Charge losses at the Si-Si0$_2$ interface in silicon strip sensors

Thomas Pöhlsen, Eckhart Fretwurst, Robert Klanner,
Jörn Schwandt, Jiaguo Zhang

University of Hamburg

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Overview

Motivation – why surface studies?

Investigated sensor & measurement procedure

Weighting potential

Observed charge losses after voltage ramping

TCAD simulations explaining the charge losses

Summary & Conclusions

Motivation – why surface studies?

High bias voltage needed:

- To overcome signal reduction due to **charge losses** in radiation induced bulk defects (e.g. HL-LHC)
- To overcome an increase of **charge collection time** due to plasma effects (high electron hole densities) (e.g. at the European X-FEL)

Sensor stability:

- In dry atmosphere **long-time run-aways** (increase of dark current) are a well known problem.
- **Early breakdowns** (especially in dry atmosphere and if no metal overhang used) limit the bias voltage.

Humidity influences the sensor performance:

- After changing the bias voltage eventually a steady-state is reached.
- Time constants are a strong function of humidity, in dry atmosphere: order of days.

Motivation – why surface studies?

Surface damage (at the European X-FEL up to 1 GGy, also present at LHC / HL-LHC …)

⇒ Interface states & fixed oxide charges
  ⇒ Electron accumulation layer
  ⇒ High electric fields at the interface, **impact on break down voltage**
  ⇒ Charge losses at the interface

Simulations

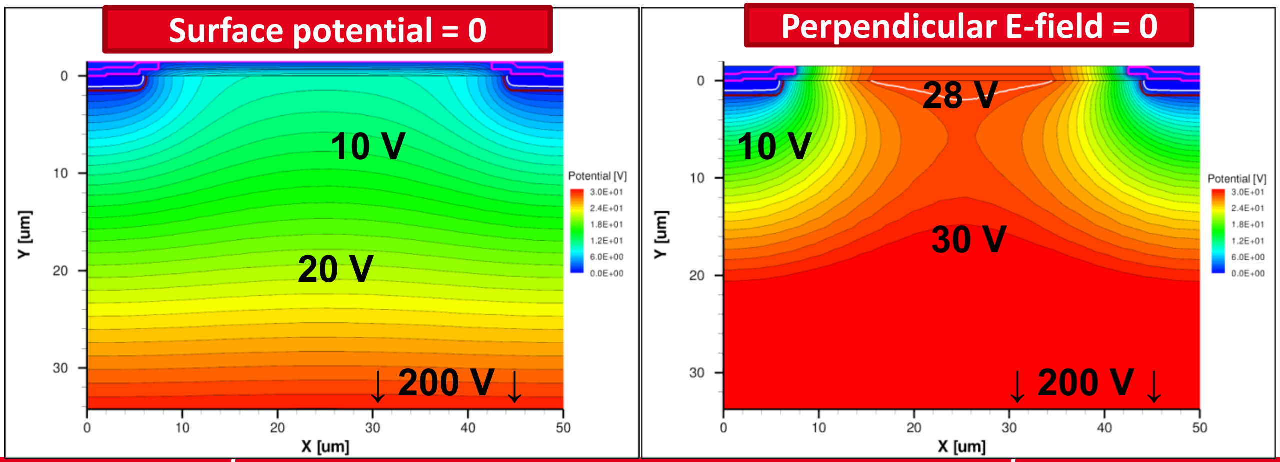
may be used to optimise the sensor design and predict the sensor performance (charge collection, break-down voltages, capacitances, …)

⇒ **Boundary conditions?**

Different results for
- Dirichlet (left)
- and Neumann (right)

boundary conditions

Simulated electrostatic potential

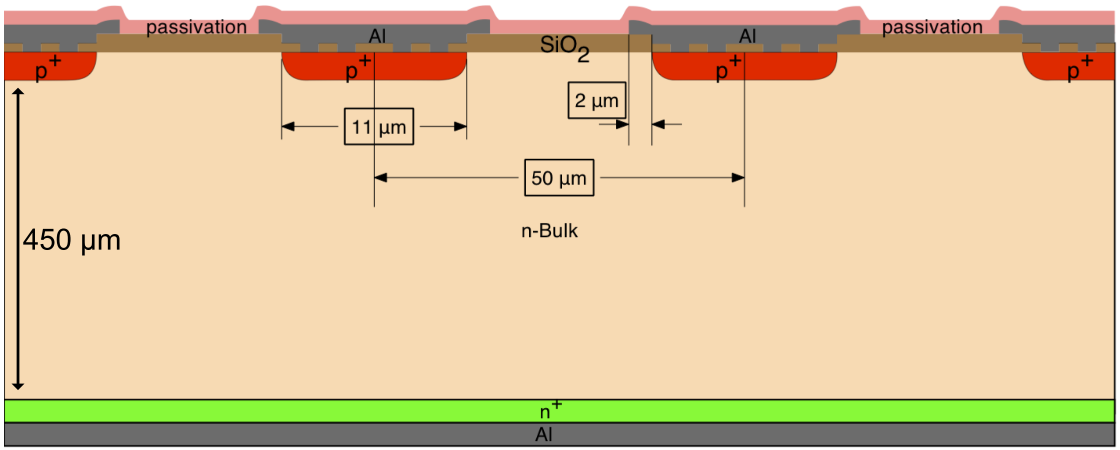


Surface potential = 0

Perpendicular E-field = 0

Investigated strip sensor

DC coupled strip sensor (Hamamatsu Photonics)



Effects in pixel sensors similar?

- Here: strip sensor with 39 µm = 78 % gap
- Pixels: usually less gaps, but gaps still present, especially relevant for break-down voltage

Irradiation:

a) 0 Gy

b) 1 MGy 12 keV x-rays → surface damage only (300 keV needed for bulk damage)

Atmosphere during measurement:

- Humid (> 60% humidity)
- Dry (< 5% humidity)

T ≈ 24 °C (room temperature)

Operation voltage:

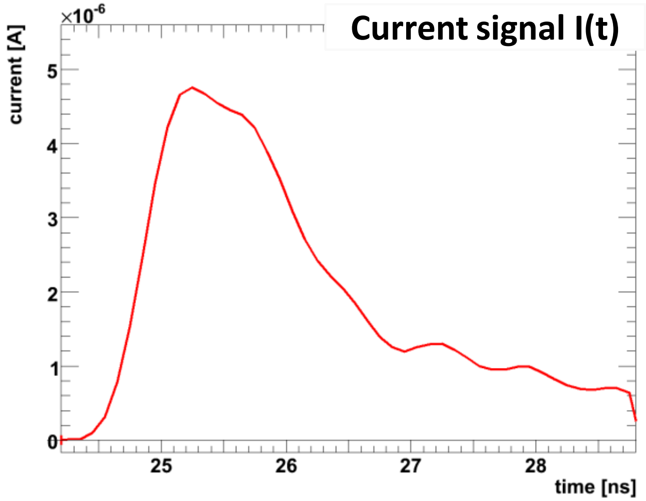
- All shown measurements at 200 V
- Full depletion voltage ~155 V

Measurement procedure (red laser TCT)

Red laser light (illumination at strip side, λ = 660 nm, penetration depth ~ 3 µm)

Sub ns-pulses (FWHM 100 ps, 1 kHz, ~ 100 000 eh-pairs)

Focus: σ = 3 µm (+ tails)



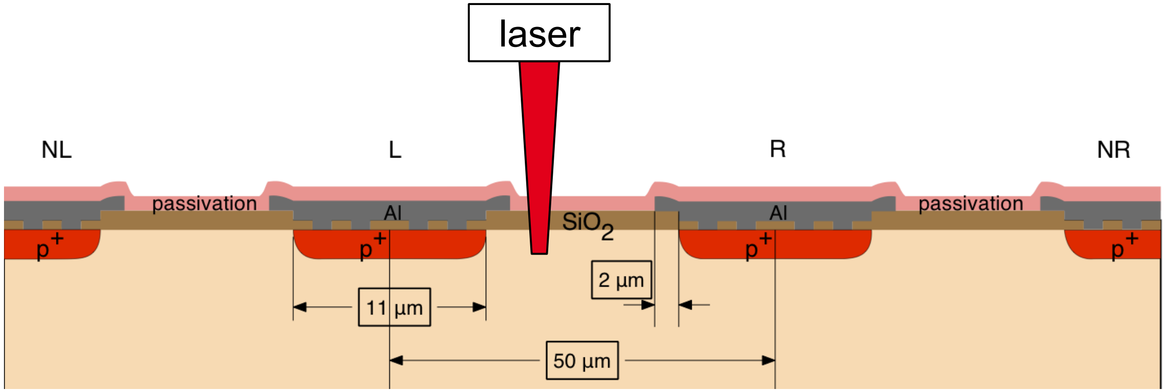
Readout: 2 strips + 1 rear contact

- Femto HSA-X-2-40 current amplifiers
- Tektronix oscilloscope, 2.5 GHz bandwidth

