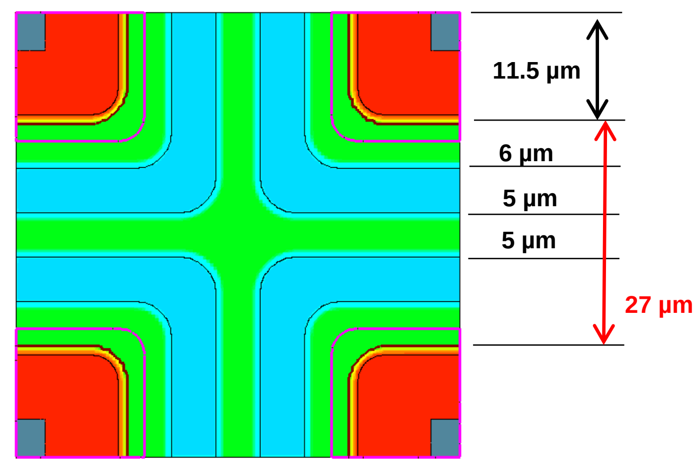


- ❑ **Corner region structures applied for V_{bd} simulations**
- ❑ **N_{pstop} = 5e16 cm^{-3}**

Normal: p-spray



Normal: p-stop



Back-up: 25x100 pixel: corner region cut, Normal vs Wide

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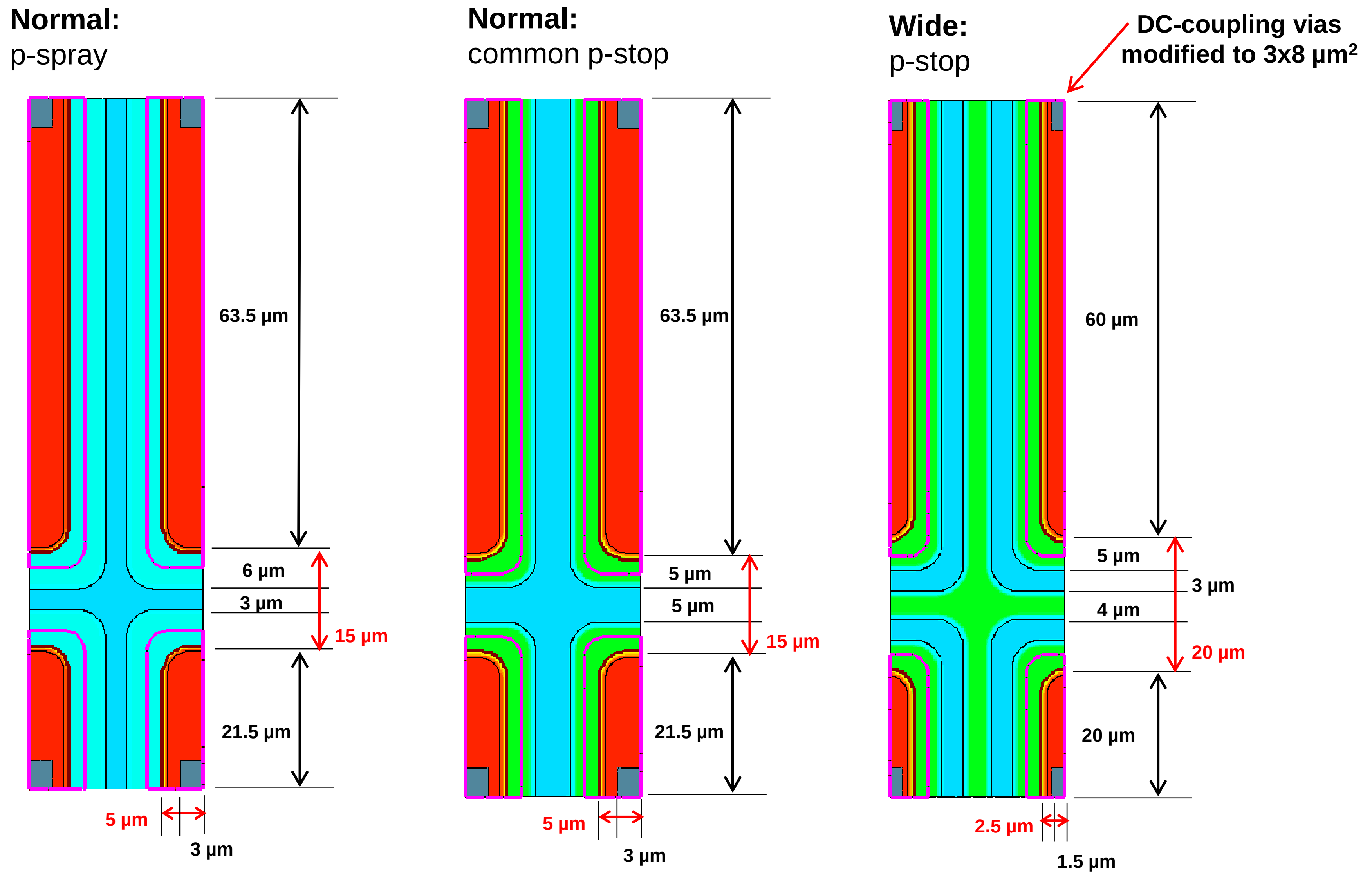
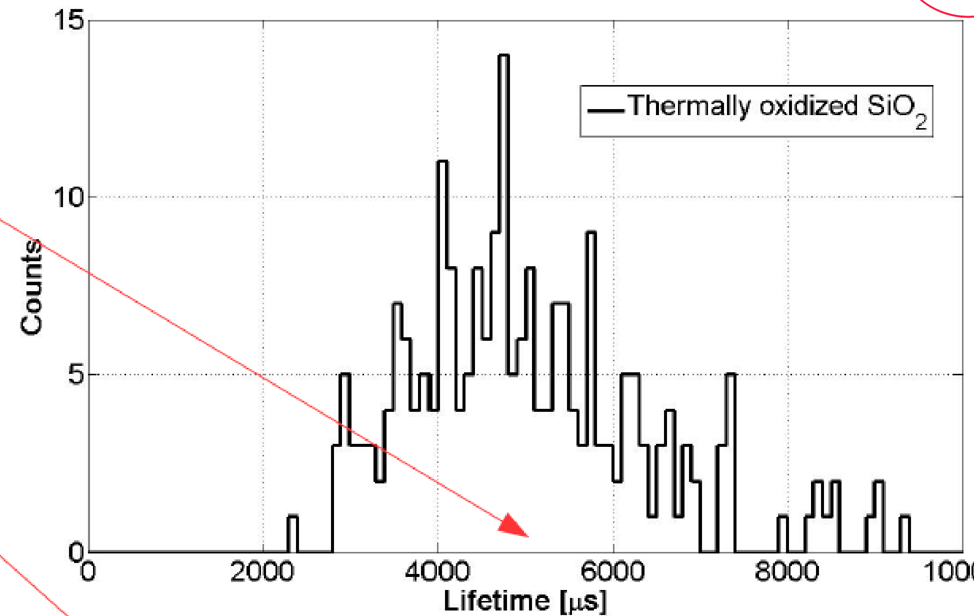
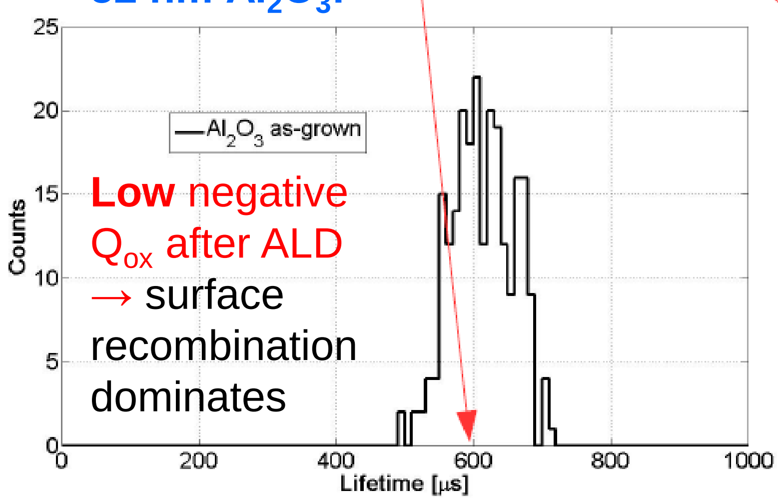


