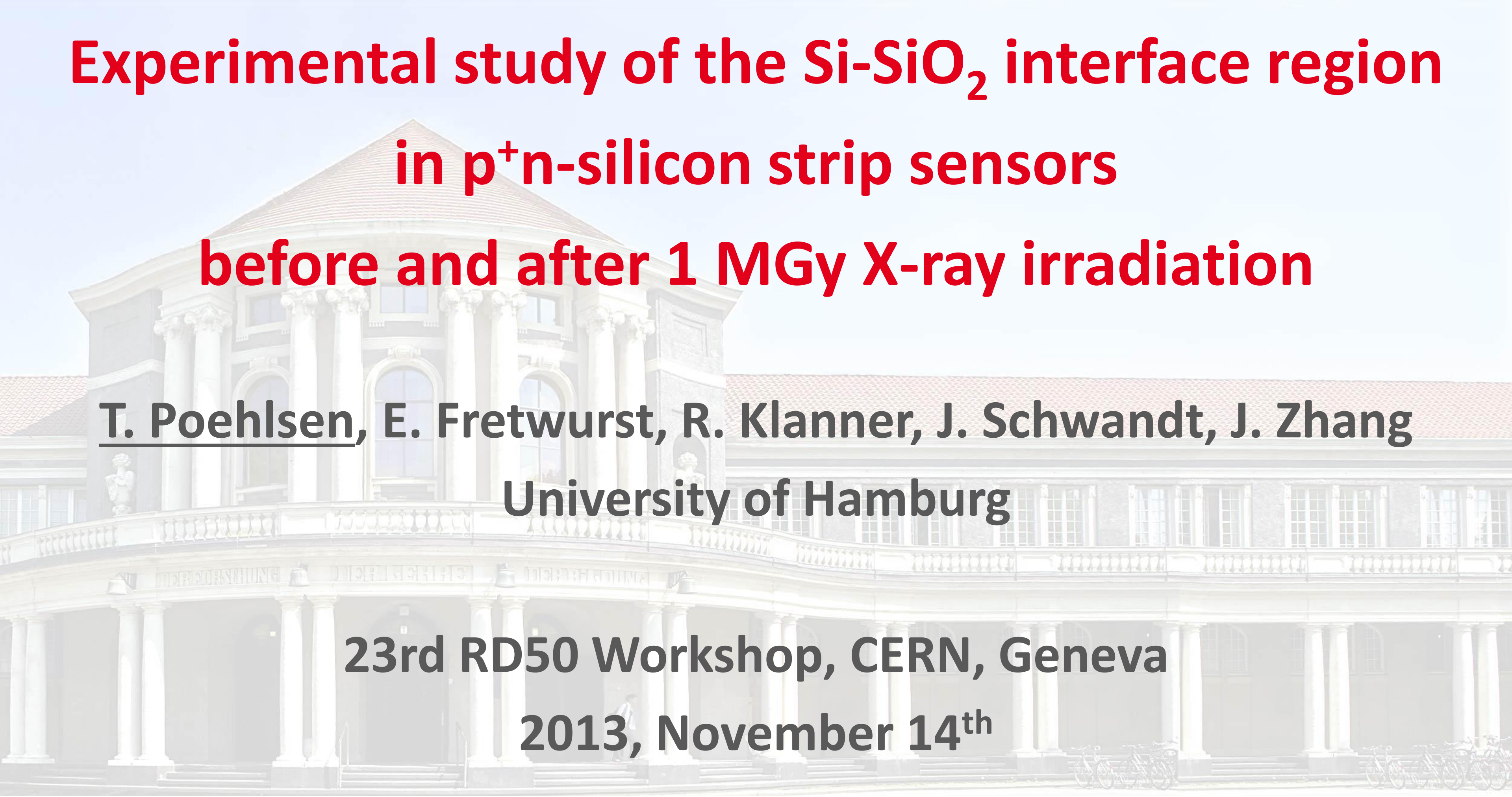
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

SPONSORED BY THE
Federal Ministry of Education and Research

European XFEL

AGIPD



Experimental study of the Si-SiO_2 interface region in p^+n-silicon strip sensors before and after 1 MGy X-ray irradiation

T. Poehlsen, E. Fretwurst, R. Klanner, J. Schwandt, J. Zhang
University of Hamburg

23rd RD50 Workshop, CERN, Geneva

2013, November 14th

Motivation – why surface studies

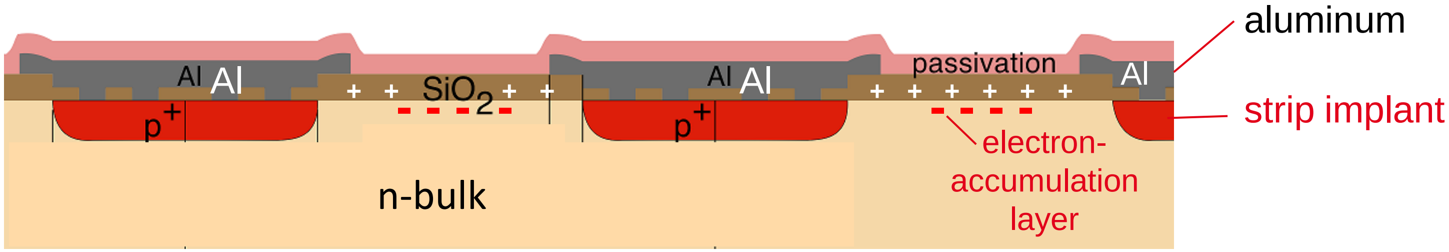
The region close to the Si-SiO$_2$ interface is highly relevant:

- **Highest electric fields** → **charge multiplication** or **breakdown**.
- **Electron or hole accumulation layers** → **short cuts** or **increase of the capacitance** between the electrodes, may **lower breakdown voltage**.
- **Lowest electric fields** → **increase of charge-collection times** → ballistic deficit, pile-up.

Requirements for silicon sensors:

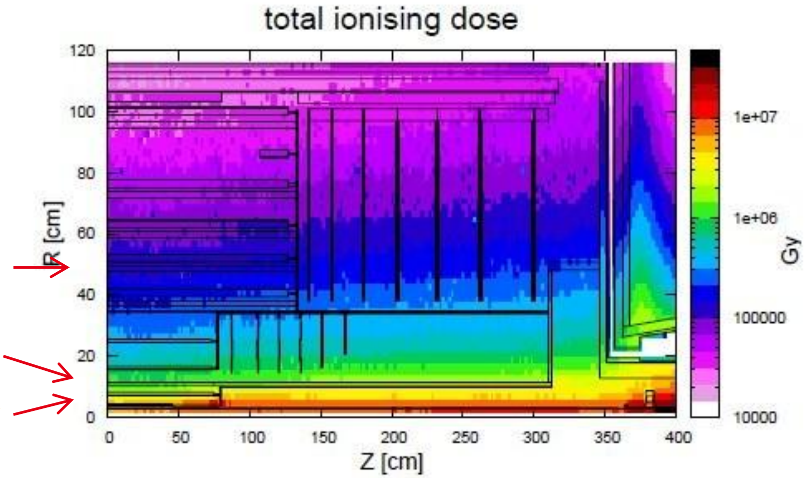
… also after surface radiation damage (e.g. up to ~1 GGy at X-FEL, up to ~4 MGy at HL-LHC (pixel))
(companies will not guarantee stable sensor operation after irradiation)

- **High bias voltages** for fast charge collection (e.g. 500 V for AGIPD at the European X-FEL)
- **Stable sensor operation** (problems: **long-time run-aways**, **early breakdowns, non-Gaussian noise hits, …**).
- Low inter-strip capacitances, low currents, …



Expected dose and oxide charge densities

ATLAS expected dose:



~100 kGy

~1 MGy

~4 MGy

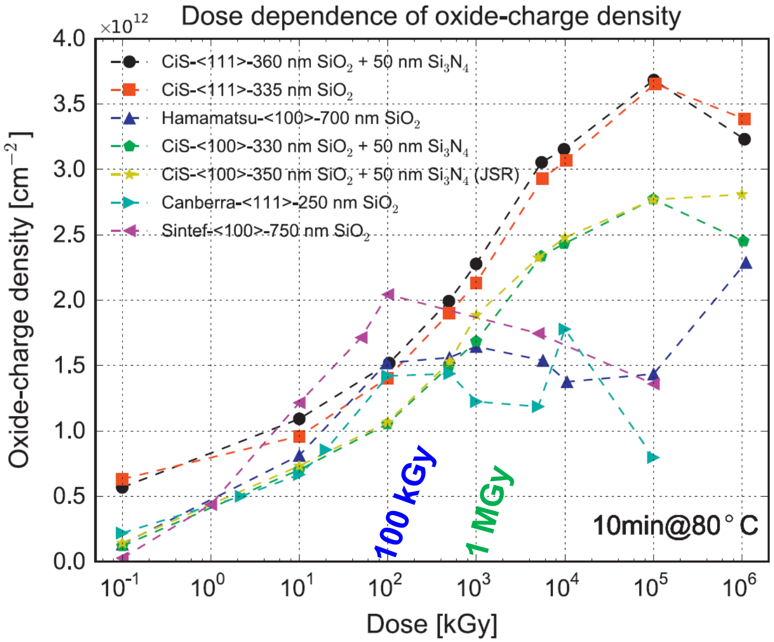


Fig. 1. Dependence of the surface-charge density, N_{ox}, on X-ray dose obtained from measurements on MOS capacitors from four different vendors after annealing for 10 min at 80 °C.

R.Klanner et al. NIM A, DOI: 10.1016/j. nima.2013.05.131

$\Rightarrow$ Oxide charge densities of 1 to $2 \cdot 10^{12}$ cm^{-2} are expected at the HL-LHC (for R<60 cm)

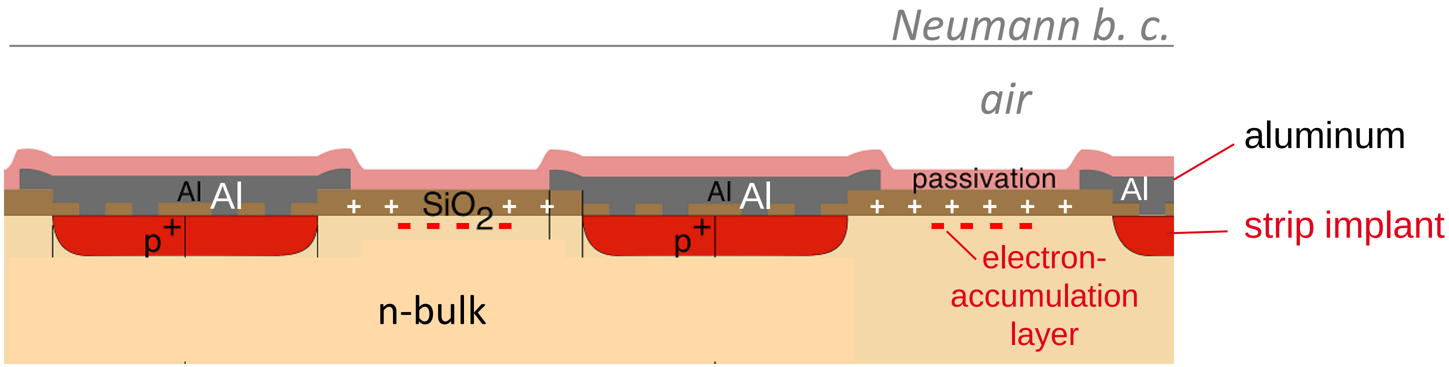
Motivation – Questions

Simulations may be used to **predict the sensor performance** (electric field, charge collection, breakdown voltage, capacitances, …) and to **optimise the sensor design**.

- What **boundary conditions** should be used on the top of the passivation? (or shall one introduce a box above sensor with b.c. there, and put charges on SiO_2 surface?)
- Does the electric field, and do the boundary conditions **develop in time** ?
- How does **humidity** influence the electric field / boundary conditions?
- What is the **charge distribution at the Si-SiO_2 interface**?

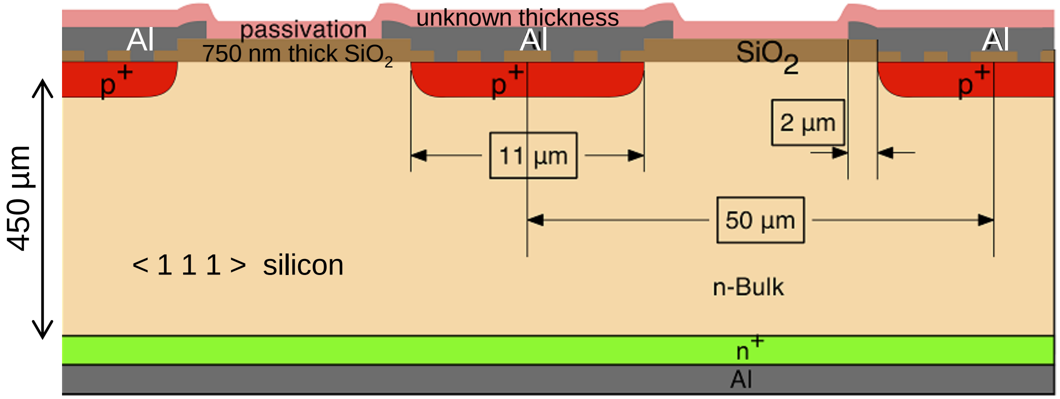
Approach:

Study charge losses at the Si-SiO_2 interface and correlate them to the **electric-field distribution and the boundary conditions.**



Investigated strip sensor

p^+n silicon strip sensor (Hamamatsu Photonics)



Another p^+n silicon strip sensor produced by CiS has also been tested → similar results

Only results for the Hamamatsu sensor will be shown

Irradiation:

a) None (0 Gy)

b) 12 keV X-rays (1 MGy in SiO_2)

→ surface damage only

(300 keV needed for bulk damage)

Atmosphere during measurement:

- T ≈ 24 °C (room temperature)
- Humidity (rh.): < 1% to 85 %

Operation voltage

- 200 V for all measurements shown (full-depletion voltage: 155 V)
- Different biasing histories:

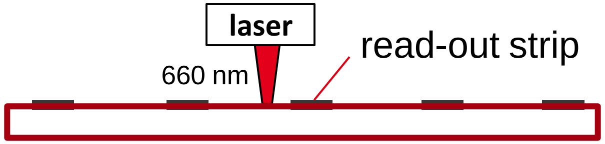
0 V → 200 V

500 V → 200 V

Measurement procedure: Transient Current Technique (TCT)

Illumination:

- At the strip side
- $\lambda = 660$ nm, attenuation length ≈ 3.5 µm
- $\lambda = 830$ nm, attenuation length ≈ 13 µm
- Sub-ns pulses (FWHM 100 ps)
- Focus: $\sigma = 3$ µm
- ~100 000 eh pairs generated per pulse

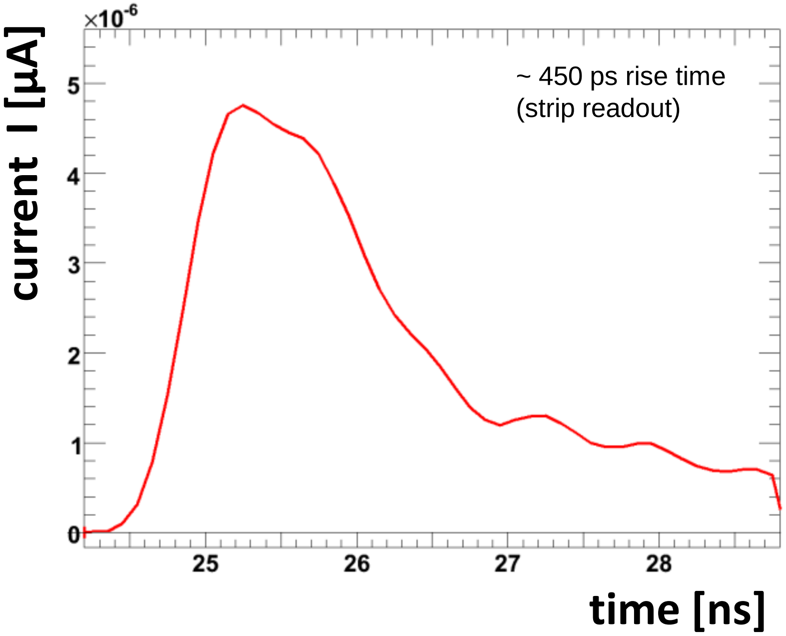


Readout:

- Two strips & the rear contact
- Femto HSA-X-2-40 current amplifiers
- Tektronix oscilloscope, 2.5 GHz bandwidth
- Neighbouring strips on ground (via 50 Ω)

- Charge Q calculated offline:

$$Q = \int I(t)\ \mathrm{d}t$$



~ 450 ps rise time
(strip readout)

Measurement procedure: Transient Current Technique (TCT)

Illumination:

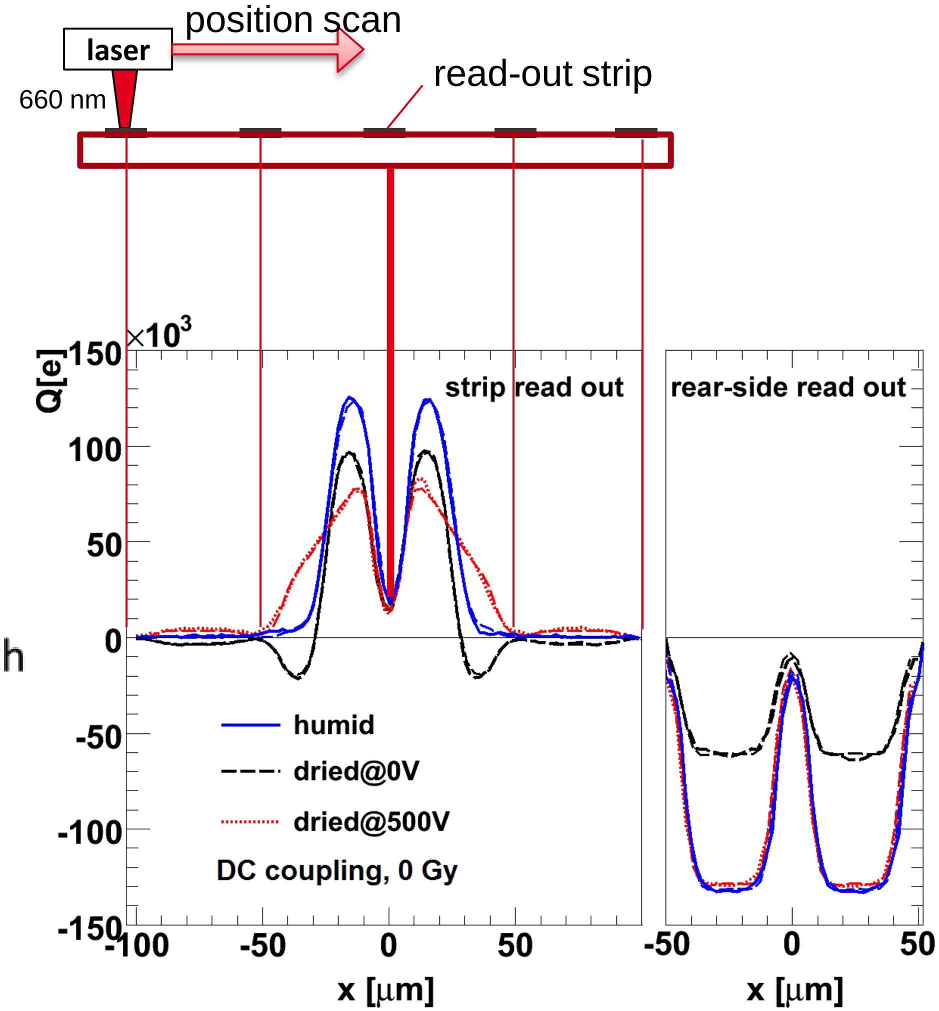
- At the strip side
- $\lambda = 660$ nm, attenuation length ≈ 3.5 μm
- $\lambda = 830$ nm, attenuation length ≈ 13 μm
- Sub-ns pulses (FWHM 100 ps)
- Focus: $\sigma = 3$ μm
- ~100 000 eh pairs generated per pulse

Readout:

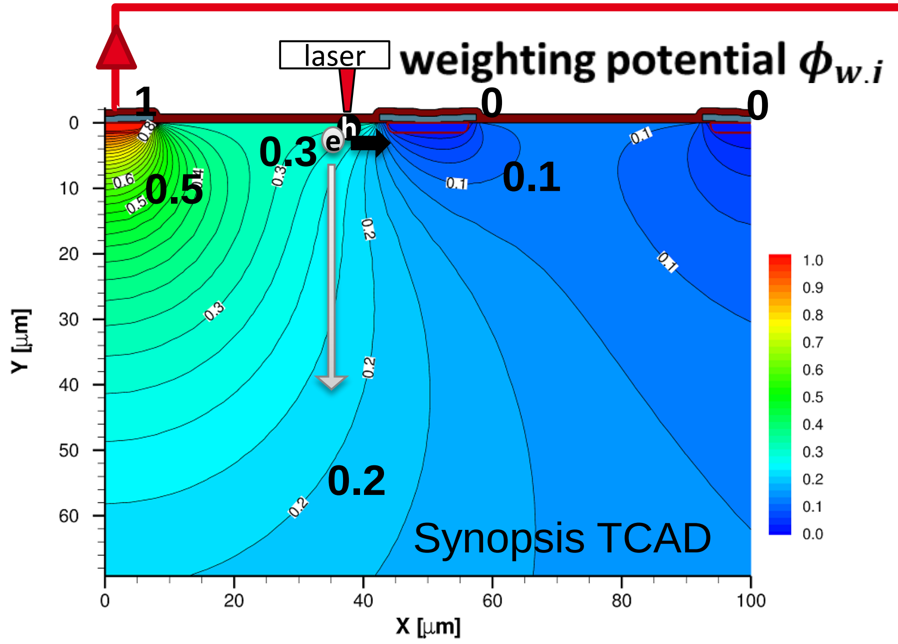
- Two strips & the rear contact
- Femto HSA-X-2-40 current amplifiers
- Tektronix oscilloscope, 2.5 GHz bandwidth
- Neighbouring strips on ground (via 50 Ω)

- Charge Q calculated offline:

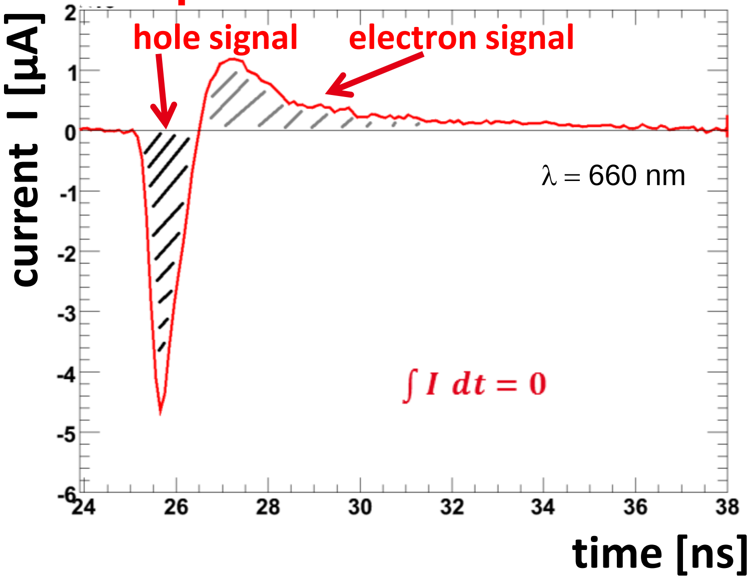
$$Q = \int I(t)\ \mathrm{d}t$$



Weighting potential and induced signals for strip readout



strip readout



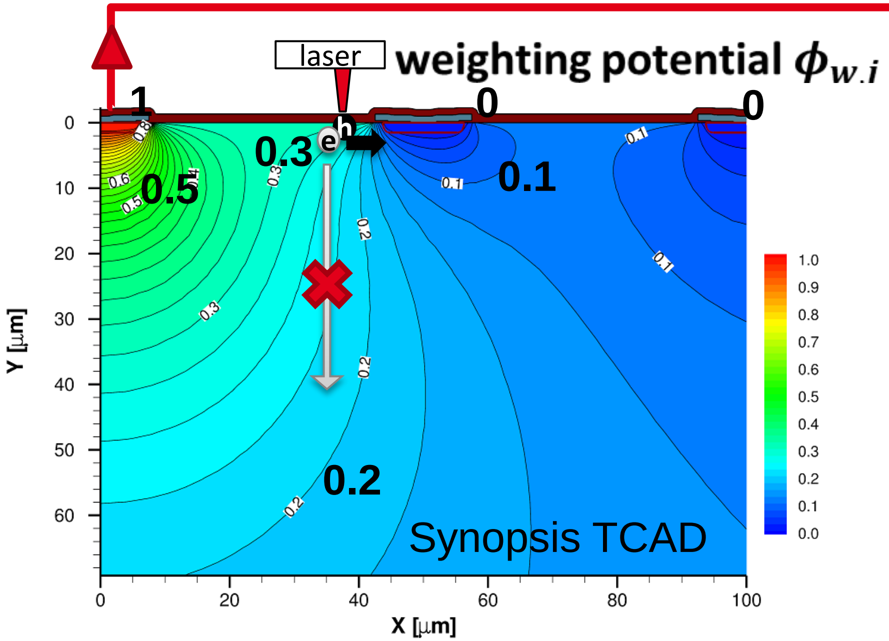
- Measurement 1 (0 Gy, humid)

⇒ Electron and hole collection

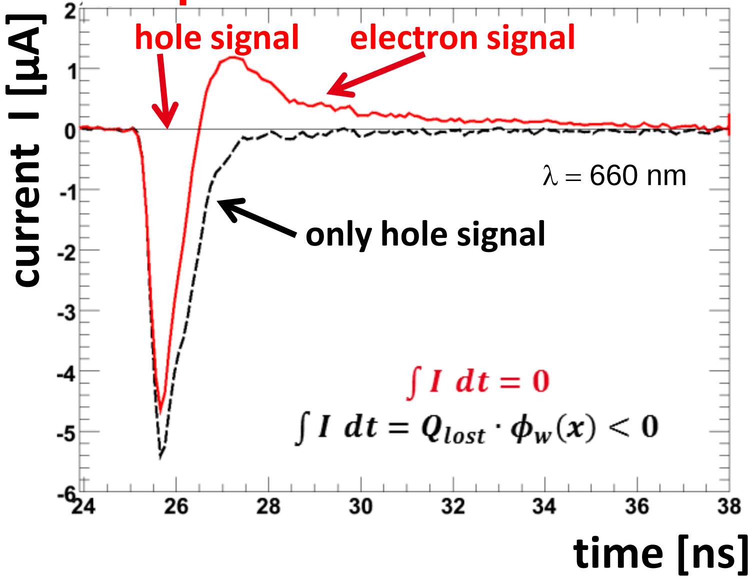
Weighting potential calculation takes into account the accumulation layer:

$$\phi_{w,j} = \boxed{\begin{array}{c}\text{read out strip j: 1 V}\\ \text{other strips: 0 V}\\ \text{rear side: 200 V}\end{array}} - \boxed{\begin{array}{c}\text{readout strip j: 0 V}\\ \text{other strips: 0 V}\\ \text{rear side: 200 V}\end{array}}$$

Weighting potential and induced signals for strip readout



strip readout



- Measurement 1 (0 Gy, humid)

⇒ Electron and hole collection

- Measurement 2 (1 MGy, dried@0V)

⇒ Only hole collection

(~95% electron losses)

Weighting potential calculation takes into account the accumulation layer:

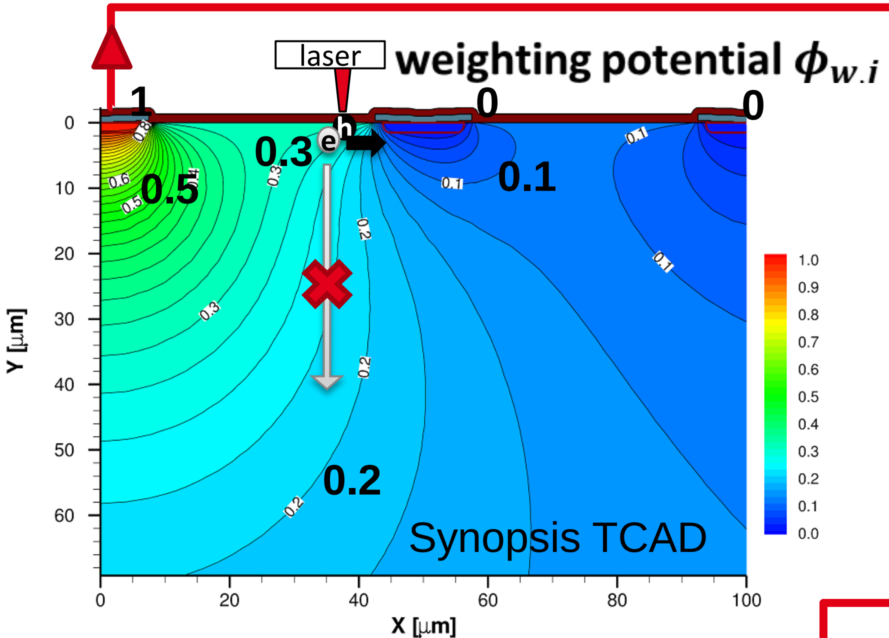
$\phi_{w,j}$ =

read out strip j: 1 V
other strips: 0 V
rear side: 200 V

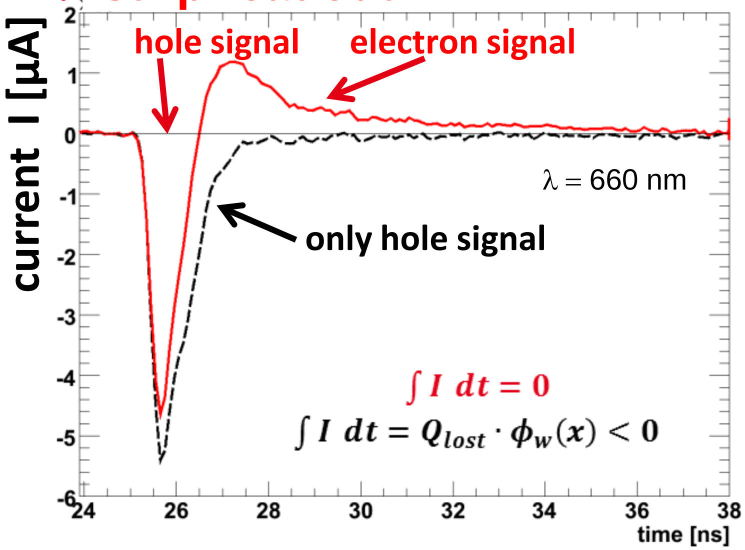
−

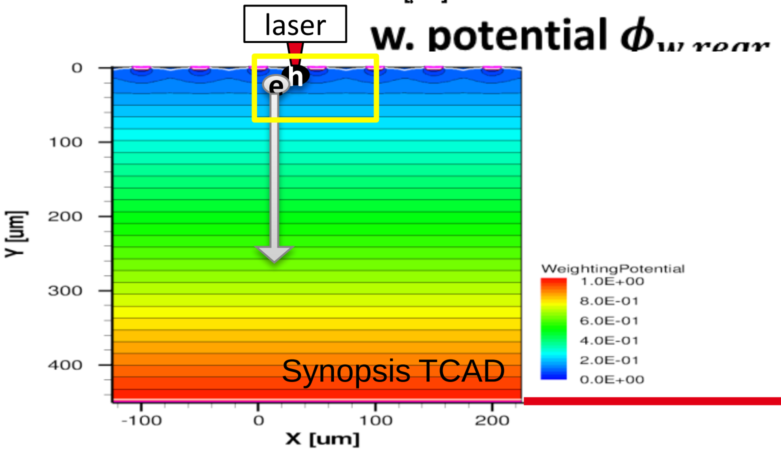
readout strip j: 0 V
other strips: 0 V
rear side: 200 V