Neighbour strips on ground (via 50 Ω)

Charge Q calculated offline:

$Q = \int I(t)\, dt$

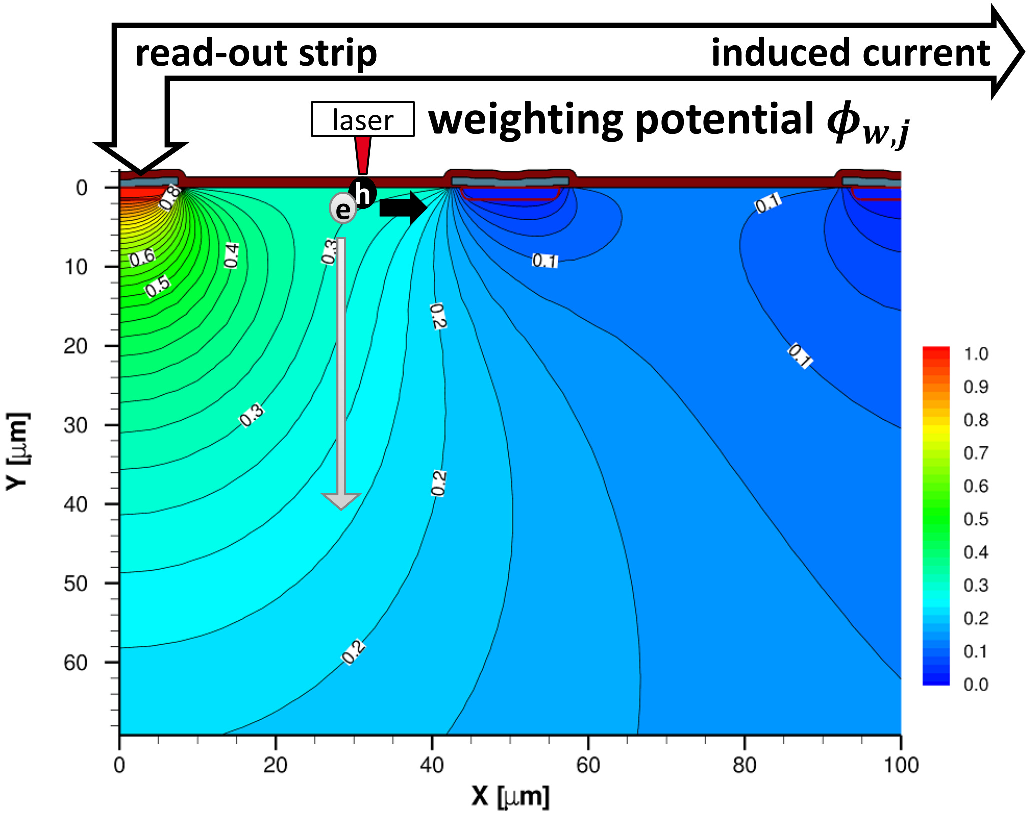


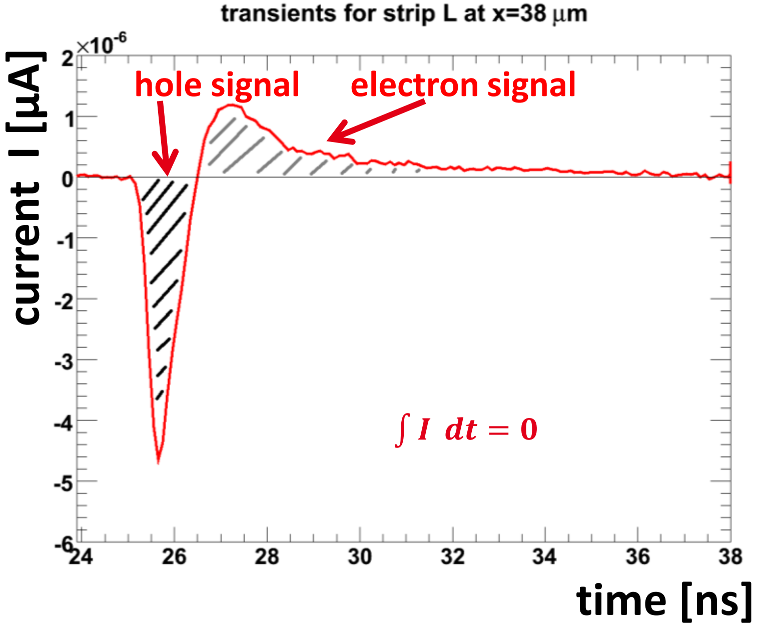
Weighting potential and induced signals

Charge carriers (q)

- Drift in the electric field: $\vec{v}_{dr} = \mu\vec{E}$,
- Induced current: $I_j = q\, \vec{E}_{w,j} \cdot \vec{v}_{dr}$, $\vec{E}_{w,j} = \vec{\nabla}\phi_{w,j}$

Collected charge: $Q_j = \int I_j \, dt$





- Case 1

$\Rightarrow$ Electron and hole collection

(0 Gy, humid)

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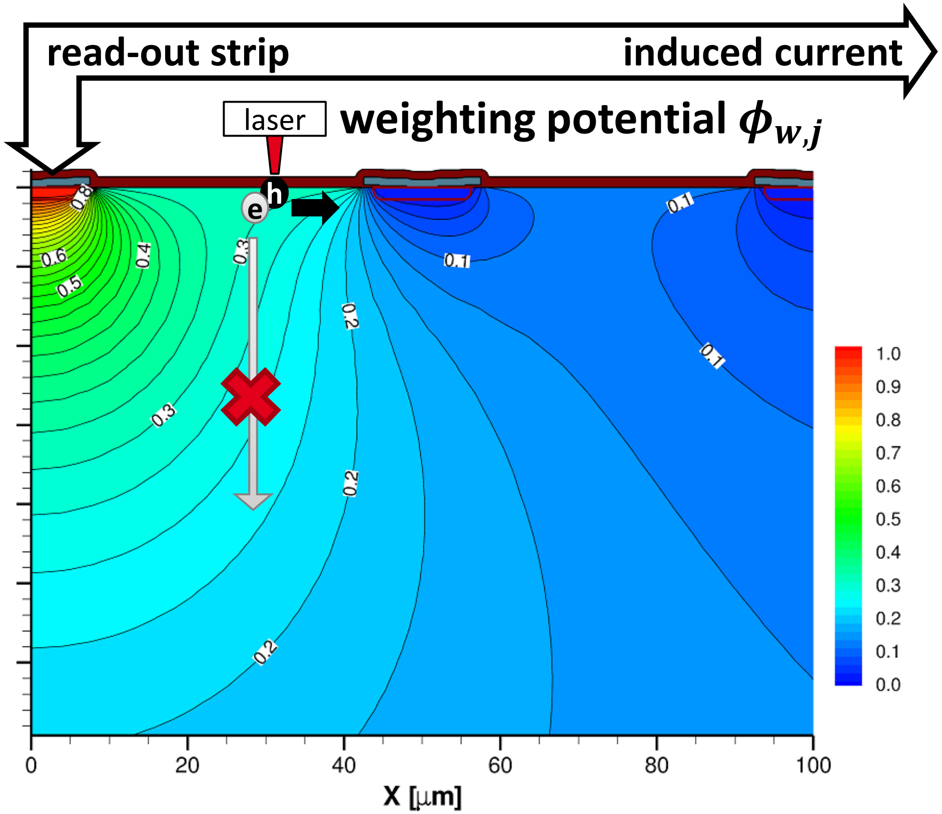
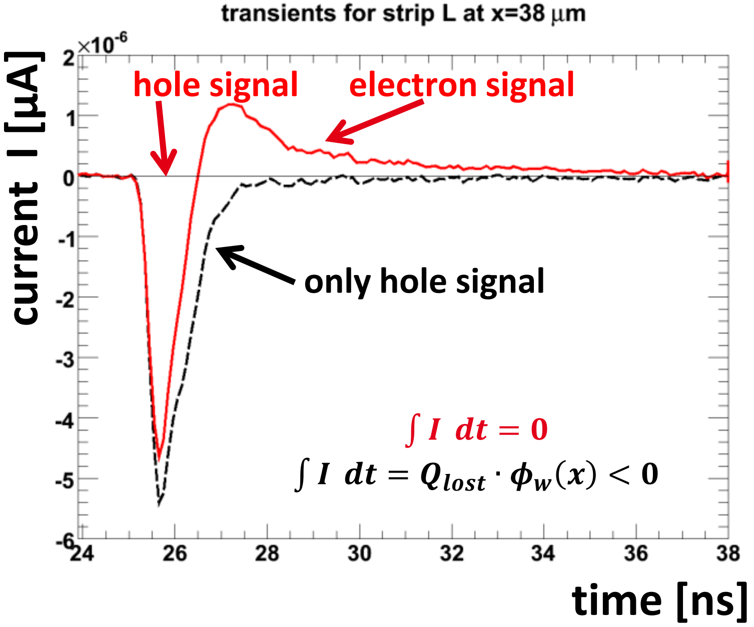


read-out strip

induced current

weighting potential $\phi_{w,j}$



$\int I \, dt = 0$

$\int I \, dt = Q_{lost} \cdot \phi_w(x) < 0$

- Case 1

$\Rightarrow$ Electron and hole collection

(0 Gy, humid)

- Case 2

$\Rightarrow$ Only hole collection

(~100% **electron losses**!)