Back-up: ALD grown Al_2O_3: Electrical passivation

- Studied by µPCD method
- Thermally dry oxidized wafer with very high bulk lifetime
- Assumption: SiO_2 passivation reduces $S_r \rightarrow 0$
- ALD deposition of Al_2O_3
- Subsequent annealing at 370^{0}C / 30min

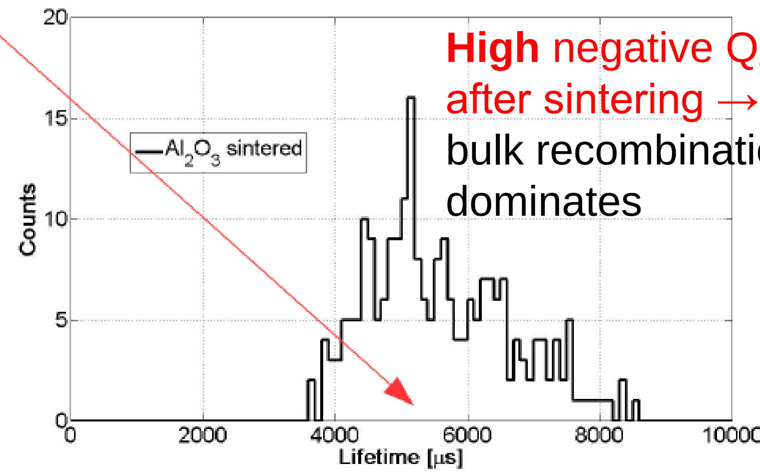


52 nm Al_2O_3:



Low negative Q_{ox} after ALD → surface recombination dominates

[1]



High negative Q_{ox} after sintering → bulk recombination dominates