Weighting potential and induced signals for strip readout

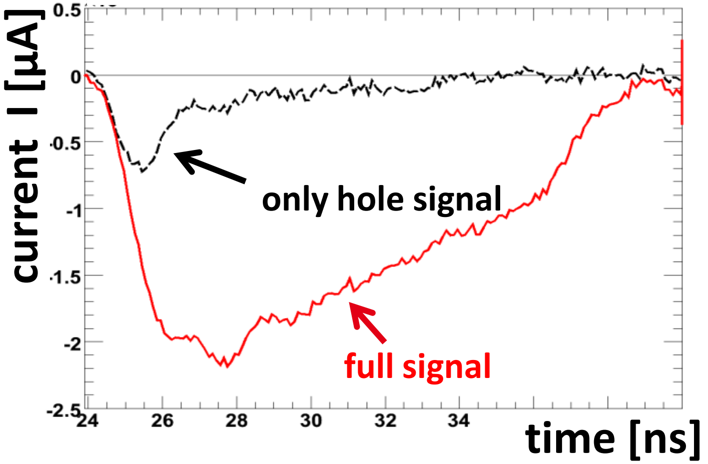


strip readout



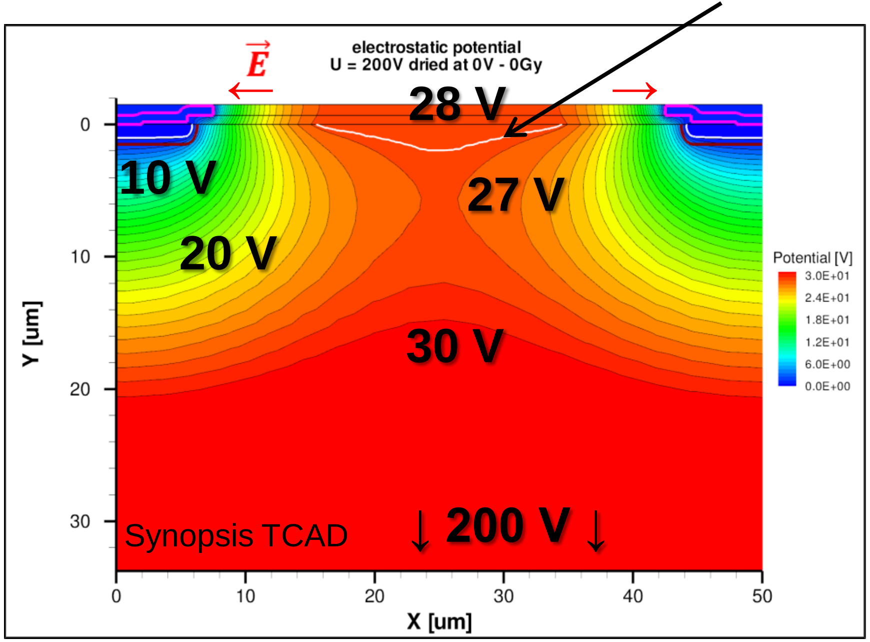


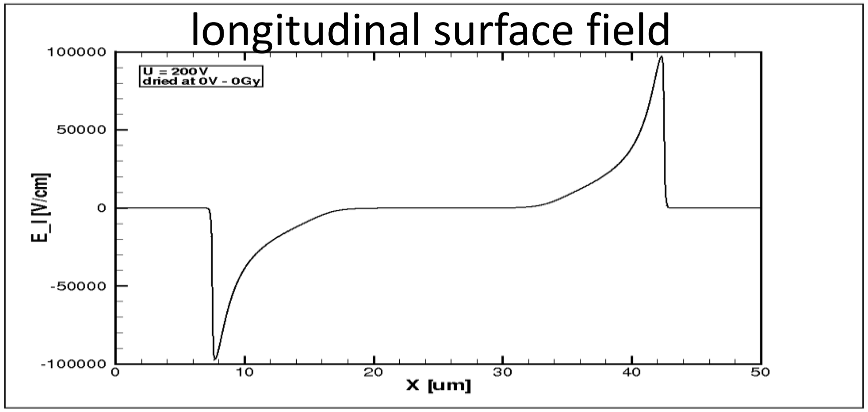
rear-side readout



Device simulations – 0 Gy: electric potential

0 V → 200 V ⇒ electron losses



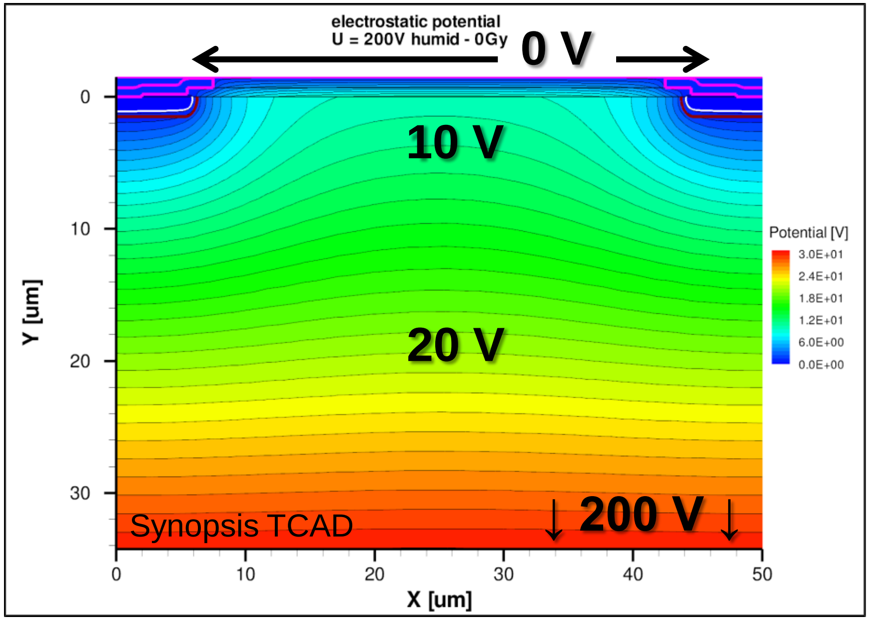


a) 0 V: ~0 surface charge → add air, go to 200V
⇒ electron losses and longitudinal E-field

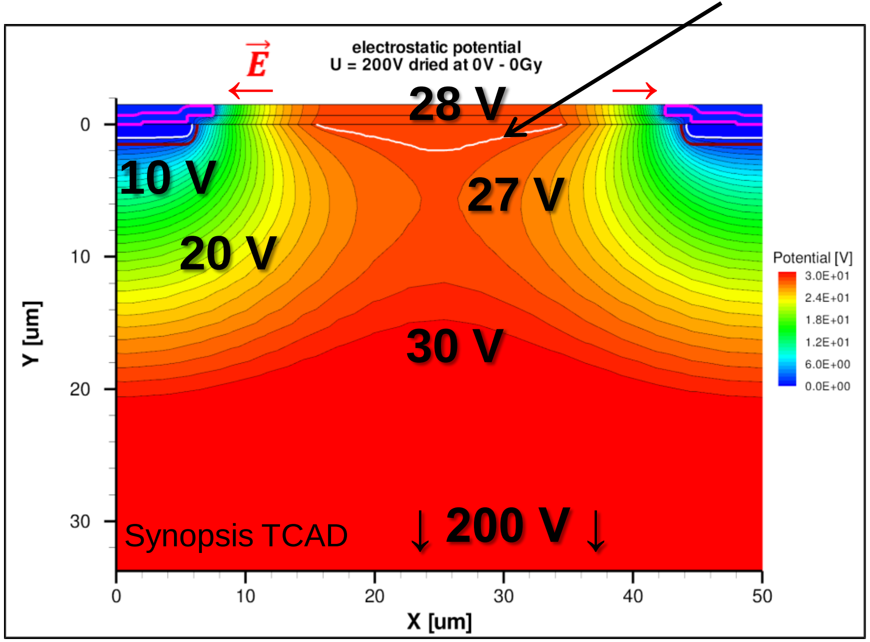
(very similar: Neumann boundary conditions)

Device simulations – 0 Gy: electric potential

steady state ⇒ no losses



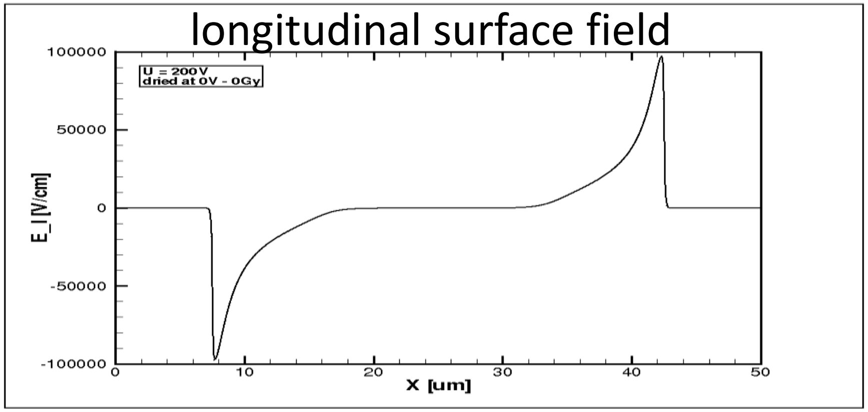
0 V → 200 V ⇒ electron losses



a) 0 V: ~0 surface charge → add air, go to 200V
⇒ electron losses and longitudinal E-field

b) redistribute surface charge at 200V bias by using gated b.c. (set surface potential = 0V)

⇒ **Boundary conditions** have a **significant impact on the E-field**


longitudinal surface field

Time development of charge losses, 0 Gy

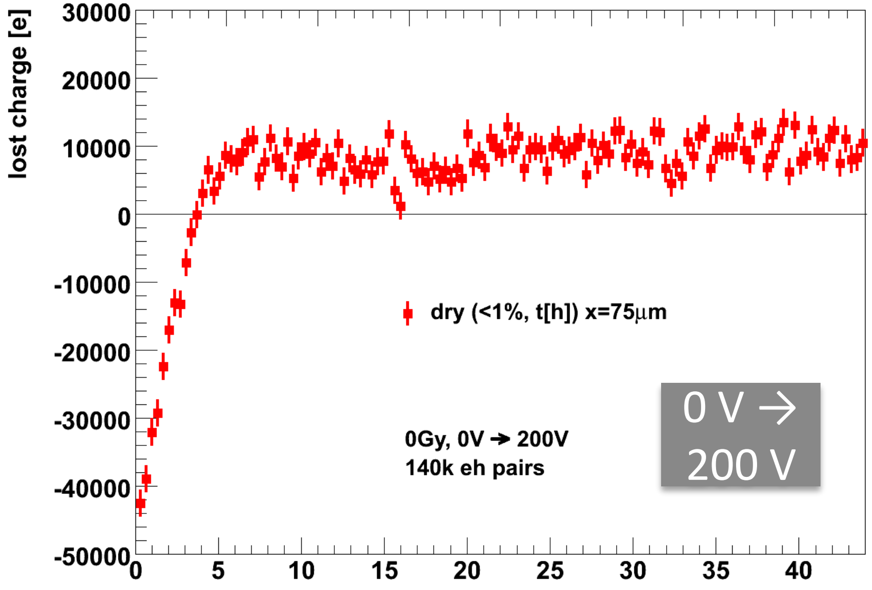
Determine lost charge

at a given position of illumination x

$$\int I\ dt = \overset{(h_{lost}-e_{lost})\cdot q_0}{Q_{lost}} \cdot \phi_w(x)$$

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

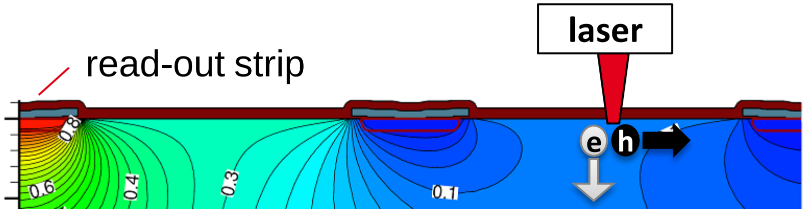
non-irradiated



dry: time[h]

0 V → 200 V at time = 0

a) In dry atmosphere (< 1 % rh.)



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

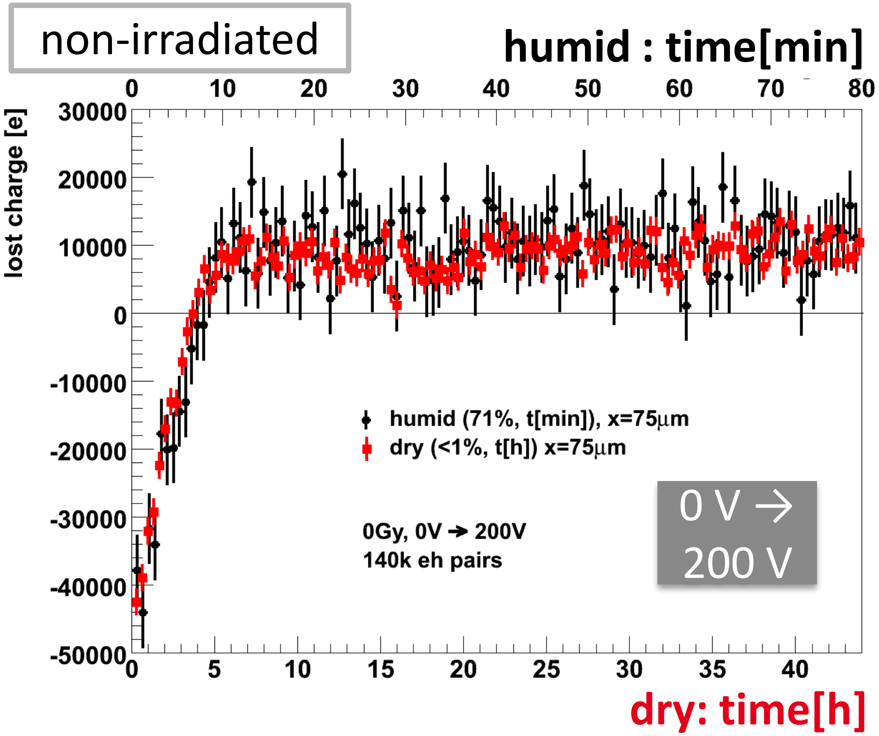
Time development of charge losses, 0 Gy

Determine lost charge

at a given position of illumination x

$$\int I\ dt = \overset{(h_{lost}-e_{lost})\cdot q_0}{Q_{lost}} \cdot \phi_w(x)$$

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

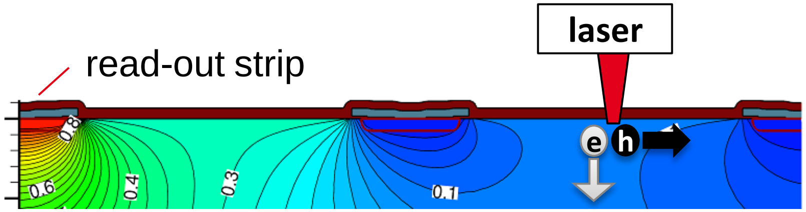


$$\frac{t^{0V\rightarrow 200V}(rh = 71\%)}{t^{0V\rightarrow 200V}(rh < 1\%)} = 0.03$$

0 V → 200 V at time = 0

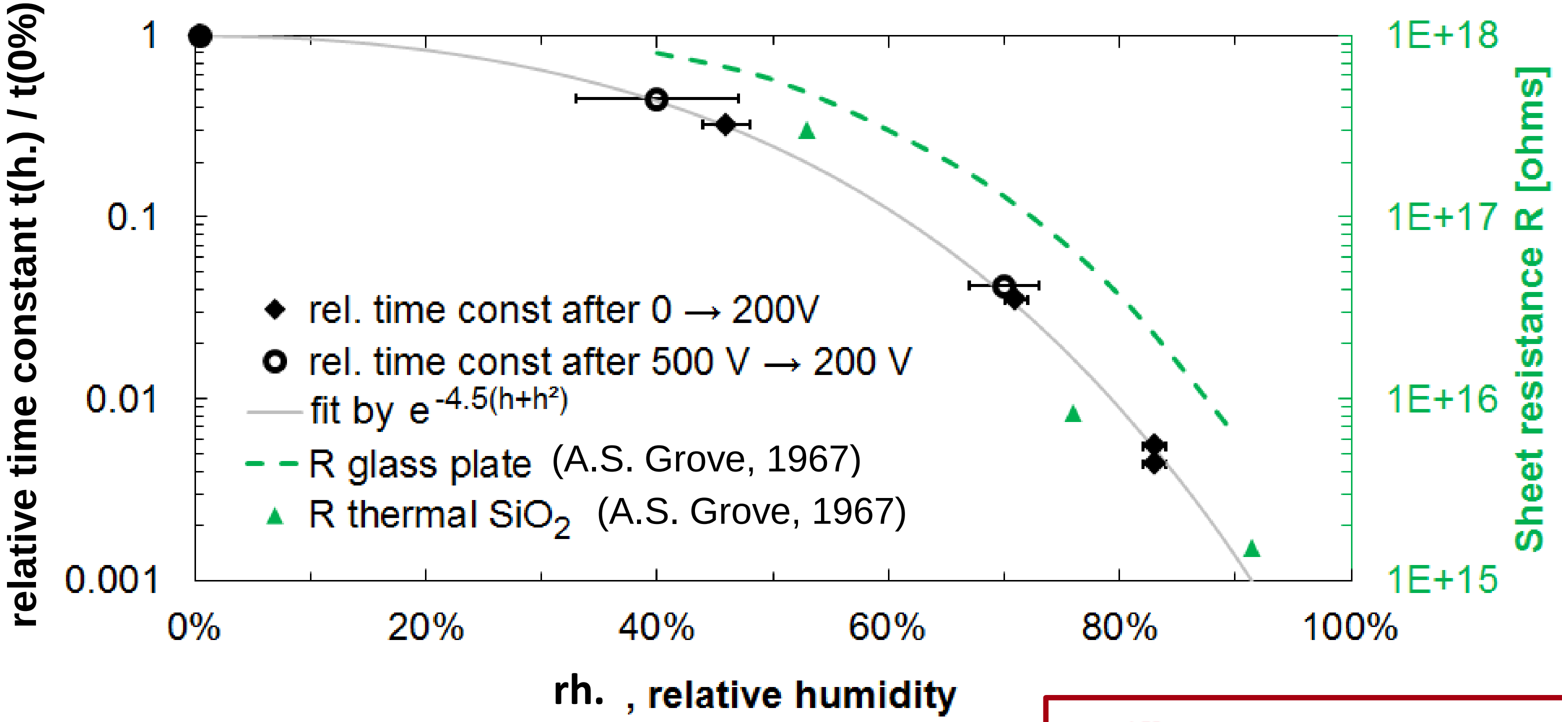
a) **In dry atmosphere** (< 1 % rh.)

b) **In humid atmosphere** (71 % rh.)



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

Relative time constants as a function of humidity for the non-irradiated sensor



A.S. Grove, *Physics and Technology of Semiconductor Devices*, John Wiley & Sons (1967).

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

$t^{0V}(h)$, $t^{500V}(h)$ → no losses

$$\left.\begin{array}{l} \dfrac{t^{0V}(rh)}{t^{0V}(0\%)} \\[2ex] \dfrac{t^{500V}(rh)}{t^{500V}(0\%)} \end{array}\right\}$$ same curve $\propto R(rh)$

Humidity dependence very similar for
time constants & sheet resistance ⇒ surface currents responsible for time development?