(1 MGy, dried@0V)

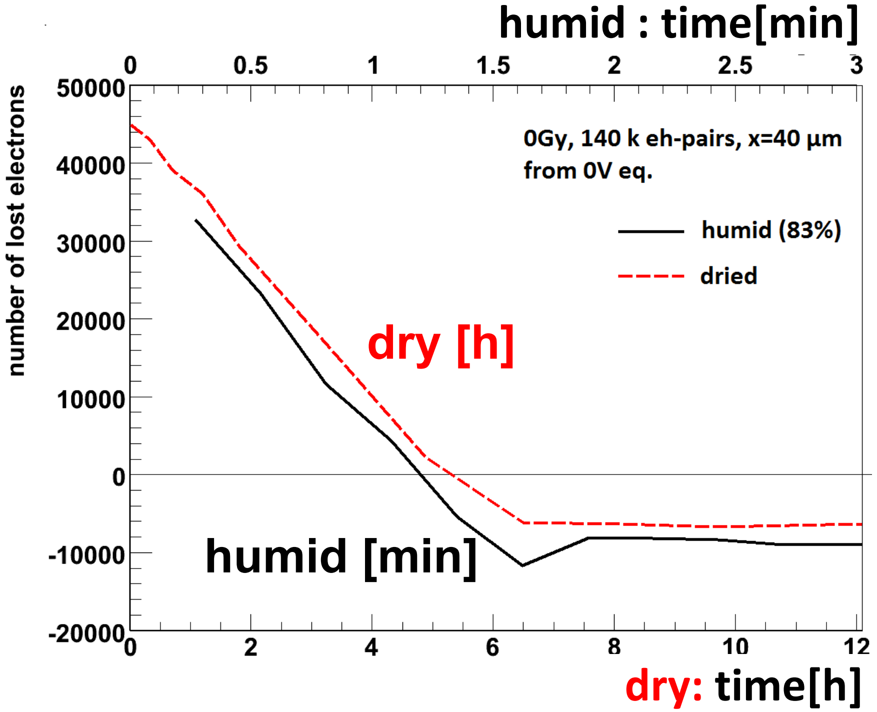
Time development of charge losses, 0 Gy

$$\int I\ dt = Q_{lost} \cdot \phi_w(x)$$

$$\Rightarrow Q_{lost} = \frac{\int I\ dt}{\phi_w(x)}$$

Here: $Q_{lost} < 0 \;\Rightarrow$ electron losses dominate

$$\#e_{lost} := \#h - \#e = \frac{Q_{lost}}{q_0}$$



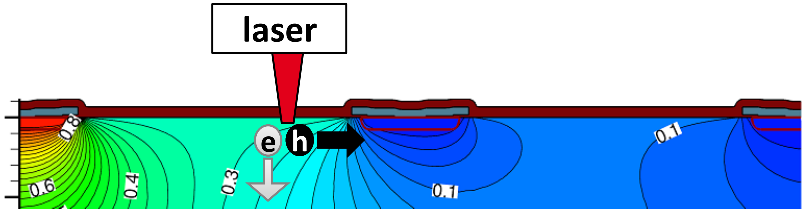
time scaling dry/humid: 240 !

0 V → 200 V at time = 0

a) **in humid atmosphere** (**83 % humidity**)

b) **in dry atmosphere** (**< 5 % humidity**)

Before: sensor at 0 V for > 2 hours in humid atmosph.



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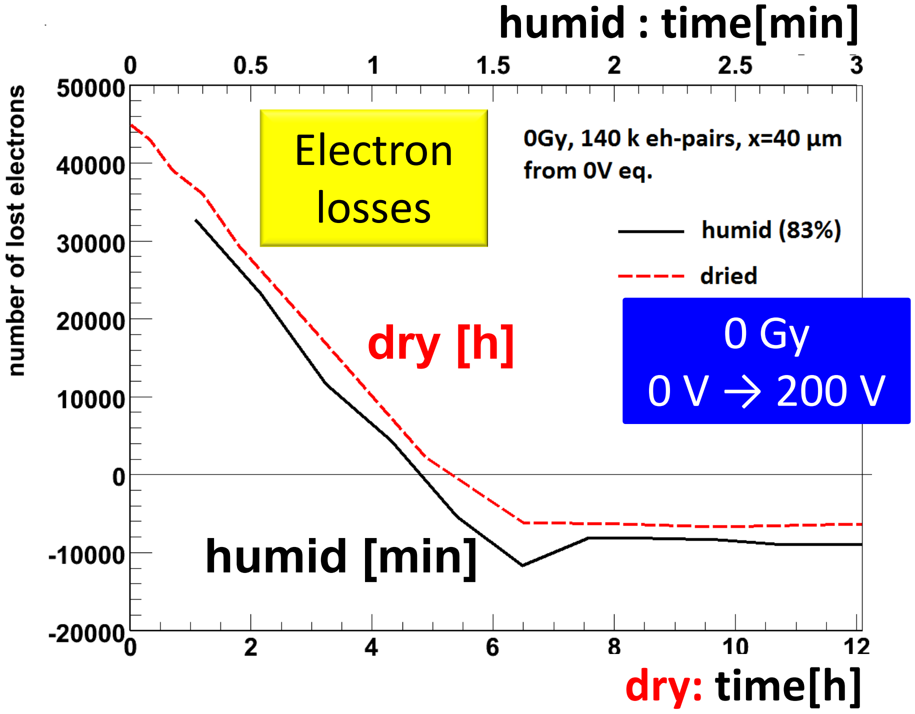
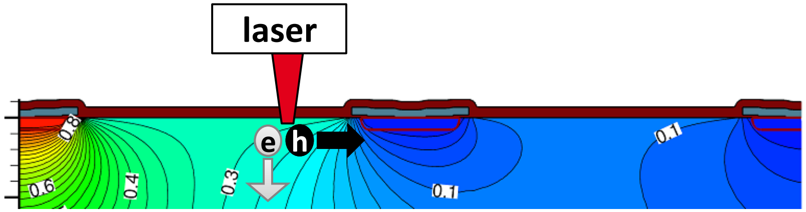
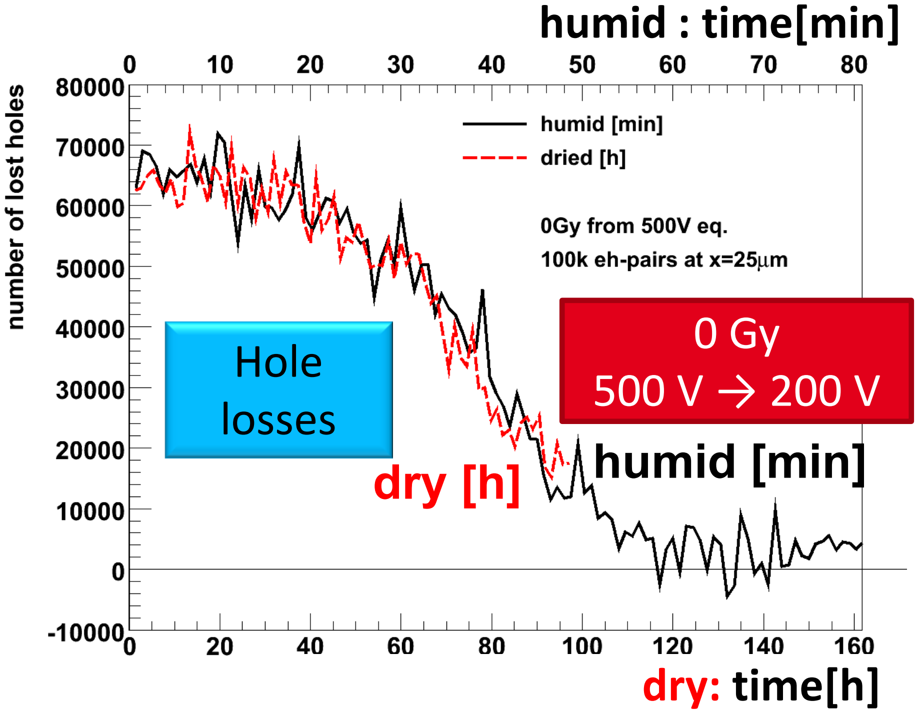


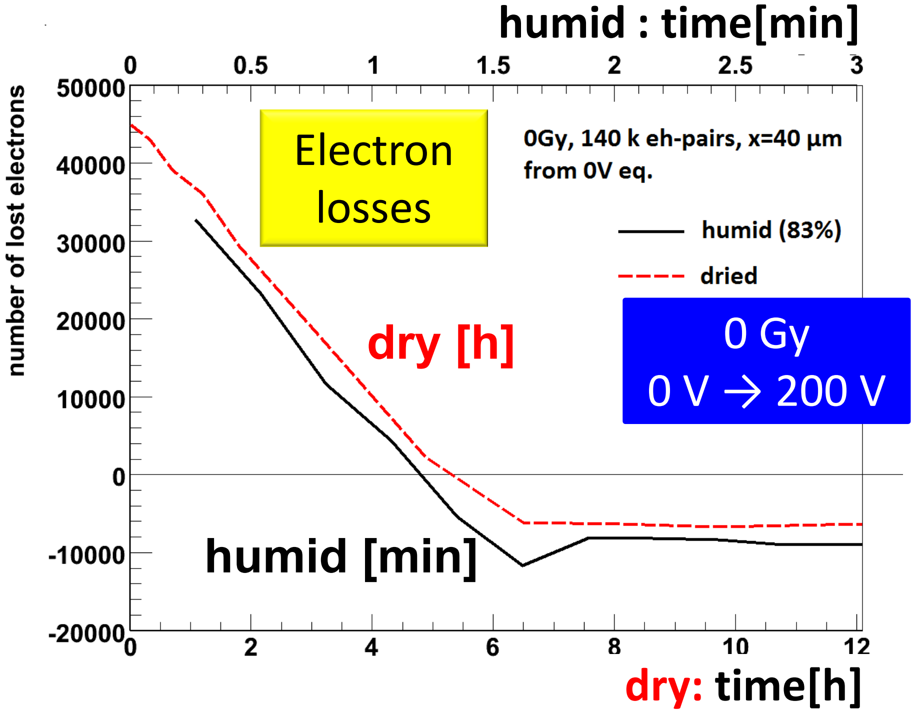
$$Q_{lost} < 0$$



Time development of charge losses before irradiation (0 Gy)



$Q_{lost} > 0$



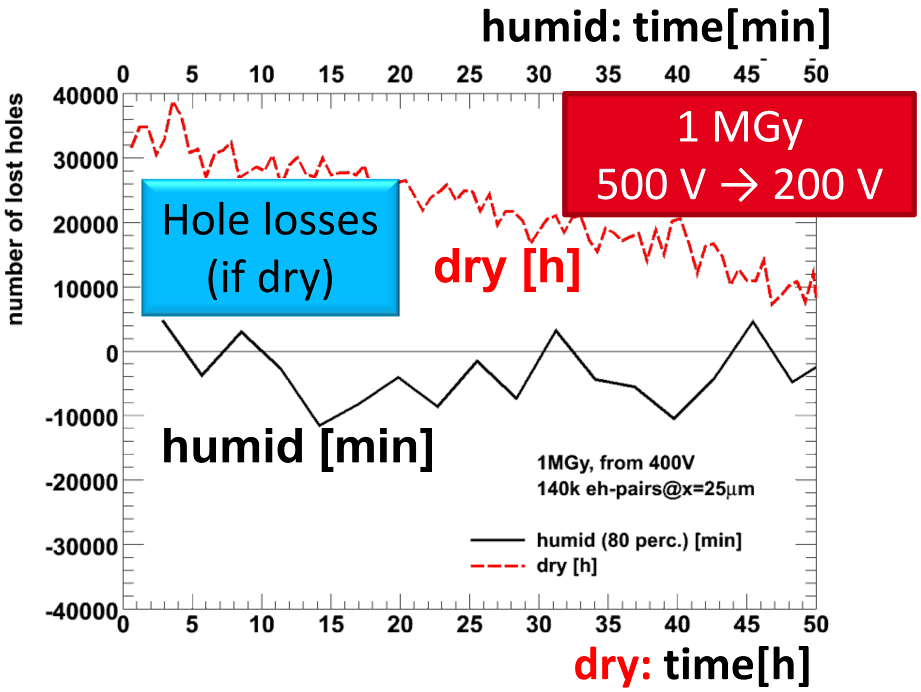
$Q_{lost} < 0$

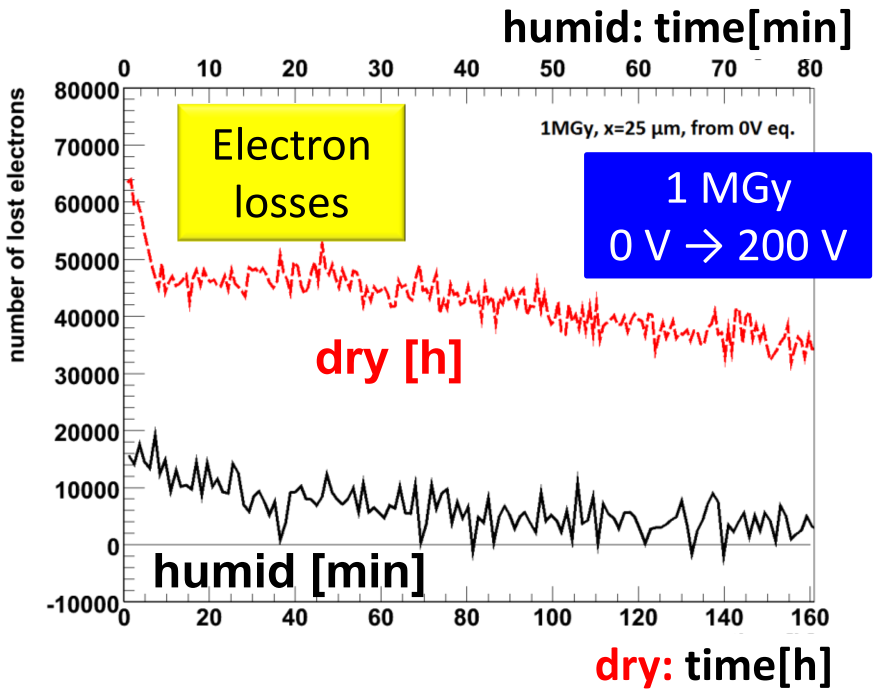
After voltage ramping: charge carrier losses

Time dependence scales with humidity (factor > 100).

Scaling compatible with surface resistivity.

Time development of charge losses after irradiation (1 MGy)





$Q_{lost} > 0$

$Q_{lost} < 0$

0 Gy → 1 MGy (→ positive oxide charges & interface states):

1. in dry atmosphere: **less hole losses, more electron losses** ← positive oxide charge
2. No obvious scaling for dry ↔ humid ← interface states?

Time development of charge losses - Summary

Non-irradiated:

0 V → 200 V ⇒ electron losses
500 V → 200 V ⇒ hole losses

Steady state 200 V ⇒ no losses

Dry: steady state reached in hours or days
Humid: steady state reached ~200 times faster (simple scaling!)

Effects to be explained in TCAD simulations,

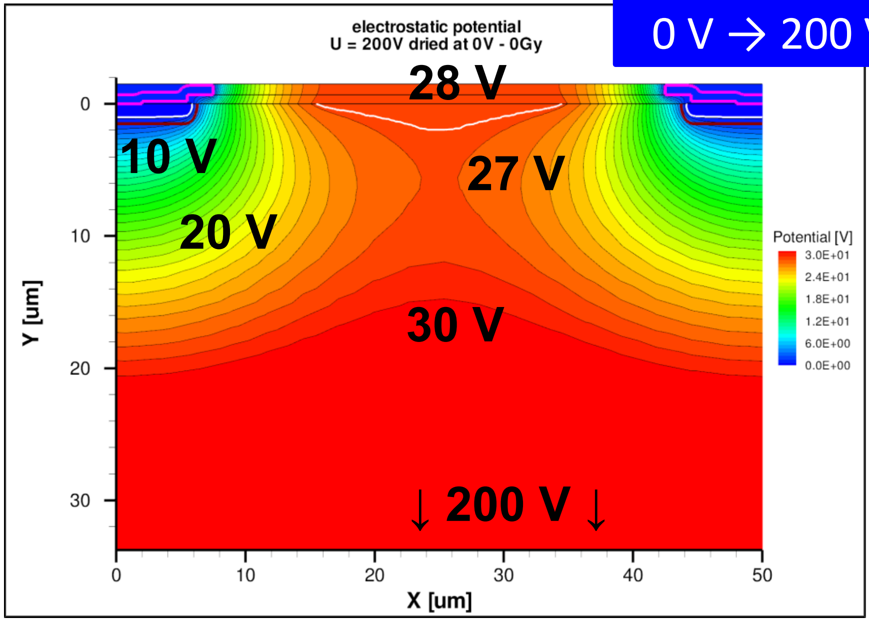
taking into account surface charge.