Qualitative conclusions (non-irradiated sensor)

Non-irradiated sensor:

Electric fields and **accumulation layers** very different for different **biasing histories**

⇒ Described by **simulations** only, if **surface charge is taken into account:**

- 0 V ⟶ 200 V ⇒ **electron losses explained** at time = 0
- 500 V ⟶ 200 V ⇒ **hole losses explained** at time = 0 (not shown)
- in steady state: ⇒ **full charge collection** (humid: minutes, dry: hours to days)

Some answers found …

Boundary conditions on the sensor surface have a significant impact on E-field distr.:

⇒ **Steady state:** constant surface potential (gated boundary conditions)

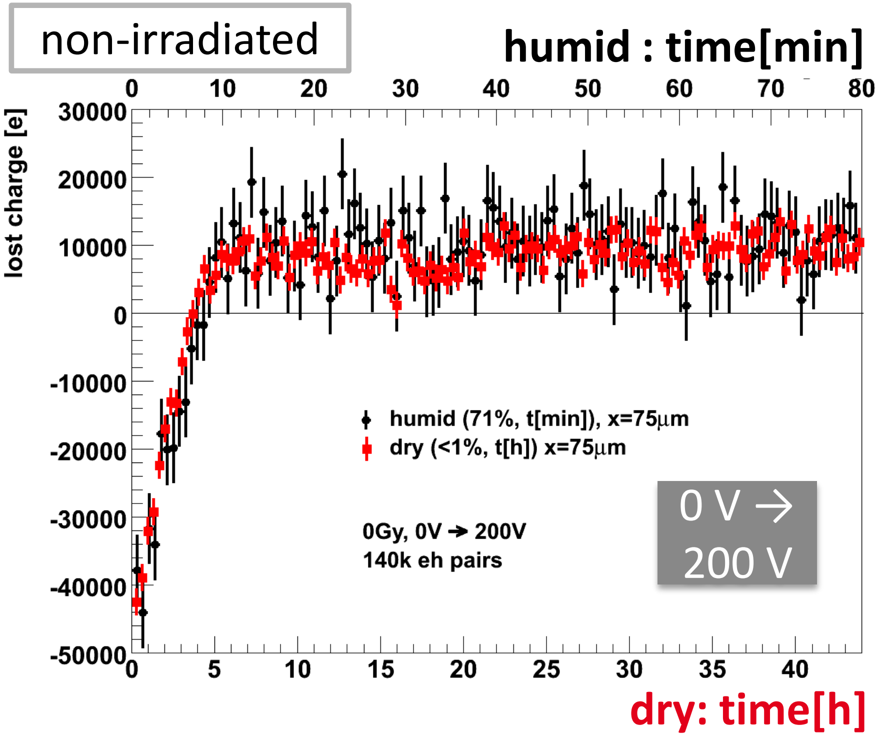
⇒ **After ramping:** calculate charges on sensor surface

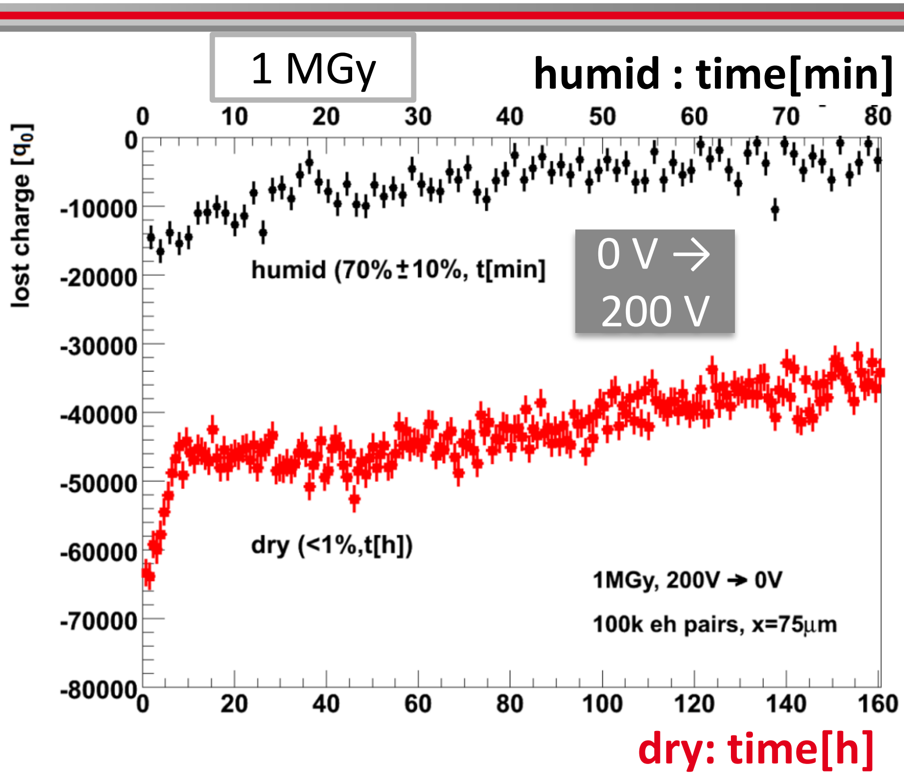
(often done: Neumann boundary conditions -> similar to state directly after ramping)

Electric field varies with time: Cannot be described with fixed boundary conditions.

Humidity -> time constants: minutes to days

Time development of charge losses non-irradiated vs. after 1 MGy





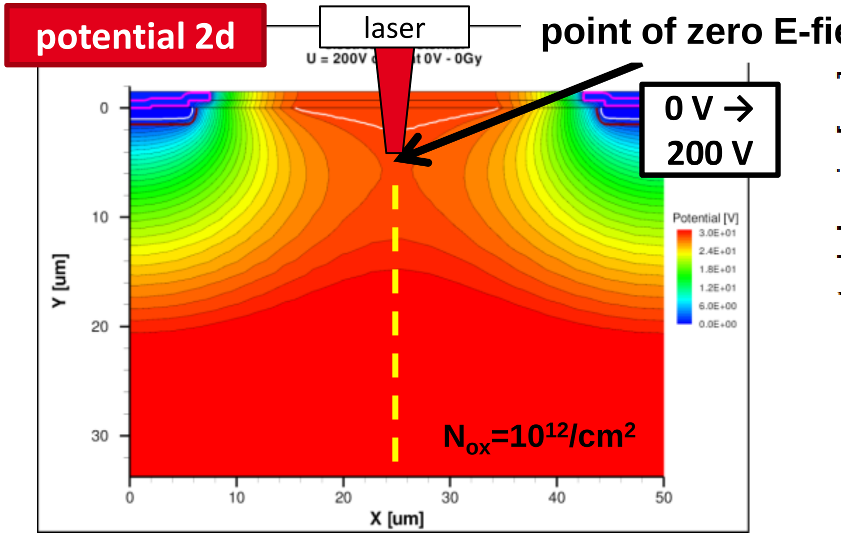
relative time const. 70% h./dry = **1/ 30**

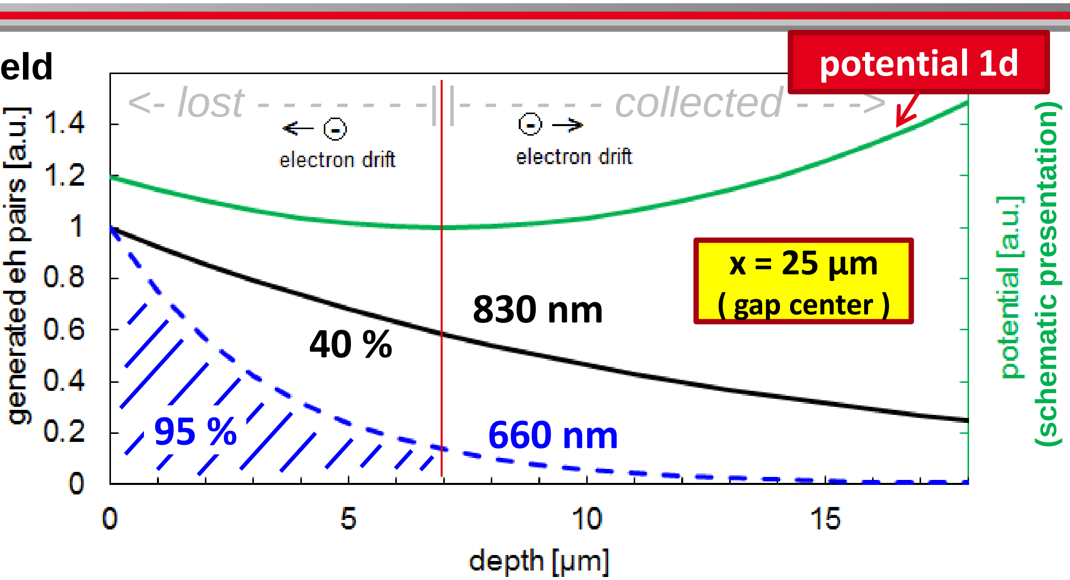
relative time const. 70% h./dry >> **1/ 10 000**
dry: E-field still changes after > 6 days

Before irradiation: time constants <-> surface resitivity,
(& simulations describe electron losses at t=0, full charge collection at t ⟶ ∞)

After irradiation: additional effects relevant (interface traps with impact on E-field ?)

A measurement of the point of zero-field for the sensor after 1 MGy X-ray irradiation





- Irradiated sensor (1 MGy, assume $N_{ox}=10^{12}$ cm^{-2})
- Dried at 0 V, directly before measurement
- Illumination in-between strips (gap centre)

Wavelength	660 nm	830 nm
Attenuation length at RT	**3.5 µm**	**13 µm**
Expected electron losses	**95 %**	**40 %**
Measured electron losses	**> 90 %**	**50 % ± 10 %**
└-> zero-field point	**> 5 µm**	**9 µm ± 2µm**

⇒ Charge losses compatible with the simulated zero-field point, 7 µm below SiO_2

(for t > 0 and in steady state this is not true -> $N_{ox}<10^{12}$ cm^{-2} ?)

Summary & Conculsions

Time dependence: The **E-field distributions changes significantly with time**
--> **not described by fixed boundary conditions**
--> surface charges must be taken into account
Time constants are a function of humidity (due to the surface resistivity)
After 1 MGy X-ray irradiation: Even stronger impact of humidity (not fully understood)
Dry atmosphere: **steady state not reached after 6 days**

Boundary conditions on the surface (-> or surface charges) and **oxide charges** have a **significant impact** on the electric field (and on the accumulation layers)
--> also impact on charge sharing?

Surface damage also relevant at the HL-LHC (up to ~5 MGy)

Charge losses at Si-SiO$_2$ interface are …

- **… very sensitive to changes in the electric field** close to Si-SiO$_2$ interface
- **… relevant for low-energy ion experiments** with strip-side illumination
- **… not studied in detail for n-on-p sensors**

Further information on studies using charge losses at the Si-SiO2 interface can be found in:
T. Poehlsen, E. Fretwurst, R. Klanner, S. Schuwalow, J. Schwandt, J. Zhang, Nucl. Instr. and Meth. A 700 (2013) 22–39
T. Poehlsen, J. Becker, E. Fretwurst, R. Klanner, J. Schwandt, J. Zhang, Nucl. Instr. and Meth. A 721 (2013) 26–34
T. Poehlsen, E. Fretwurst, R. Klanner, J. Schwandt, J. Zhang, Nucl. Instr. and Meth. A 731 (2013) 172–176
R. Klanner E. Fretwurst, I. Pintilie, J. Schwandt, J. Zhanga, Nucl. Instr. and Meth. A , DOI: 10.1016/j. nima.2013.05.131

Detailed Summary

Non-irradiated sensor (p-on-n):

Electric field at the Si-SiO_2 interface qualitatively understood:

- Charge distribution on the top of the passivation layer and **E-field changes with time**
- Humidity-dependent surface resistivity → **time constants are a function of humidity**
- **Different boundary conditions** (/surface charges) for different biasing and humidity histories **needed**, **to describe E-field, charge collection and accumulation layers.**

Sensor after 1 MGy irradiation (p-on-n):

- **For "dried at 0V" (0V->200V, at t ≈ 0):** electric field well described using $N_{ox}=10^{12}cm^{-2}$ (simulated point of zero electric field **compatible with measurements**)
- **For t > 0 and other humidity and biasing histories:** simulations **not compatible** with measurements (implement interface traps differently?)

Charge losses at Si-SiO_2 interface are …

- **… very sensitive to changes in the electric field** close to Si-SiO_2 interface
- **… relevant for low-energy ion experiments** with strip-side illumination
- **… not studied in detail for n-on-p sensors** (for p-on-n: not relevant for MIPs)

Further information on the topic can be found in:

T. Poehlsen, E. Fretwurst, R. Klanner, S. Schuwalow, J. Schwandt, J. Zhang, Nucl. Instr. and Meth. A 700 (2013) 22–39
T. Poehlsen, J. Becker, E. Fretwurst, R. Klanner, J. Schwandt, J. Zhang, Nucl. Instr. and Meth. A 721 (2013) 26–34
T. Poehlsen, E. Fretwurst, R. Klanner, J. Schwandt, J. Zhang, Nucl. Instr. and Meth. A 731 (2013) 172–176

The electric potential for a typical assumption on the oxide charge density N_{ox}

After 1 MGy of X-ray irradiation we measured:

$\Rightarrow$ Oxide charge density: $1.4 \cdot 10^{12}/\mathrm{cm}^2$ (+)
(from flat band voltage)

$\Rightarrow$ Interface state density: $1.6 \cdot 10^{12}/\mathrm{cm}^2$ (?)
(from TDRC meas.)

Implement in device simulations:
fixed charge density $1 \cdot 10^{12}/\mathrm{cm}^2$ at interface

- Simulated potential mainly independent of surface charges. Agrees with measurements only for „0 V → 200 V" at t = 0.

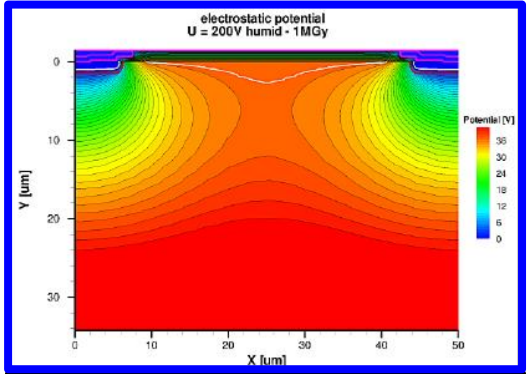
$\Rightarrow$ For t>0 and for other biasing histories: Interface charge < $1 \cdot 10^{12}/\mathrm{cm}^2$?

Interface traps to be implemented as defects?

observed losses

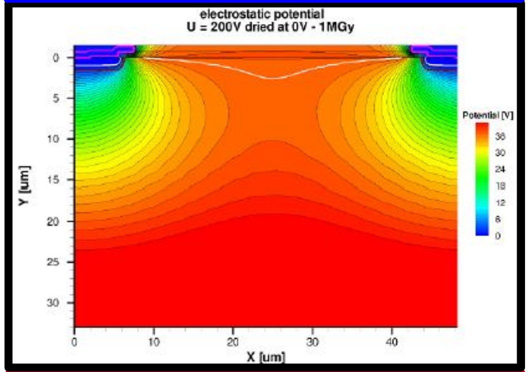
200 V, in steady st.

40 % to 10 % electron losses



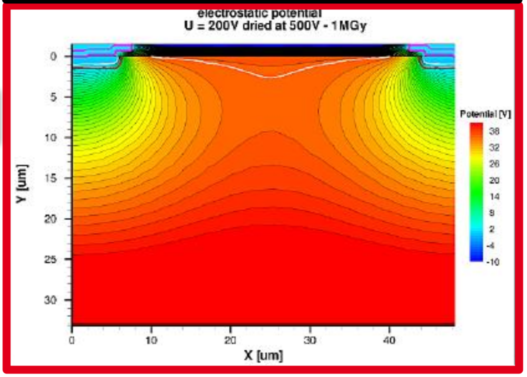
0 V → 200 V

100 % to 90 % electron losses



500 V → 200 V

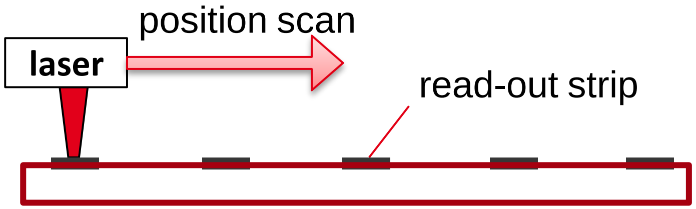
0 to 30% hole losses



Collected electrons and holes, accumulation layer width for different biasing histories

Position scans, strip- & rear-side readout
⇒ extract number of **electrons** and **holes** collected & **accumulation layer width**

Q(x) is described by a model calculation



Fit results – non-irradiated

	humid	**dried at 500V**	**dried at 0V**
electrons*	135 000	137 000	**58 000**
holes	133 000	**64 000**	133 000
acc. layer	-	31 µm	36 µm

* shown is the average number of electrons (of the position scan)

Fit results – after 1 MGy

	humid	**dried at 500V**	**dried at 0V**
electrons*	**91 000**	124 000	**5 000**
holes	121 000	**112 000**	126 000
acc. layer	34 µm	-	36 µm

* shown is the average number of electrons (of the position scan)

Depending on the biasing history:

- **electron losses (~50 %)**,
- **full charge collection**, and
- **hole losses (~50 %)**

are observed in non-irradiated sensor.