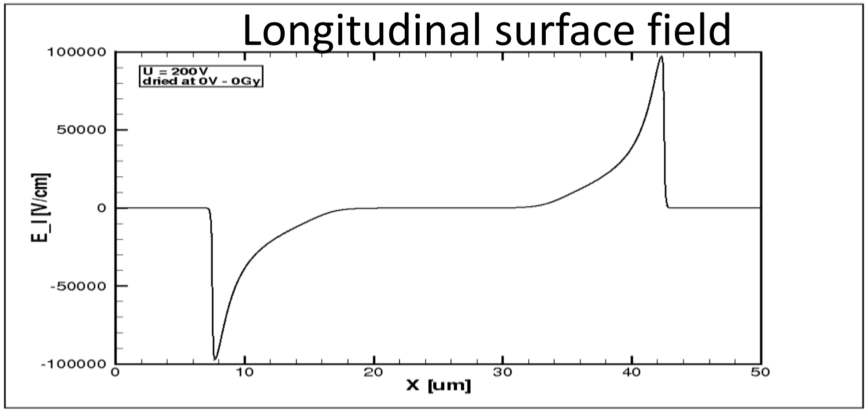
Irradiated:

- Qualitatively similar, but
  - more electron losses ← positive oxide charges
  - no obvious scaling ← interface states ?

TCAD simulations: electrostatic potential

a) 0 Gy
0 V → 200 V



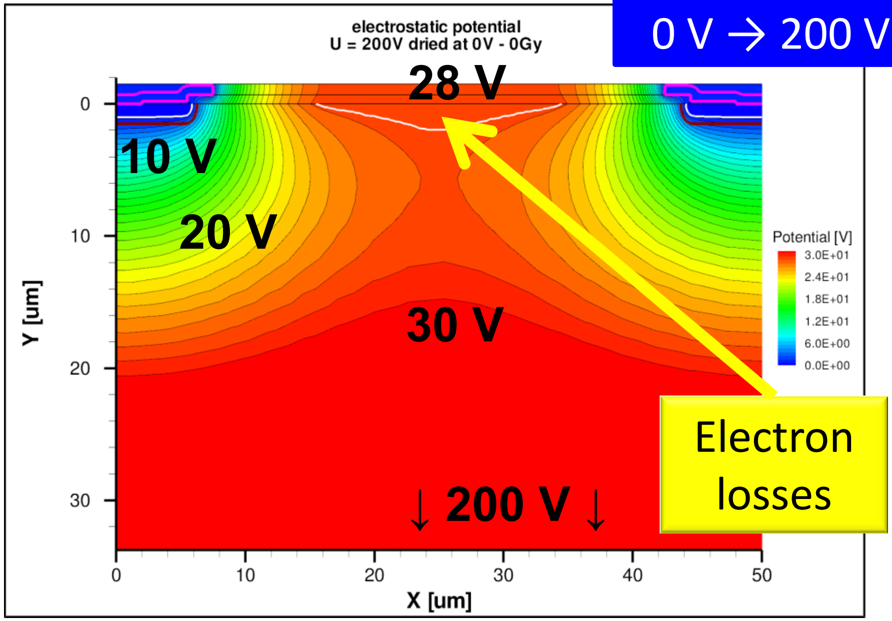

Longitudinal surface field

a) 0 V, fix surface charge → 200 V

⇒ Longitudinal surface field

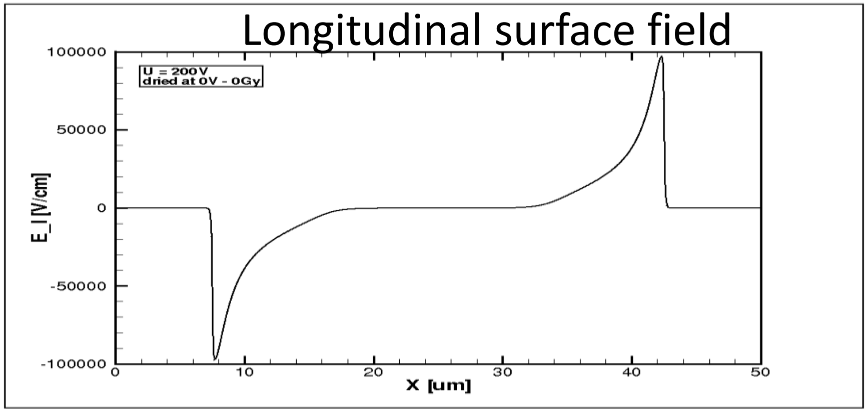
TCAD simulations: electrostatic potential

a) 0 Gy
0 V → 200 V



Electron losses

Longitudinal surface field



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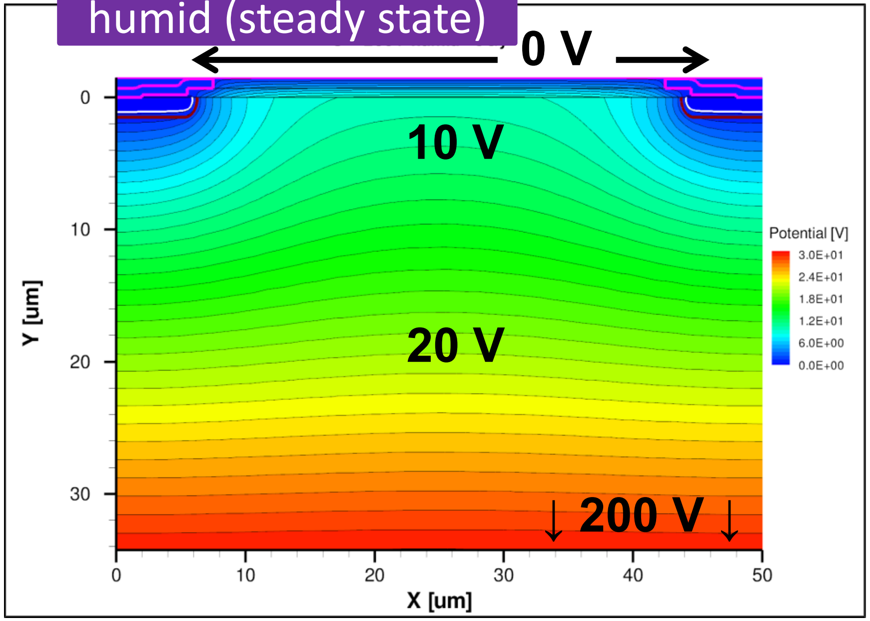
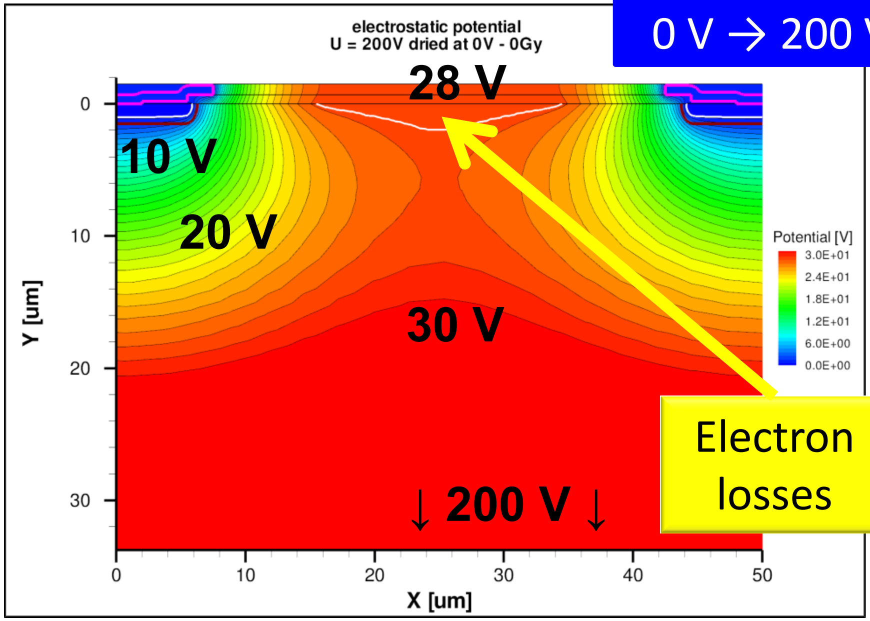
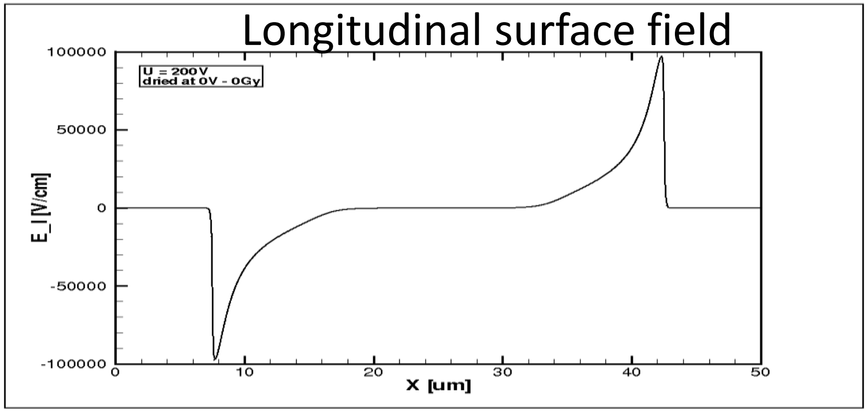


b) 200 V, 0 Gy
humid (steady state)



a) 0 Gy
0 V → 200 V

Electron losses



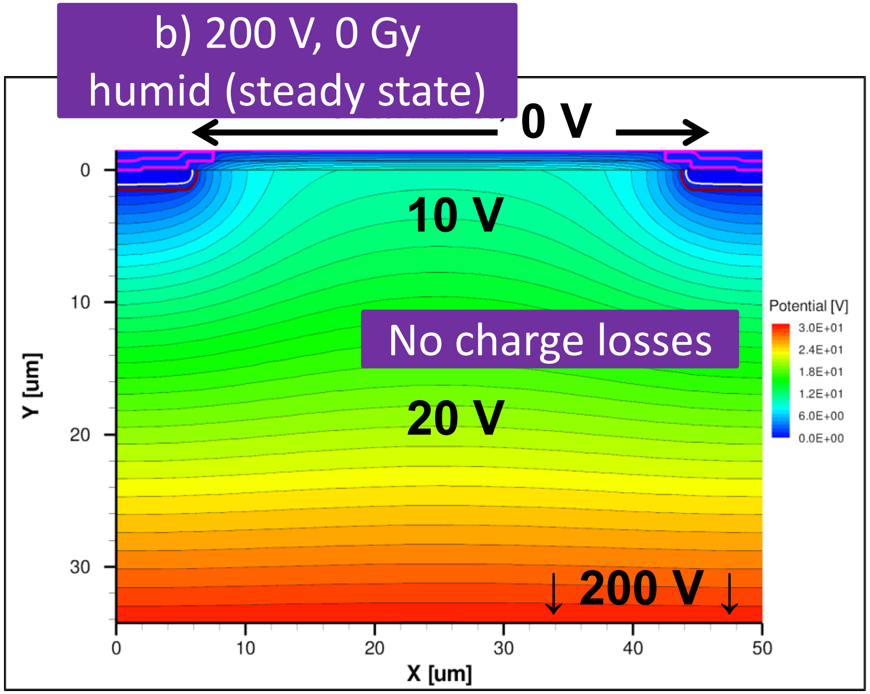
Longitudinal surface field

a) 0 V, fix surface charge → 200 V

⇒ Longitudinal surface field

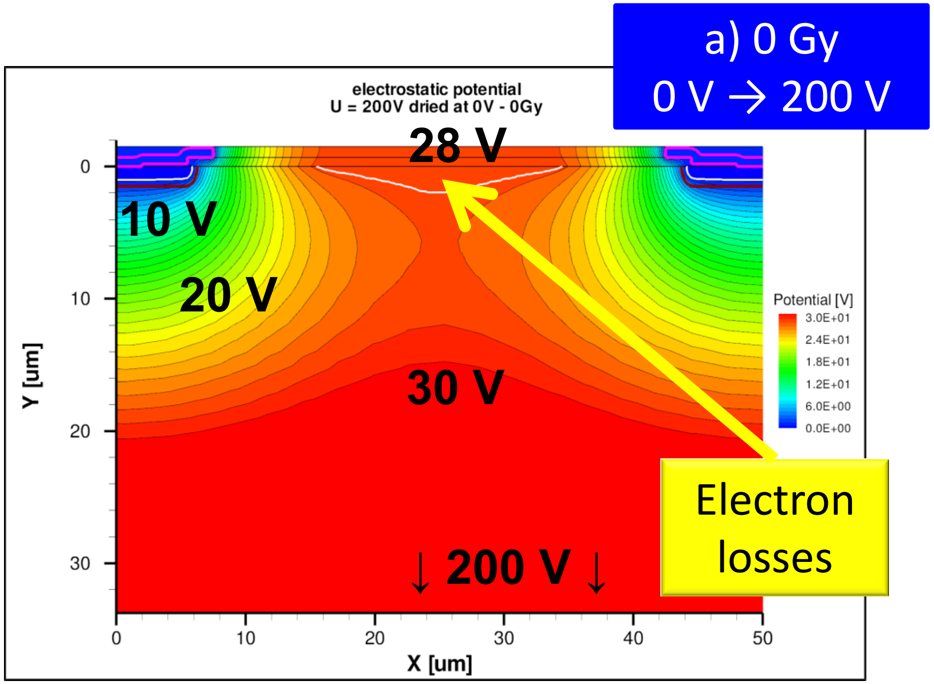
b) redistribute surface charge by setting surface potential = 0 V

TCAD simulations: electrostatic potential



b) 200 V, 0 Gy
humid (steady state)