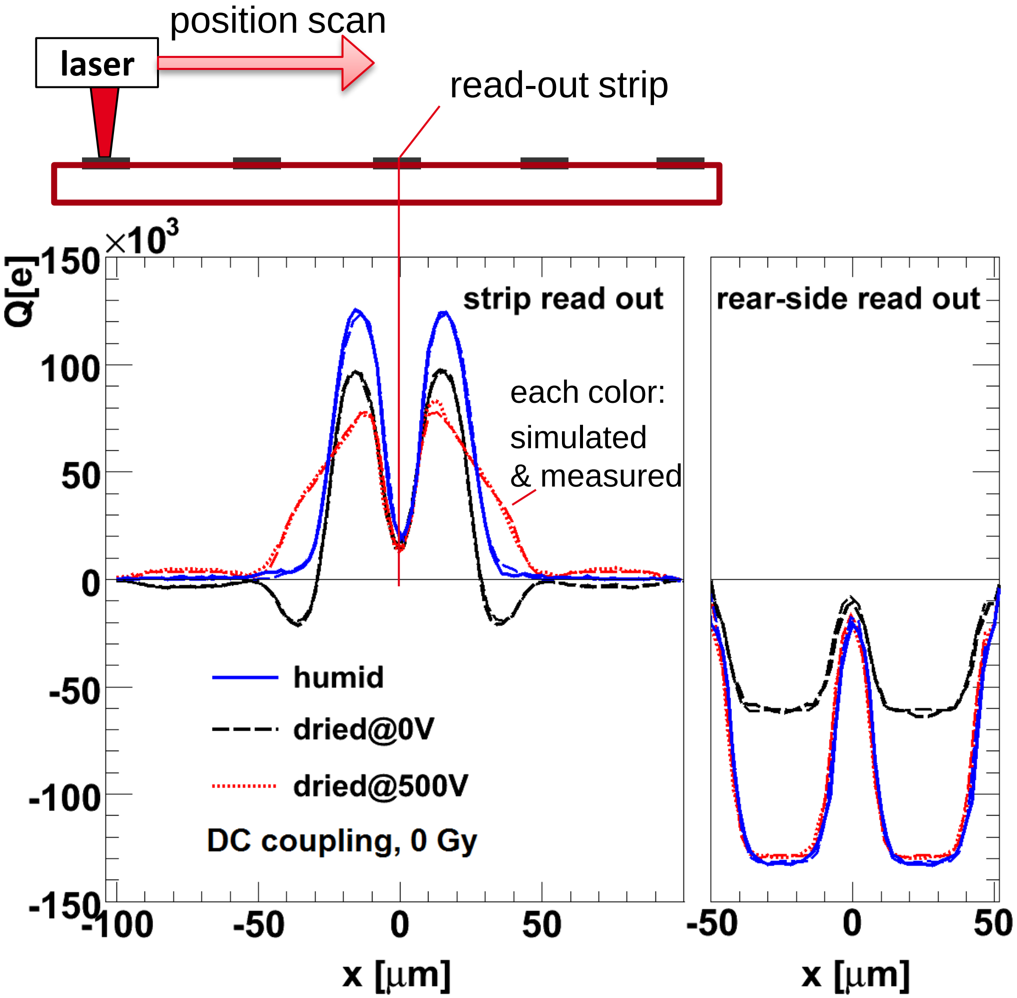
Depending on the biasing history:

- **strong electron losses (~95 %)**,
- **few electron losses**, and
- **few hole losses**

are observed after 1 MGy irradiation.

Charge as a function of light-spot position
Simulated and measured

Position scans, strip- & rear-side readout
⇒ extract number of **electrons** and **holes** collected & **accumulation layer width**



Q(x) is described by a model calculation

Fit results

	humid	**dried at 500V**	**dried at 0V**
electrons*	135 000	137 000	**58 000**
holes	133 000	**64 000**	133 000
acc. layer	-	31 μm	36 μm

* shown is the average number of electrons

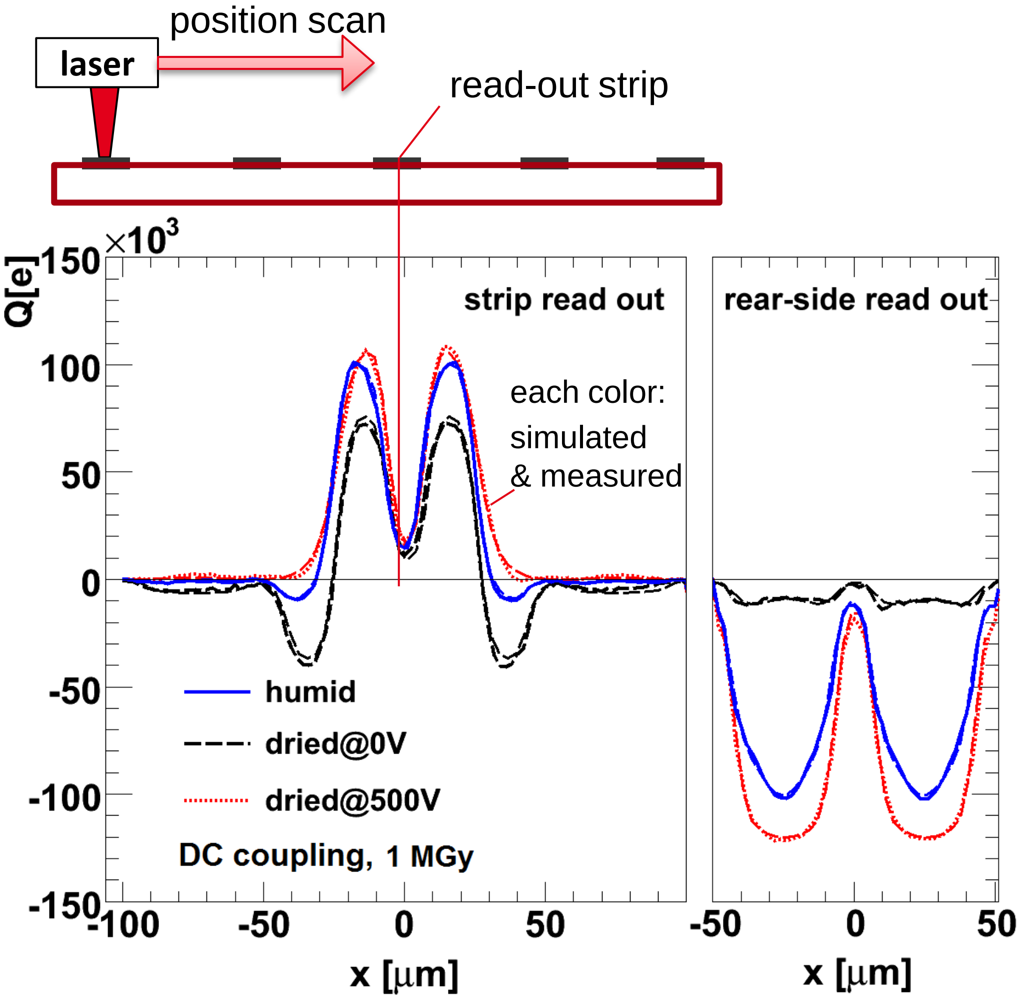
Depending on the biasing history

- **Electron losses**,
- **Full charge collection**, and
- **Hole losses**

are observed in the non-irradiated sensor.

Charge as a function of light-spot position after 1 MGy – simulated and measured

Position scans, strip- & rear-side readout
⇒ extract number of **electrons** and **holes** collected & **accumulation layer width**



Q(x) is described by a model calculation

Fit results

	humid	**dried at 500V**	**dried at 0V**
electrons*	**91 000**	124 000	**5 000**
holes	121 000	**112 000**	126 000
acc. layer	34 μm	-	36 μm

* shown is the average number of electrons

Depending on the biasing history:

- **strong electron losses (~95 %)**,
- **few electron losses**, and
- **few hole losses**

are observed after 1 MGy irradiation.

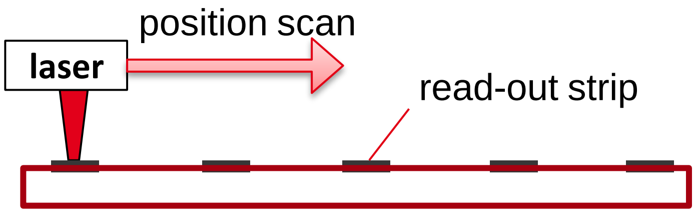
Collected charge as a function of position

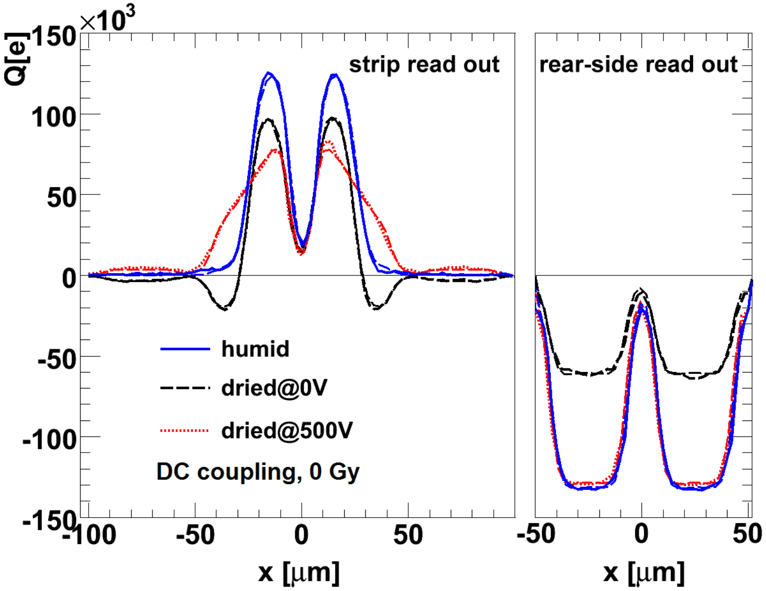
Biasing and humidity history (start with 60% h.):

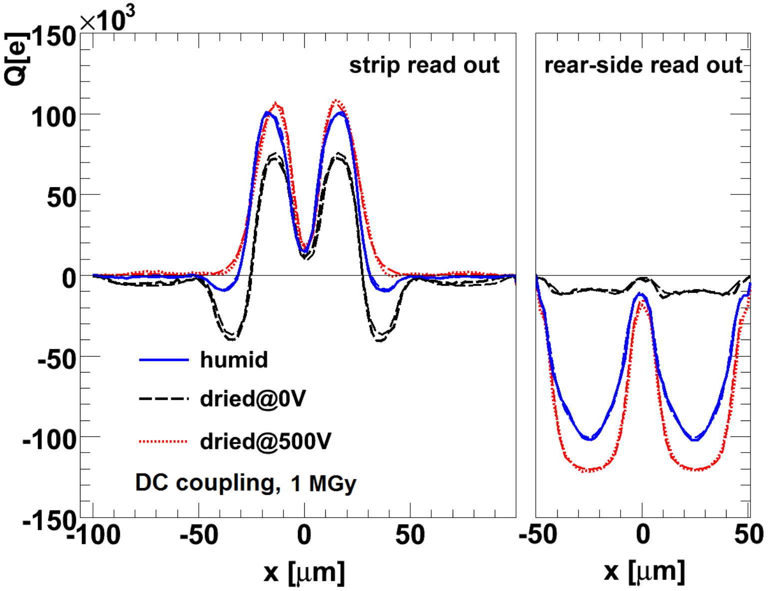
dry at 0 V, → 200 V

→ 200 V, **humid** (humidity > 60 %)

→ 500 V, **dry at 500 V**, → 200 V

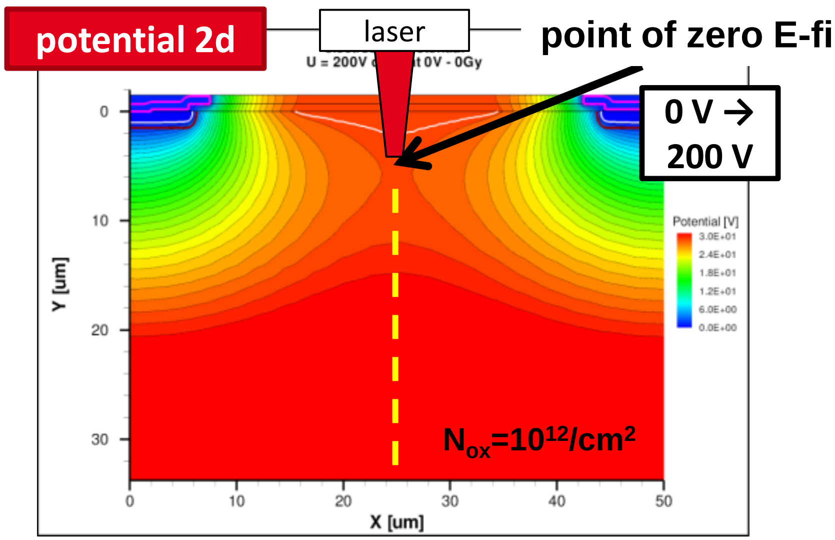


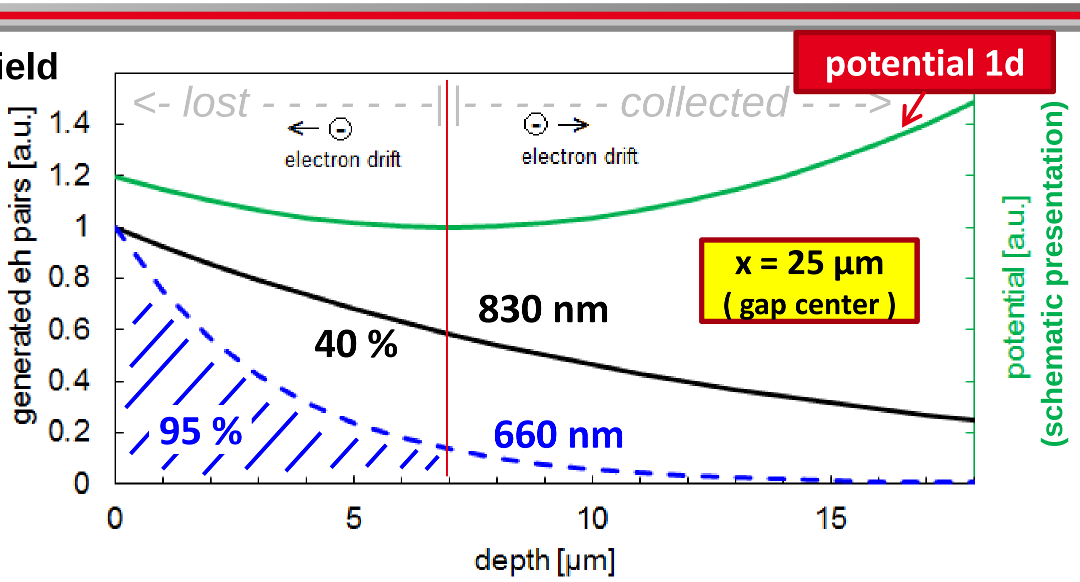




	humid 0 Gy	dried@500 V 0 Gy	dried@0 V 0 Gy	humid 1 MGy	dried@0 V 1 MGy	dried@500 V 1 MGy
N_e^c	128 000	129 000	53 000	109 000	0	123 000
N_e^e	143 000	145 000	63 000	72 500	9 400	124 000
N_h	133 000	64 000	133 000	121 000	126 000	112 000
x_0	0.90 μm	1.83 μm	- 0.18 μm	1.64 μm	0.77 μm	0.80 μm
d_{acc}	(34 μm)	31 μm	36 μm	34 μm	36 μm	(6 μm)
σ_{diff}	2.7 μm	14.1μm	3.1 μm	2.2 μm	2.1 μm	5.4 μm

A measurement of the point of zero-field for the sensor after 1 MGy x-ray irradiation





- Irradiated strip sensor (1 MGy)
- Dried at 0 V directly before meas.
- Illumination in-between strips (centre)

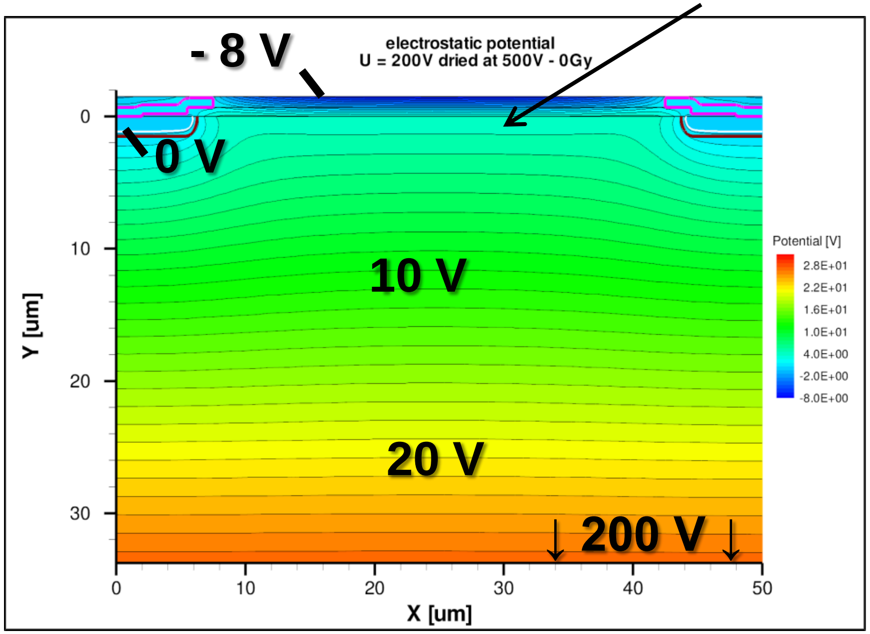
Wavelength	660 nm	830 nm
Measured electron losses	95 % ± 10 %	50 % ± 10 %
Measured zero-field point	> 5 µm	9 µm ± 2µm
Non-irradiated sensors:		
Measured electron losses	35 % ± 10 %	20 % ± 10 %
Measured zero-field point	1.5 ± 0.5 µm	2.8 ± 1 µm

⇒ **Measured zero-field point 9 µm below the SiO_2**

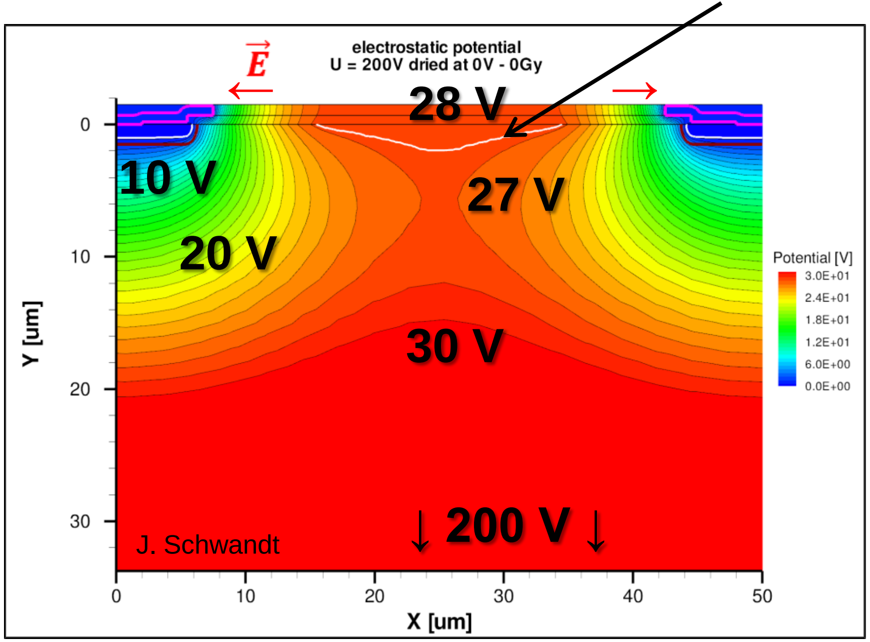
(compatible with 7 µm according to simulations for $N_{ox} = 10^{12}\ cm^{-2}$)

TCAD simulations: electrostatic potential

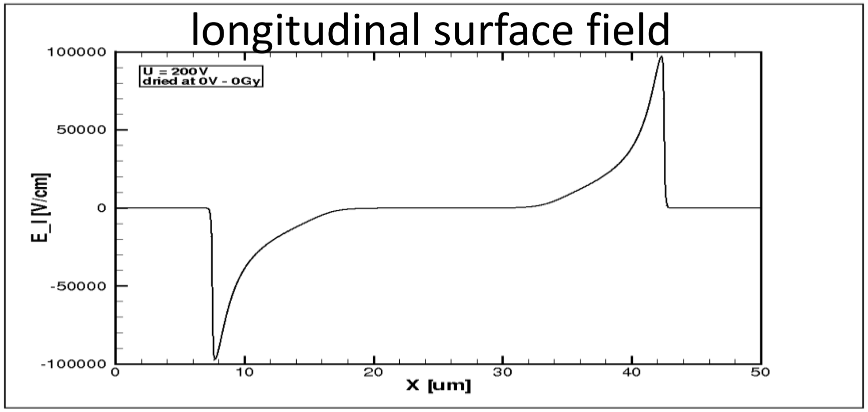
500 V → 200 V ⇒ hole losses



0 V → 200 V ⇒ electron losses



longitudinal surface field



a) 0 V, fix surface charge → 200 V

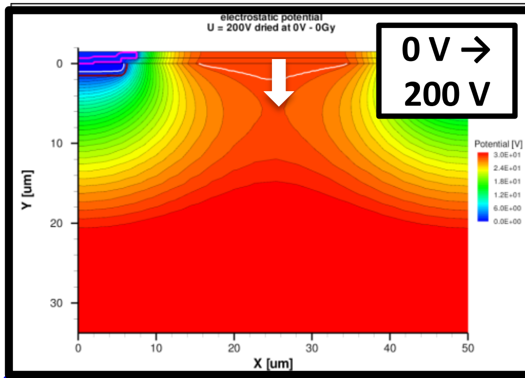
⇒ Longitudinal surface field

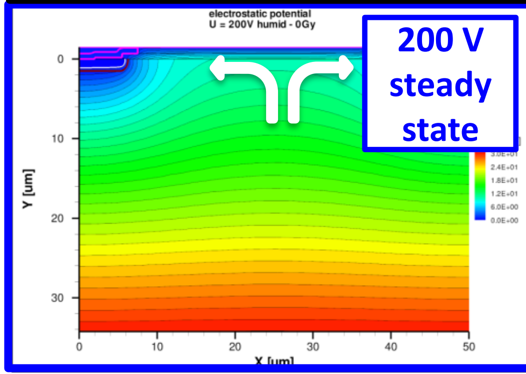
c) → 500 V, redistribute and fix surface charge (0 V surface potential) → 200 V

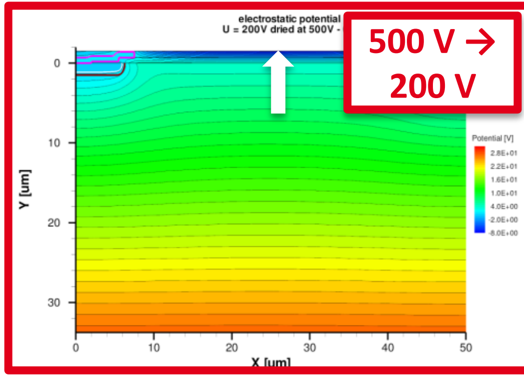
The electric potential for different biasing histories

Simulations describe the measurements qualitatively

- electric field **points out of the SiO_2** into the silicon bulk
  ⇒ **electron losses** observed
- electric field **points in the direction of the readout strips**
  ⇒ **full charge collection** observed
- electric field **points from the silicon bulk into the SiO_2**
  ⇒ **hole losses** observed **(and a hole accumulation layer)**







Some answers found …

- What **boundary conditions** should be used on the top of the passivation?
- Does the electric field **develop in time**?
- How does **humidity** influence the electric-field distribution?
- What is the **charge distribution at the interface**?

In simulations assumed an oxide charge density **10^{11} cm^{-2}**

The electric potential for different biasing histories and different oxide charge densities

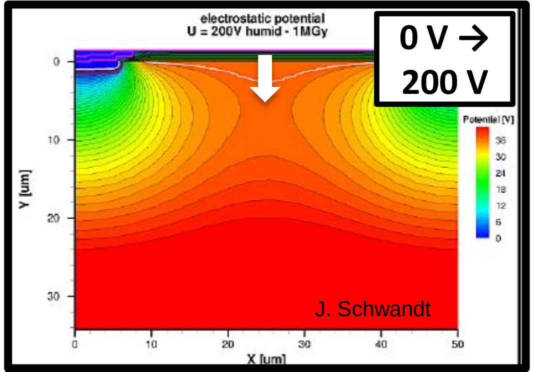
After 1 MGy of x-ray irradiation:

$\Rightarrow$ Oxide charge density: $1.4 \cdot 10^{12}/\text{cm}^2$ (+)

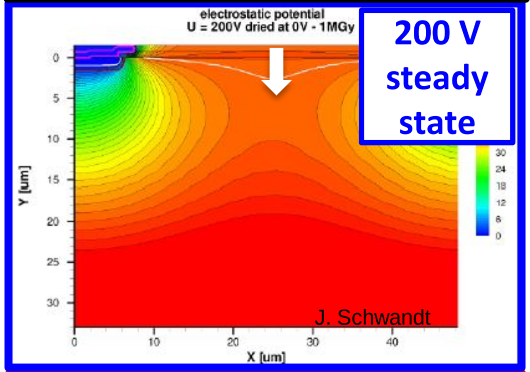
$\Rightarrow$ Interface state density: $1.6 \cdot 10^{12}/\text{cm}^2$ (?)

Implement in device simulations: $1 \cdot 10^{12}/\text{cm}^2$

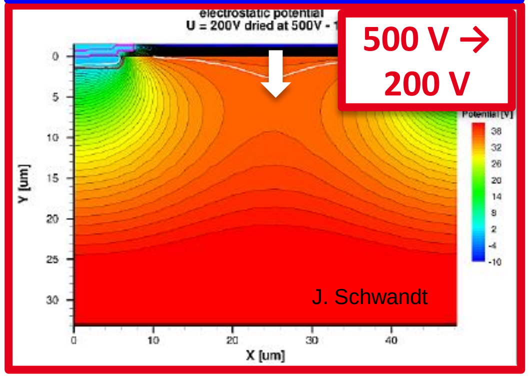
- $\Rightarrow$ The dependence on the biasing history is negligible
- $\Rightarrow$ Electron losses are expected for all biasing histories



0 V → 200 V



200 V steady state



500 V → 200 V

The electric potential for different biasing histories and different oxide charge densities

After 1 MGy of x-ray irradiation:

$\Rightarrow$ Oxide charge density: $1.4 \cdot 10^{12}/\mathrm{cm}^2$ (+)

$\Rightarrow$ Interface state density: $1.6 \cdot 10^{12}/\mathrm{cm}^2$ (?)

Implement in device simulations: $1 \cdot 10^{12}/\mathrm{cm}^2$

$\Rightarrow$ The dependence on the biasing history is negligible

$\Rightarrow$ Electron losses are expected for all biasing histories

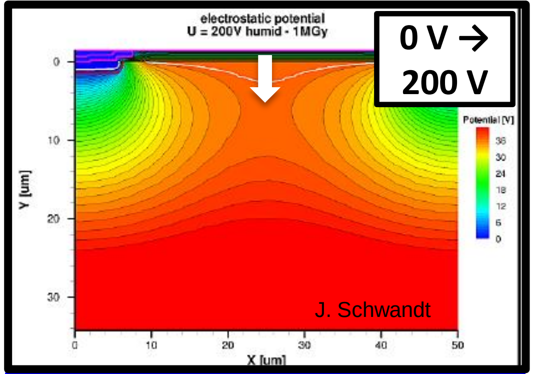
- Observed losses are not fully reproduced by the simulation

- **For some biasing histories** the oxide charge is smaller than $1 \cdot 10^{12}/\mathrm{cm}^2$

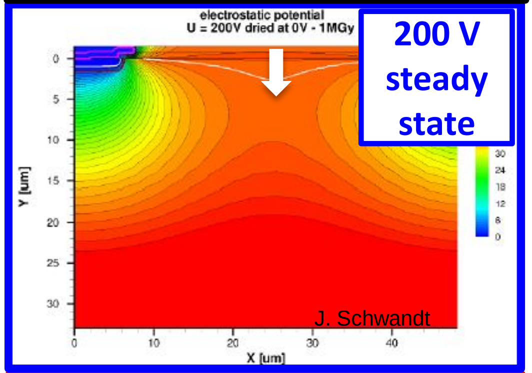
  $\Rightarrow$ **Interface states give a significant negatively contribution**

observed losses

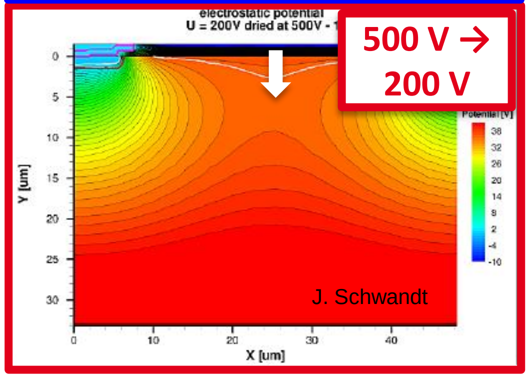
100 % to 80 % electron losses



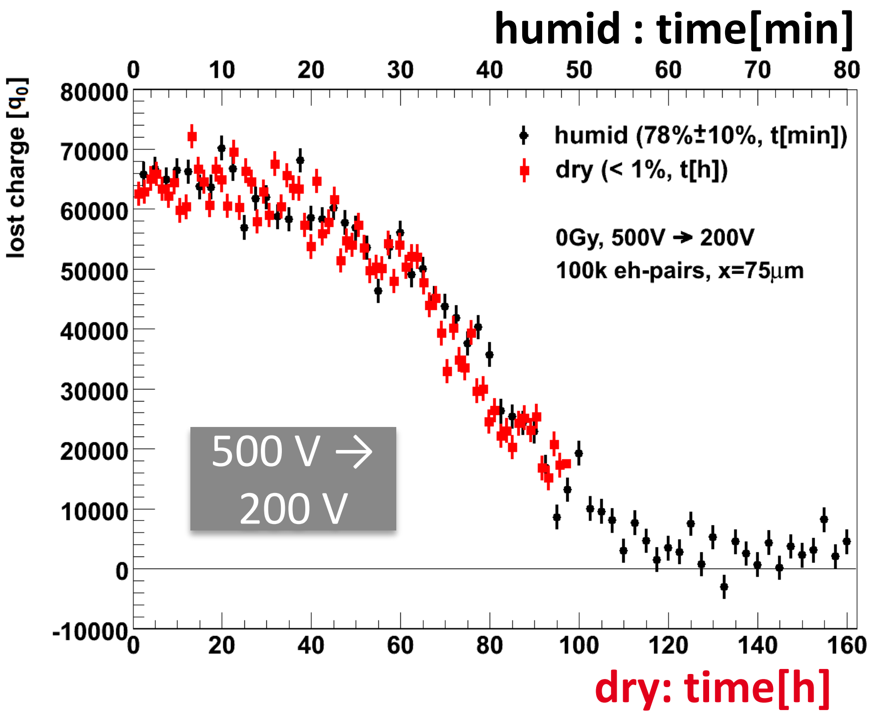
40 % to 10 % electron losses

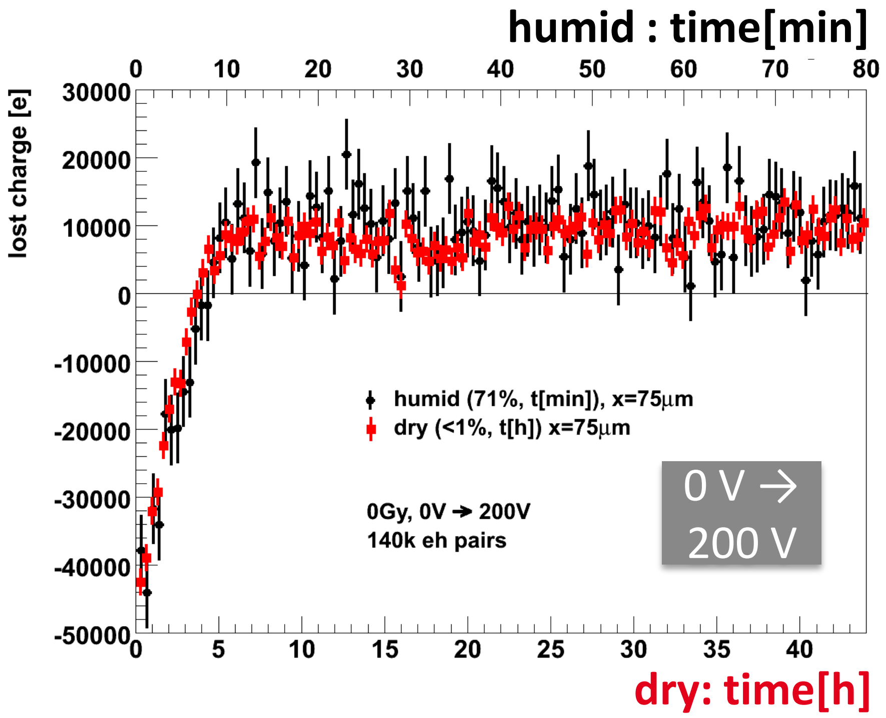


0 to 30% hole losses



Time development of charge losses, 0 Gy





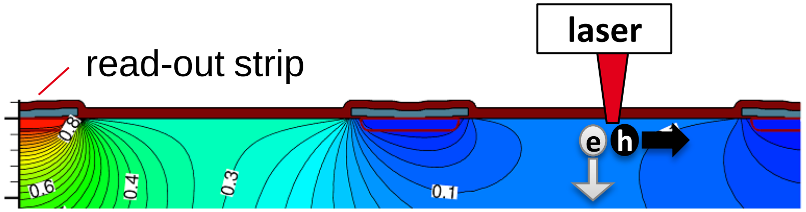
$$\frac{t^{500V\rightarrow200V}(h.\approx 78\%)}{t^{500V\rightarrow200V}(h.< 1\%)}=0.008$$

$$\frac{t^{0V\rightarrow200V}(h.= 71\%)}{t^{0V\rightarrow200V}(h.< 1\%)}=0.03$$

a) **In dry atmosphere** (< 1 % humidity)

b) **In humid atmosphere** (~78 %, 71% humidity)