No charge losses



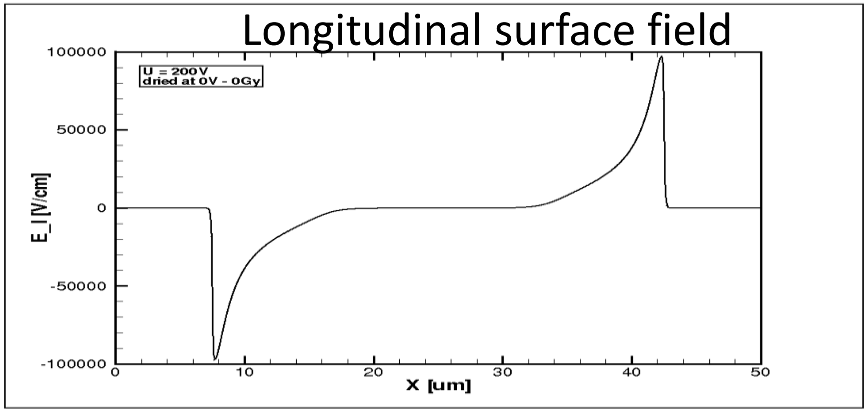
a) 0 Gy
0 V → 200 V

Electron losses

a) 0 V, fix surface charge → 200 V

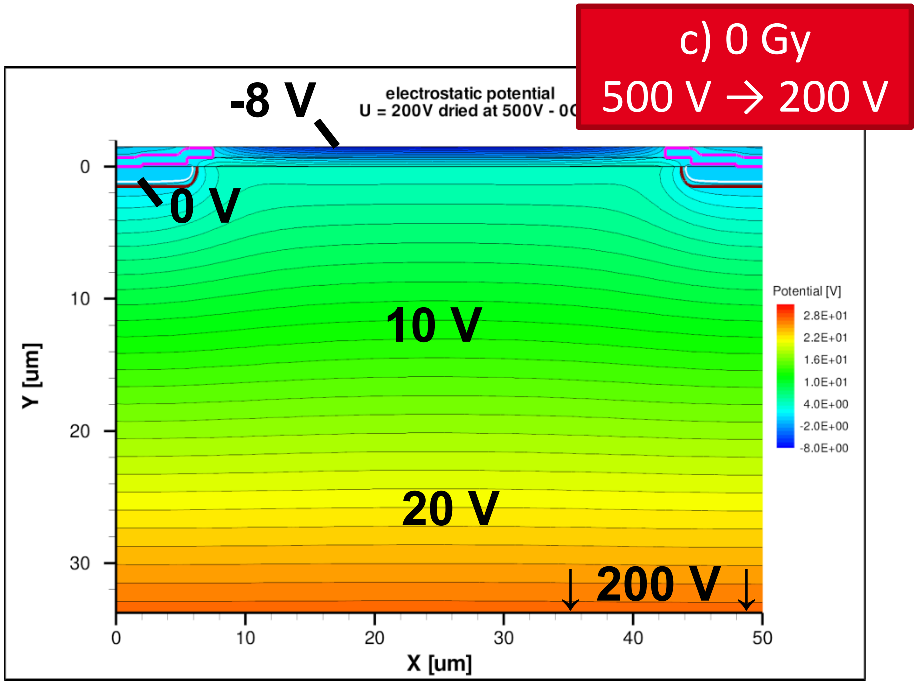
⇒ Longitudinal surface field

b) redistribute surface charge by setting surface potential = 0 V

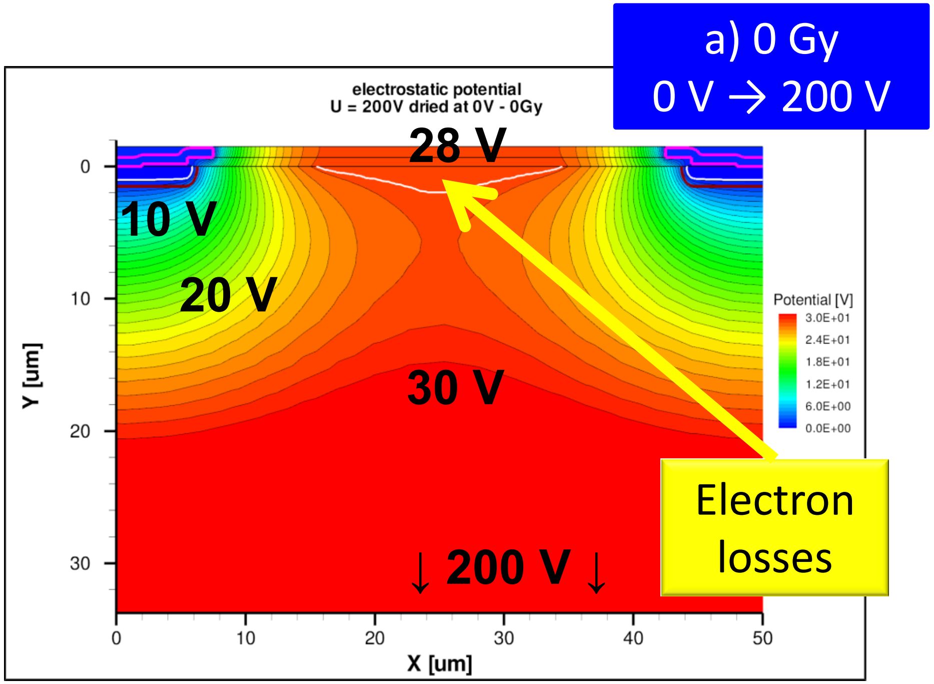


Longitudinal surface field

TCAD simulations: electrostatic potential



c) 0 Gy
500 V → 200 V



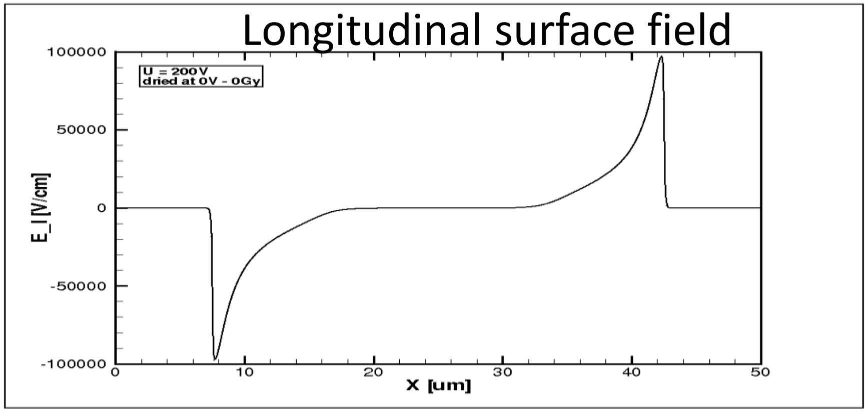
a) 0 Gy
0 V → 200 V

Electron losses

a) 0 V, fix surface charge → 200 V

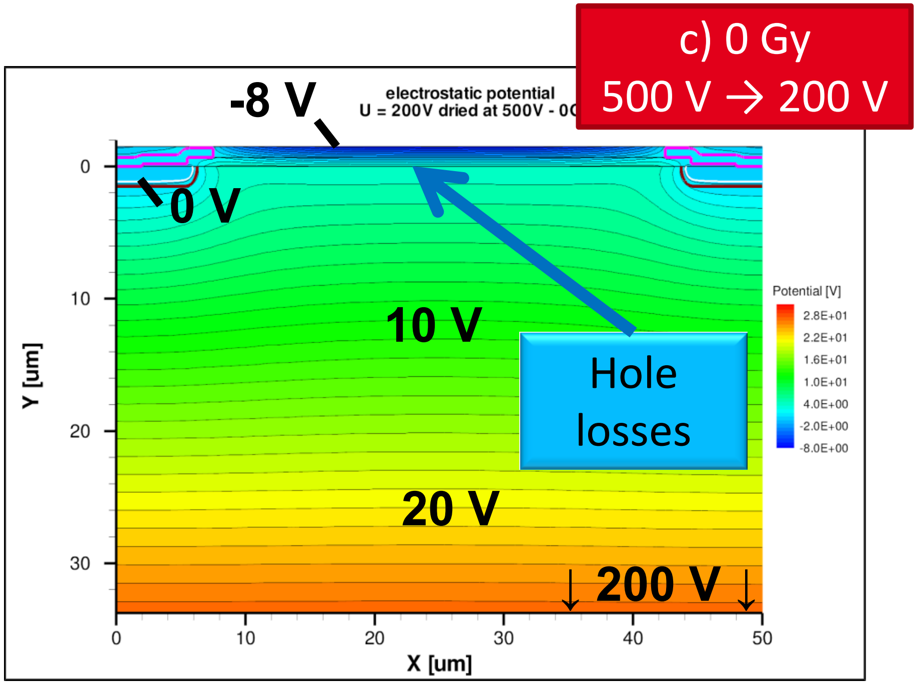
⇒ Longitudinal surface field

c) → 500 V, redistribute and fix surface charge (0 V surface potential) → 200 V



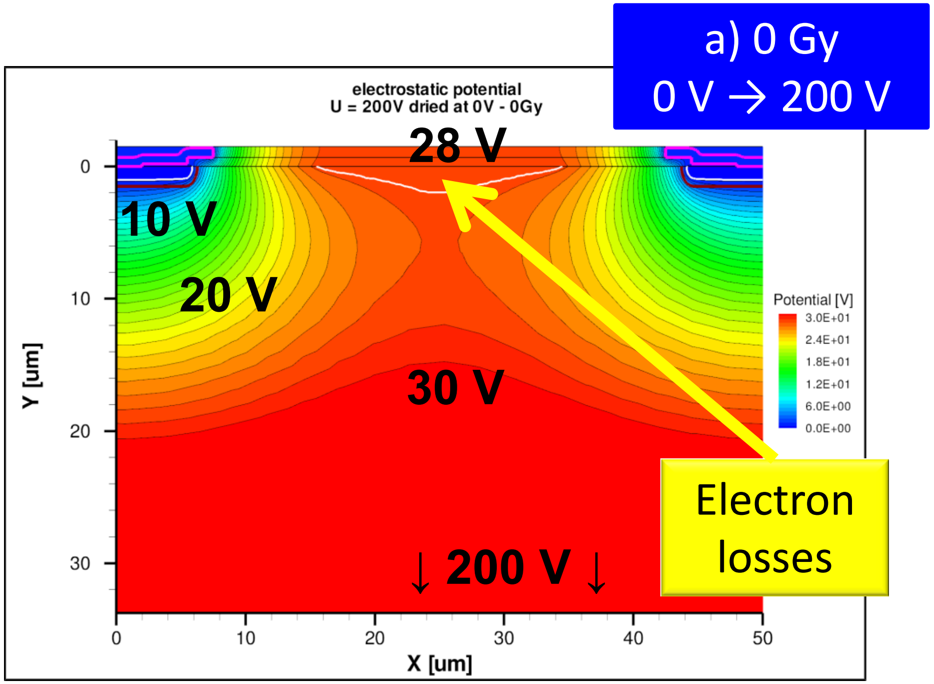
Longitudinal surface field

TCAD simulations: electrostatic potential



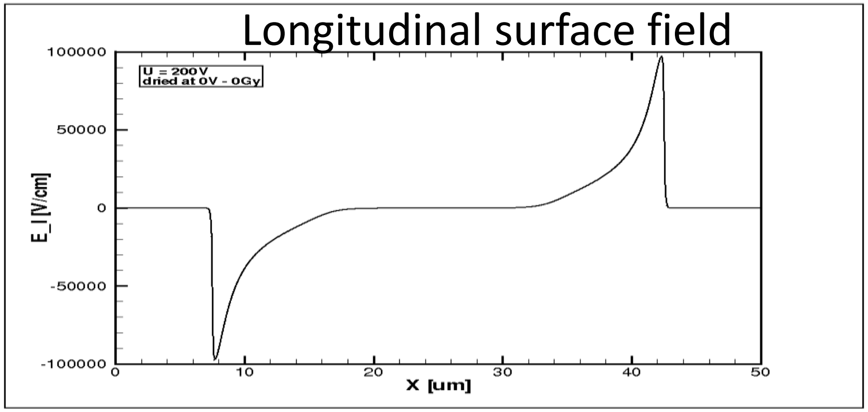
c) 0 Gy
500 V → 200 V

Hole losses



a) 0 Gy
0 V → 200 V

Electron losses


Longitudinal surface field

a) 0 V, fix surface charge → 200 V

⇒ Longitudinal surface field

c) → 500 V, redistribute and fix surface charge (0 V surface potential) → 200 V

Summary & Conclusion

Charge losses at Si-Si0$_2$ interface observed after changing the bias voltage

- Only relevant close to the Si-Si0$_2$ interface
  - relevant for low energy ion experiments with strip side illumination
  - in **X-FEL: only ~0.3%** of the photons will convert in the last 5 µm of the sensor
- **Explained with TCAD simulations** using different boundary conditions.