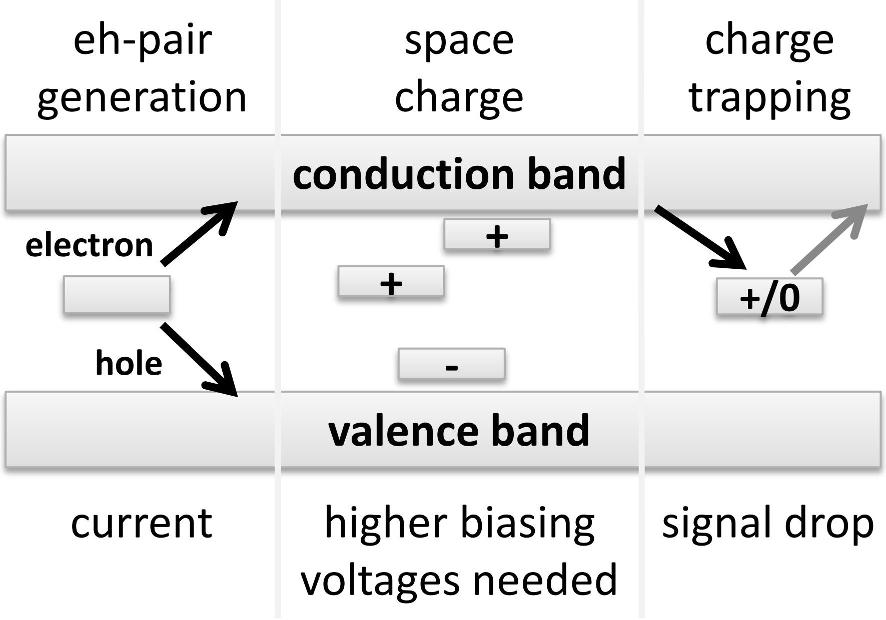
Before: sensor at 0 V / 500 V for > 2 hours in humid atmosphere



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Radiation damage

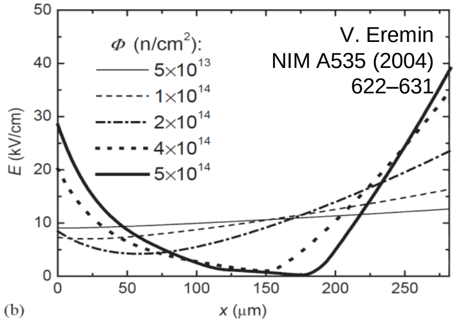
Bulk damage (by non-ionising energy loss)



eh-pair generation	space charge	charge trapping
current	higher biasing voltages needed	signal drop

Occupation of states depends on

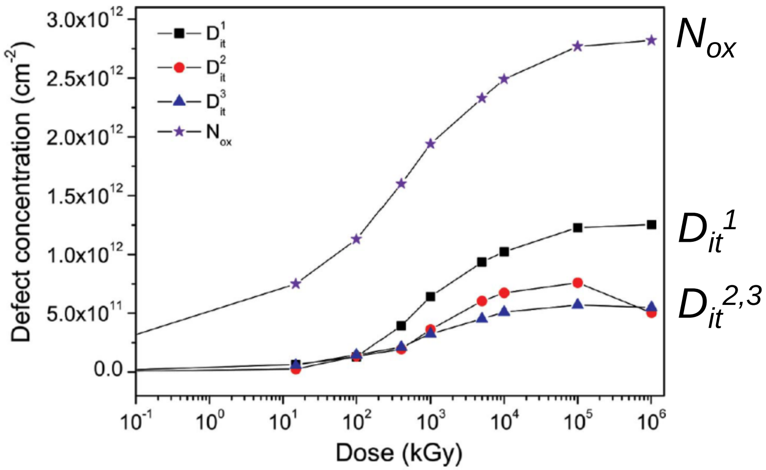
- position in band gap
- local electric field E(x)
- local current densities
- temperature
- …

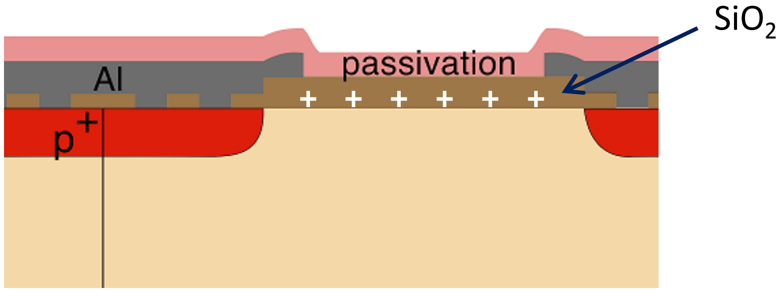


Surface damage (by ionising energy loss)

built-up of

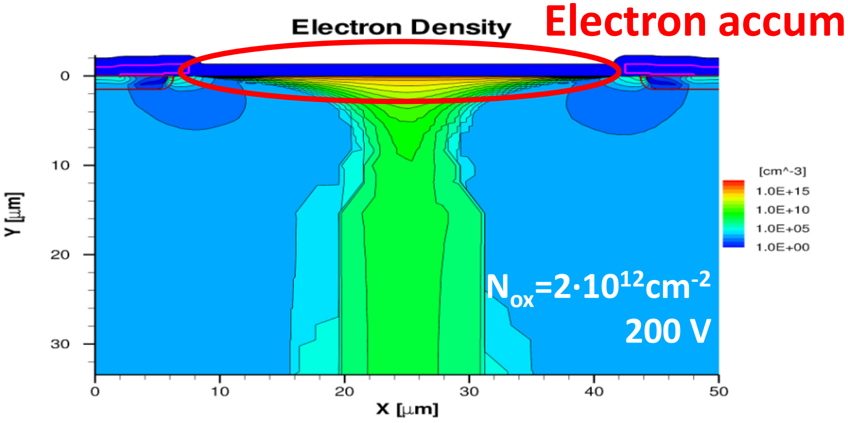
- interface states D_{it}
- fixed oxide charge N_{ox}





Accumulation layer and breakdown

Due to positive oxide charge in the SiO_2 an electron accumulation layer forms and high electric fields are present.



Electron accumulation layer

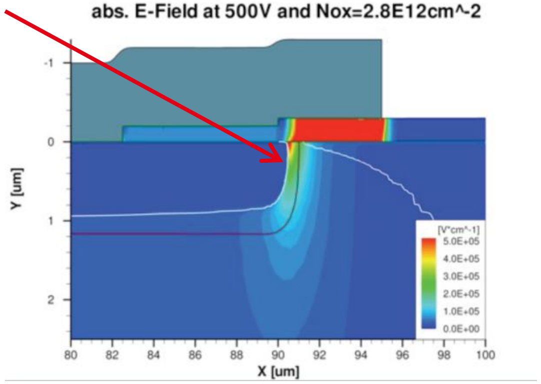
$N_{ox}=2\cdot10^{12}cm^{-2}$

200 V

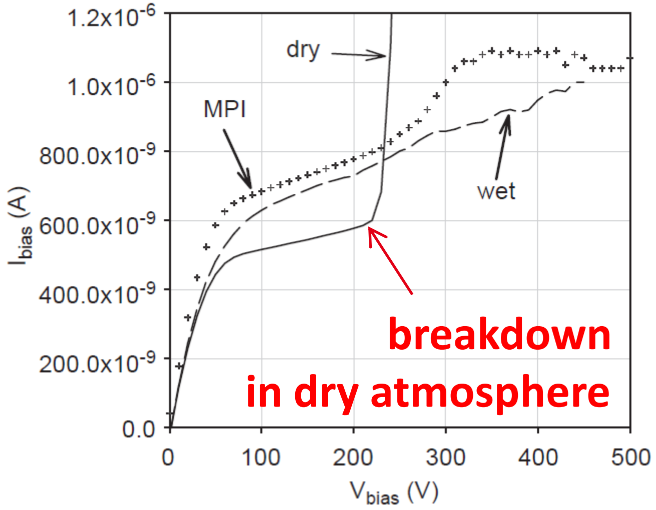
Breakdown voltage of the sensor depends on

- oxide charge (fixed oxide charge + charged interface states)
  depends on the radiation dose and crystal orientation
- oxide thickness
- humidity

High electric fields at the strip implants

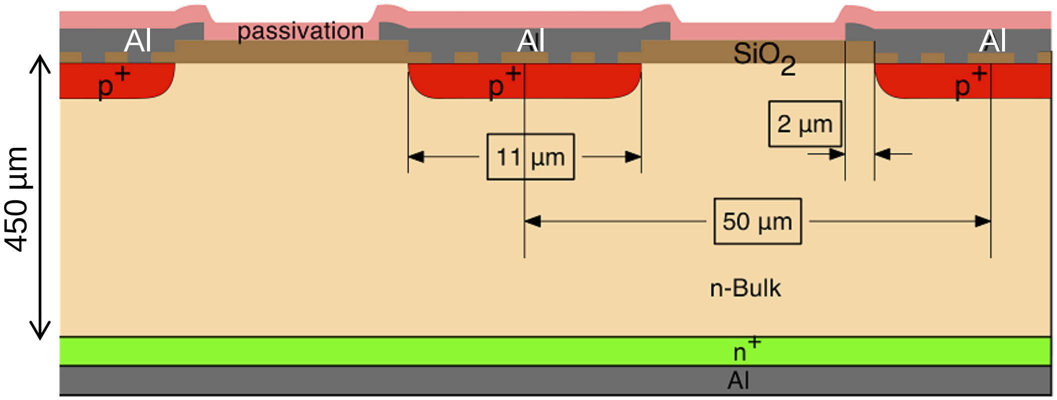


Hartjes, NIM A, 552 (2005), p. 168



breakdown in dry atmosphere

Sensor parameters

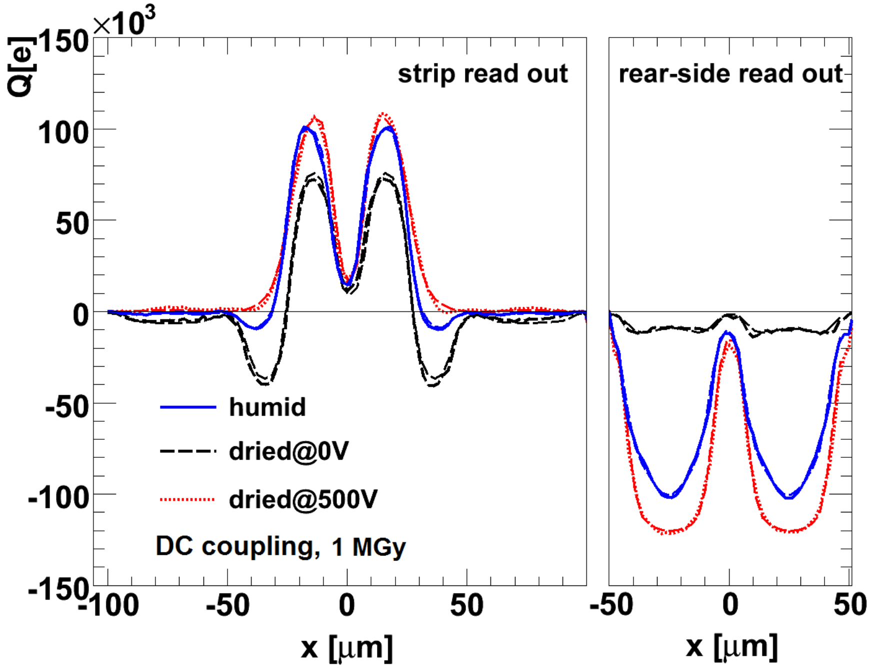


2 different p-on-n strip sensors are used showing similar results

Producer	**Hamamatsu**	CiS
Coupling	**DC**	AC
Full depletion voltage	**155 V**	63 V
n-doping	**10^{12} cm^{-3}**	8 10^{11} cm^{-3}
Pitch	**50 µm**	80 µm
Implant width	**11 µm***	20 µm
Number of strips	**128**	98
Strip length	**8 mm**	7.8 mm
Thickness	**450 µm**	285 µm
Orientation	**< 1 1 1 >**	< 1 0 0 >
SiO_2 (+Si_3N_4)	**334 nm**	300+50 nm

Fit results

	humid 0 Gy	dried@500 V 0 Gy	dried@0 V 0 Gy	humid 1 MGy	dried@0 V 1 MGy	dried@500 V 1 MGy
N_e^c	128 000	129 000	53 000	109 000	0	123 000
N_e^e	143 000	145 000	63 000	72 500	9 400	124 000
N_h	133 000	64 000	133 000	121 000	126 000	112 000
x_0	0.90 µm	1.83 µm	- 0.18 µm	1.64 µm	0.77 µm	0.80 µm
d_{acc}	(34 µm)	31 µm	36 µm	34 µm	36 µm	(6 µm)
σ_{diff}	2.7 µm	14.1µm	3.1 µm	2.2 µm	2.1 µm	5.4 µm

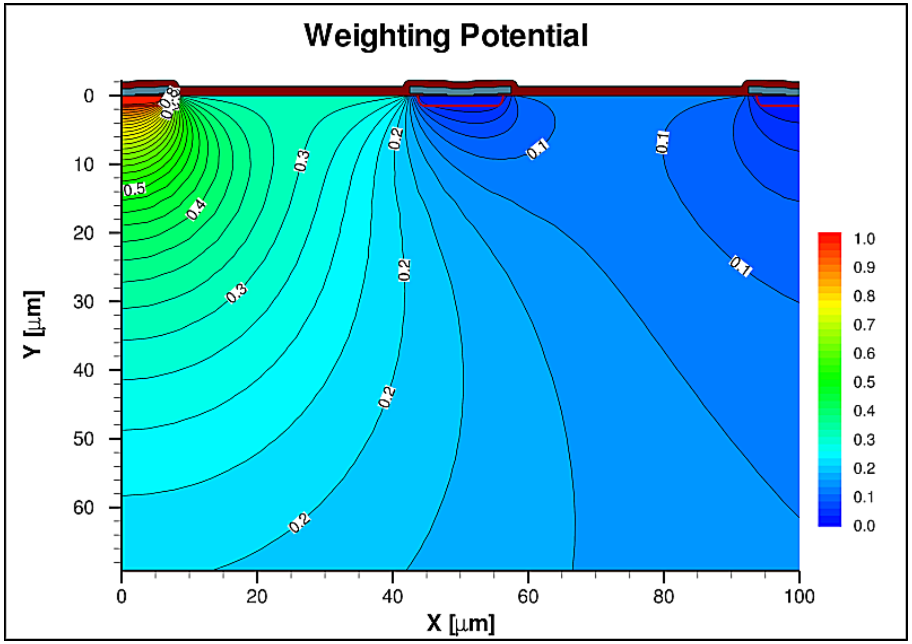


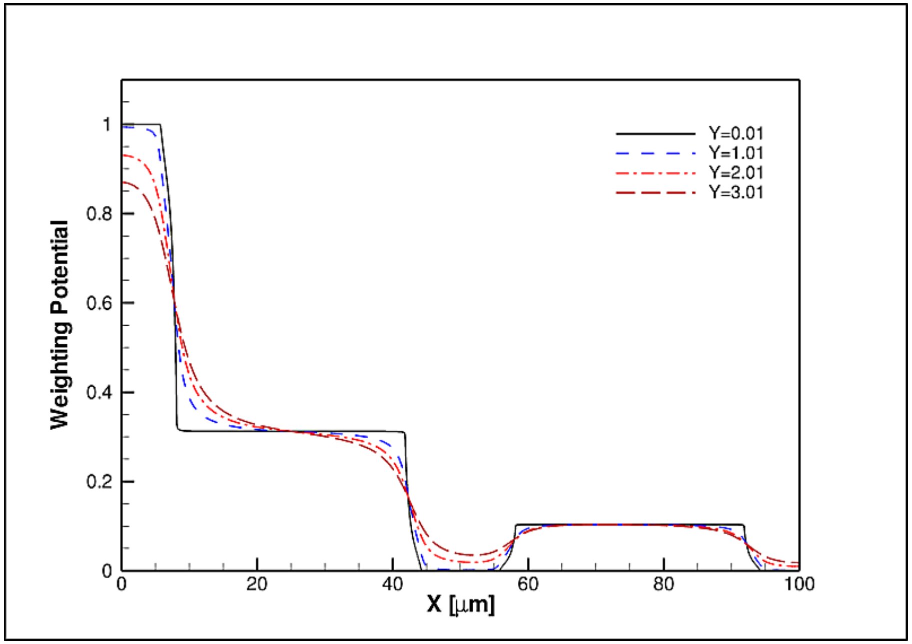
λ	830 nm	660 nm
N_e^c	49 000	0
N_e^e	73 000	9 400
N_h	108 000	126 000
x_0	-1.93 µm	0.77 µm
d_{acc}	34.7 µm	36 µm
σ_{diff}	1.2 µm	2.1 µm

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Weighting potential

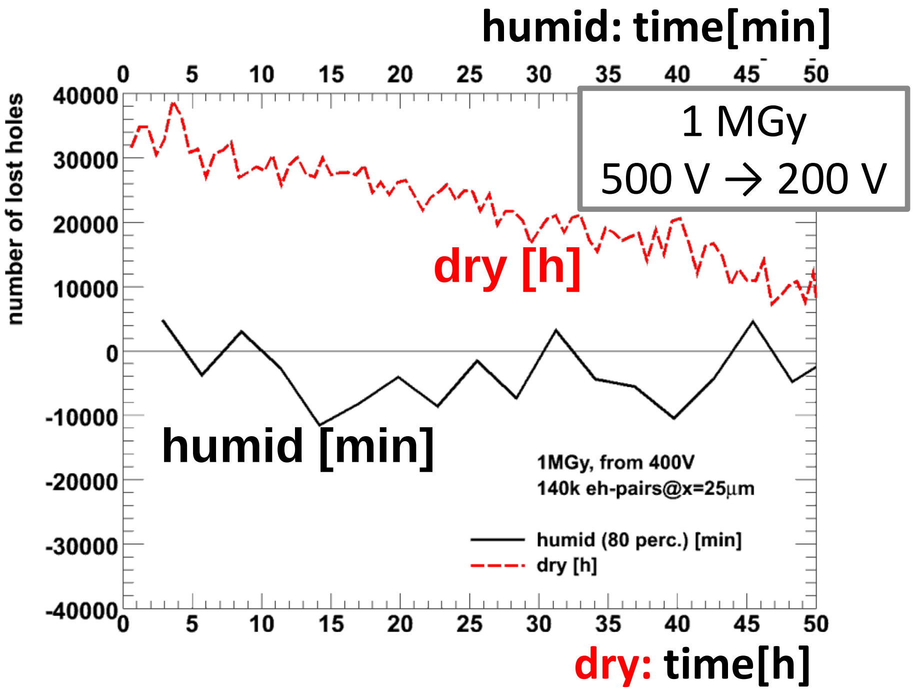
The weighting potential is constant along the accumulation layer.