Some insight into the electric field at the Si-Si0$_2$ interface was gained:

- E-field changes in time after the sensor is biased due to changes in the surface potential → impact on break-down behaviour and dark current expected

Simulations

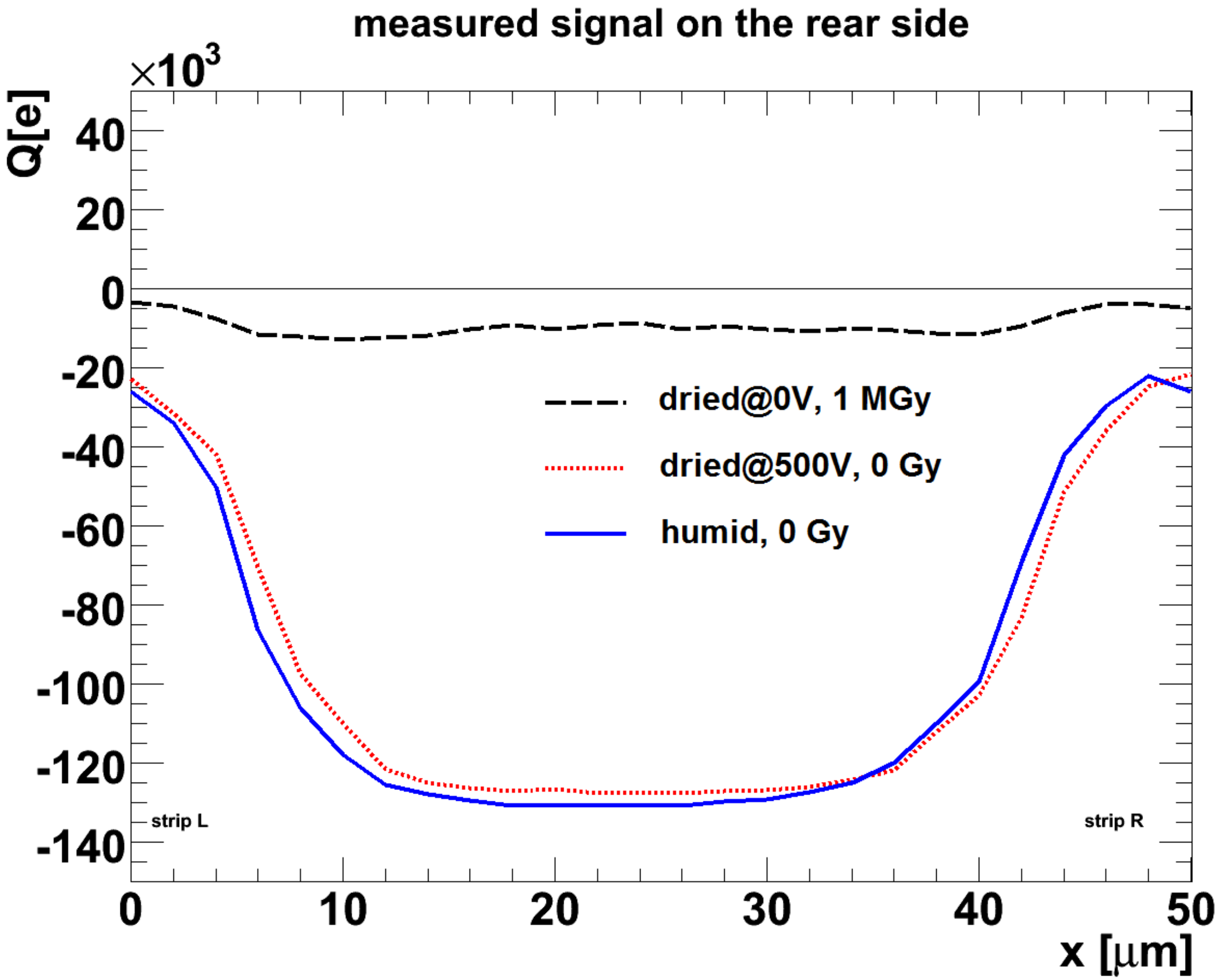
- To predict sensors performances **boundary conditions must be chosen carefully**. **Humidity and bias history should be taken into account.**

X-FEL: sensor operation foreseen in vacuum, long time constants (days) expected.

For short term operation:	Neumann boundary conditions,
For long term operation:	Constant surface potential (after days)

Also see ***arxiv.org/abs/1207.6538*** for more information

Measured charge vs. position, Rear side



Investigated sensor

Producer	HPK
Coupling	DC
Full depletion voltage	155 V
n-doping	10^{12} cm^{-3}
Pitch	50 µm
Implant width	11 µm*
Number of strips	128
Strip length	8 mm
Thickness	450 µm
Orientation	< 1 0 0 >
SiO_2	700 nm

* + 2 µm Al overhang

Irradiation:

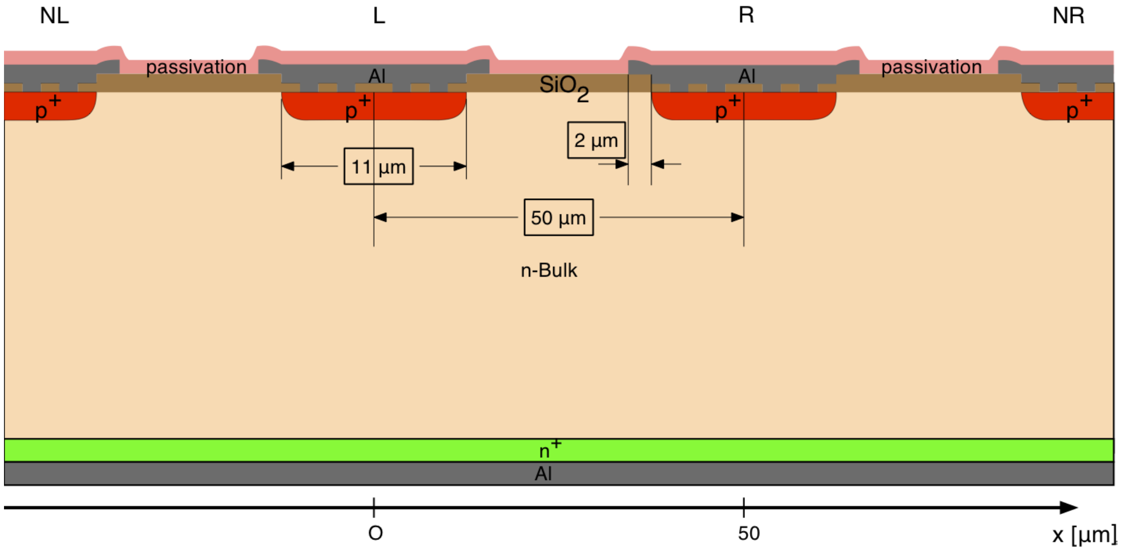
a) 0 Gy

b) 1 MGy 12 keV x-rays (surface damage only)

Atmosphere during measurement:

- Humid (> 50% humidity)
- Dry (< 5% humidity)

T = ~24 °C (room temperature)



Time development of charge losses

$$Q_{lost} = \frac{Q}{\phi_w(x)}$$

$Q_{lost} > 0 \;\Rightarrow$ dominated by hole losses

$$\#h_{lost} := \#e - \#h = \frac{Q_{lost}}{q_0}$$

1. keep non-irradiated sensor at 500 V in humid atmosphere (~70% for >2h)
   $\Rightarrow$ *steady state*
2. measure at 200 V

500 V → 200 V and measurement

a) in humid atmosphere (~70 % humidity)

b) in dry atmosphere (< 5 % humidity)