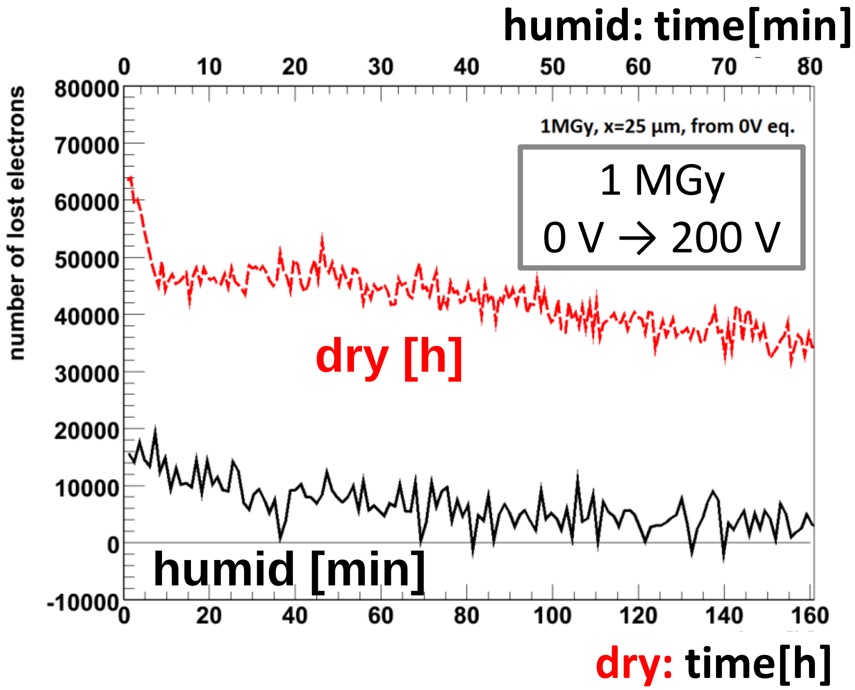




Thomas Pöhlsen
thomas.poehlsen@desy.de

Time development of charge losses after irradiation (1 MGy)



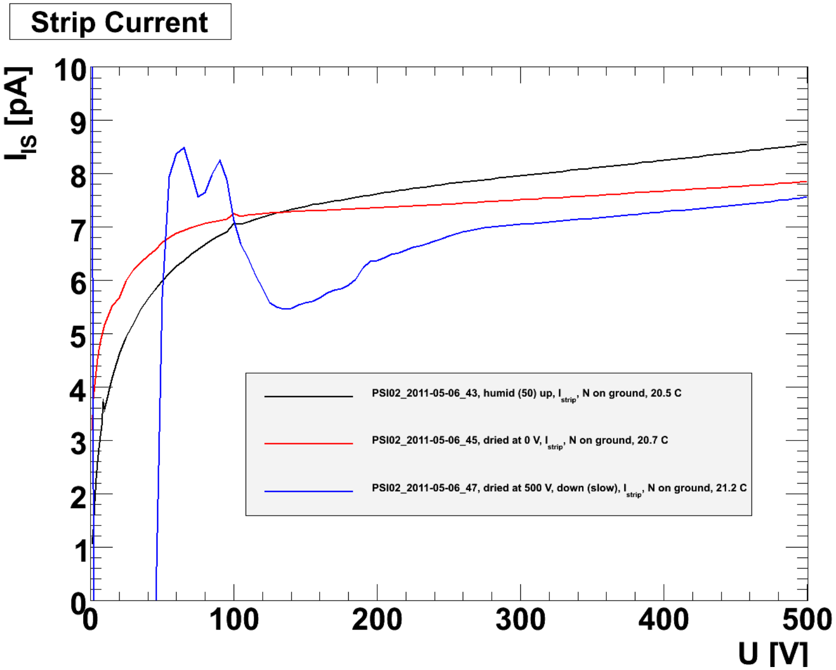


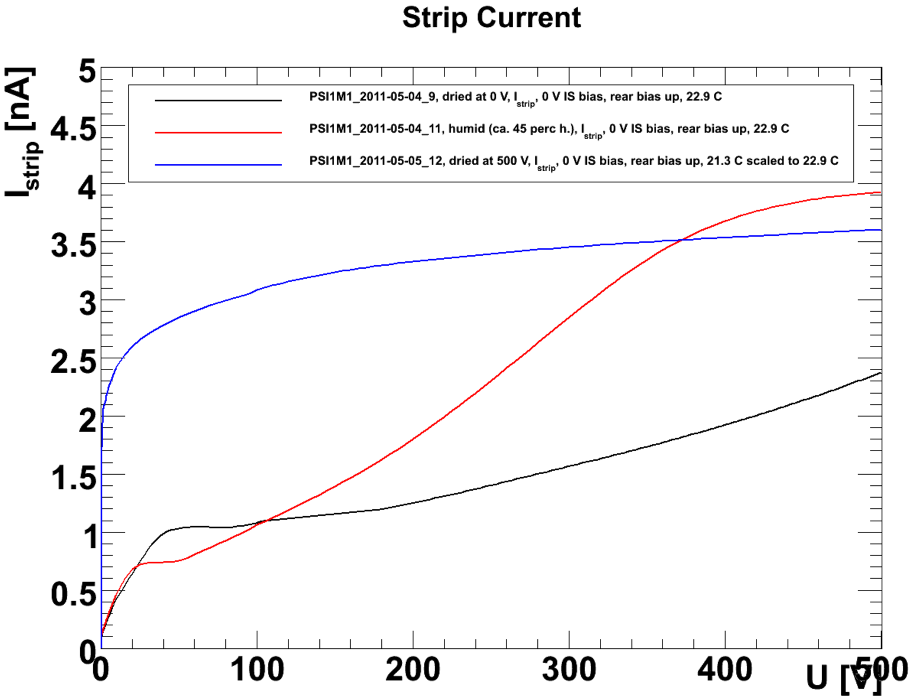
$Q_{lost} > 0$ $Q_{lost} < 0$

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

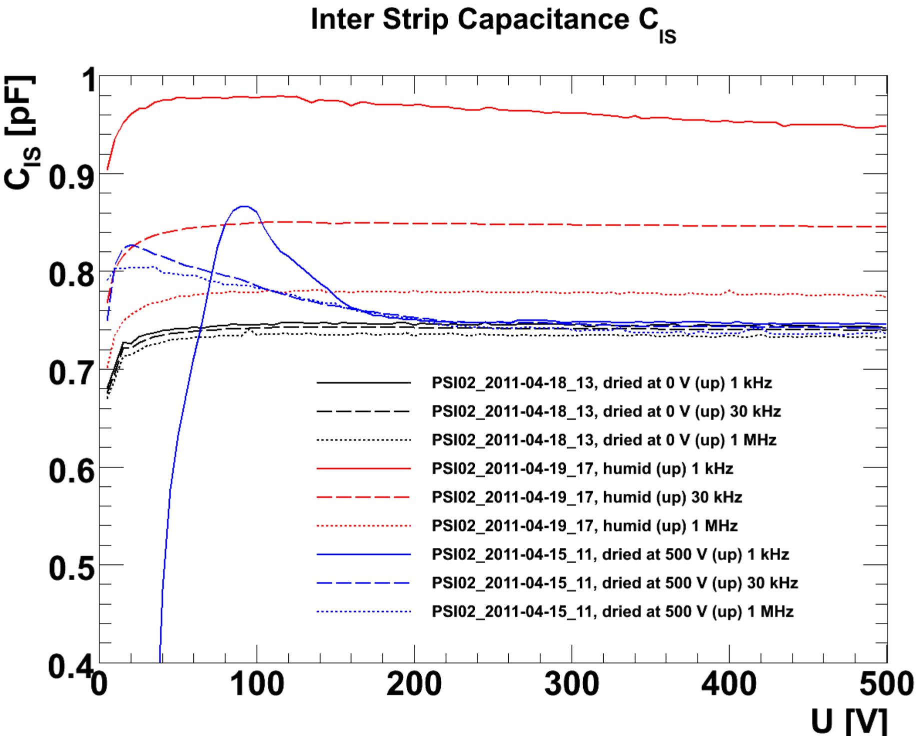
1. in dry atmosphere: **less hole losses, more electron losses** ← positive oxide charge
2. No obvious scaling for dry ↔ humid ← interface states?

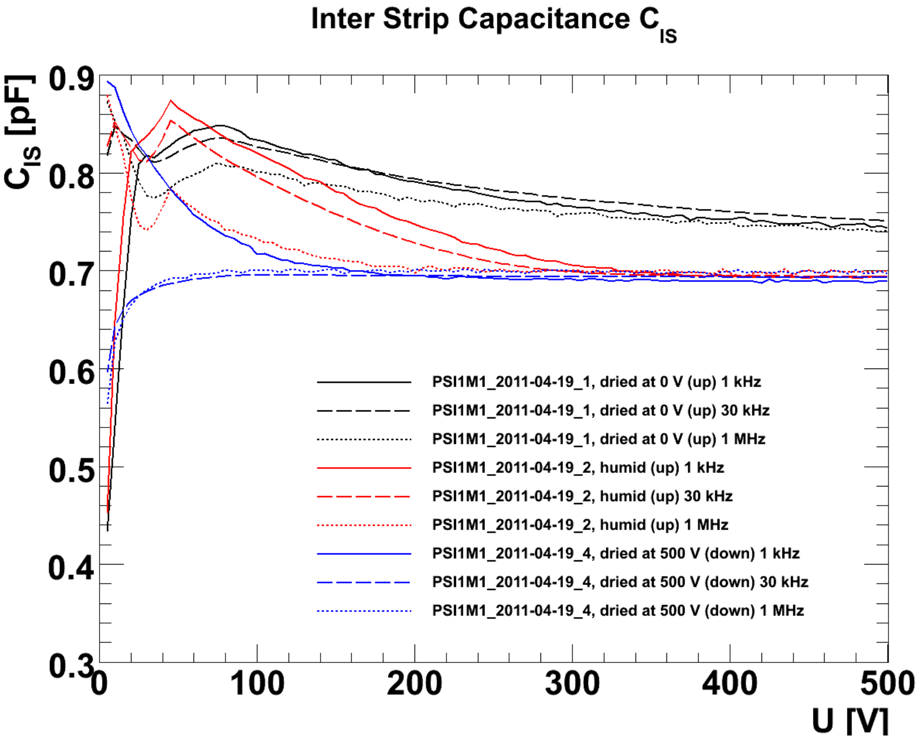
Strip current as a function of bias voltage





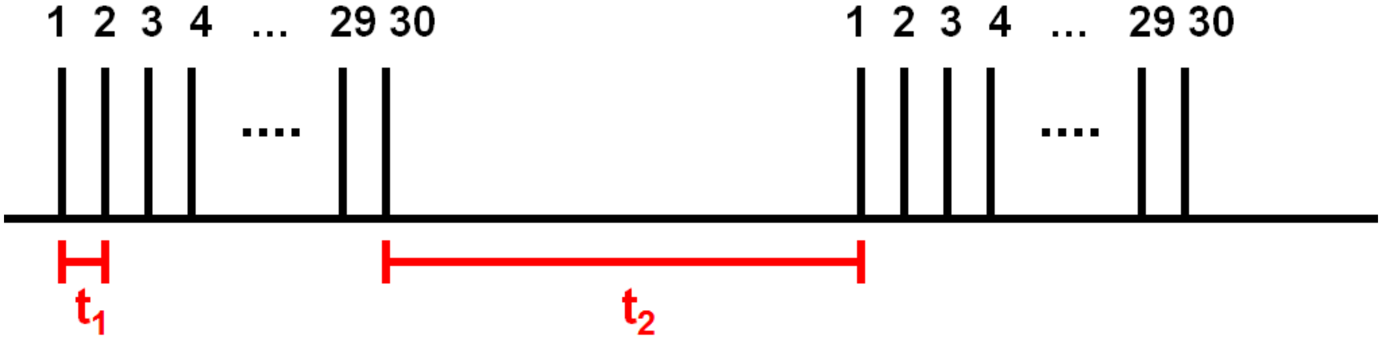
Inter strip capacitance as a function of bias voltage





Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Laser operation in burst mode



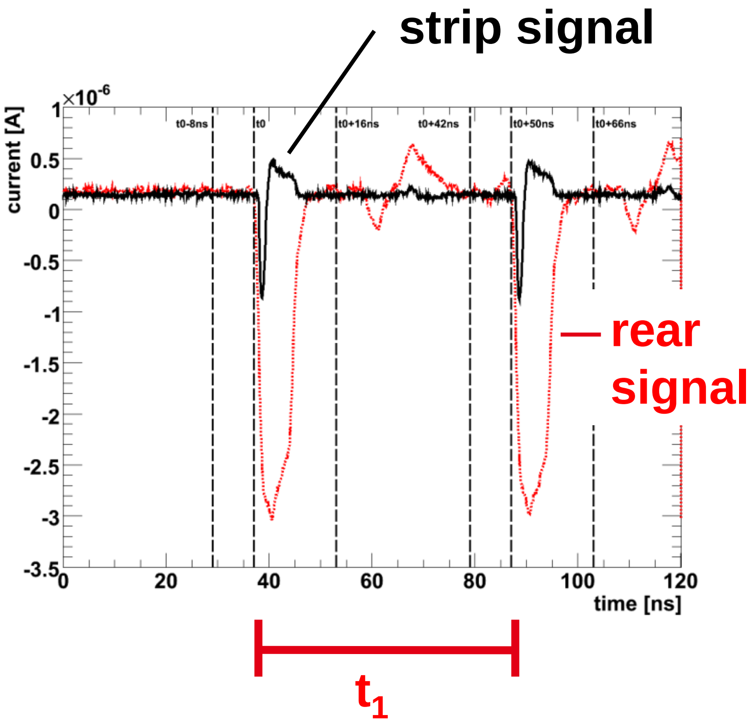
Lost charges influence the Si-SiO$_2$ interface region?

- Study charge losses in burst mode
- Typical time spacings of **t_1 = 50 ns, t_2 = 1 ms**

$$Q = \int_0^{\delta t} (I - I_{baseline})\ \mathrm{d}t \quad \propto \text{lost charge}$$

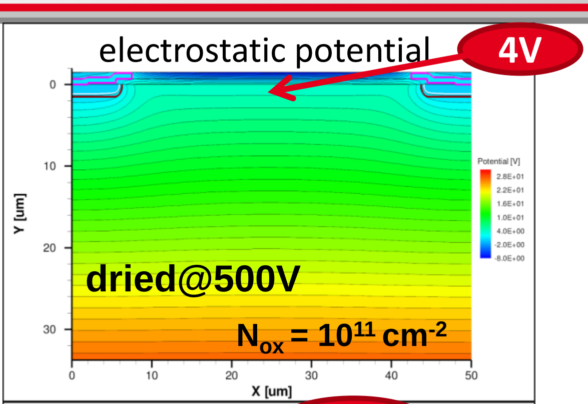
$$Q_{lost} > 0$$

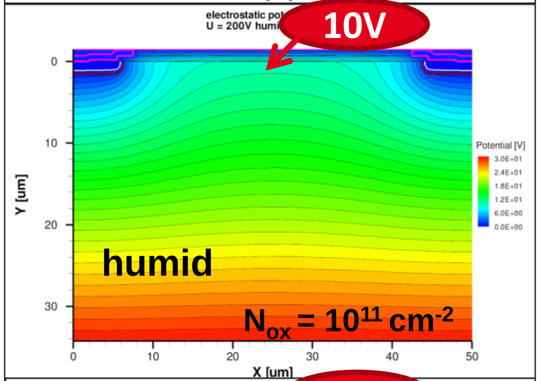
$$I_{baseline} = \frac{\int_{-8\,\mathrm{ns}}^{0} I \cdot \mathrm{d}t}{8\,\mathrm{ns}}$$

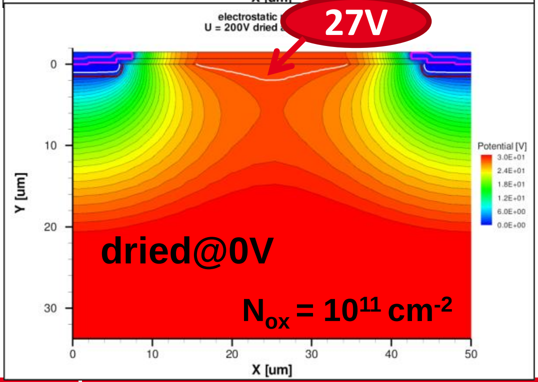

strip signal

rear signal

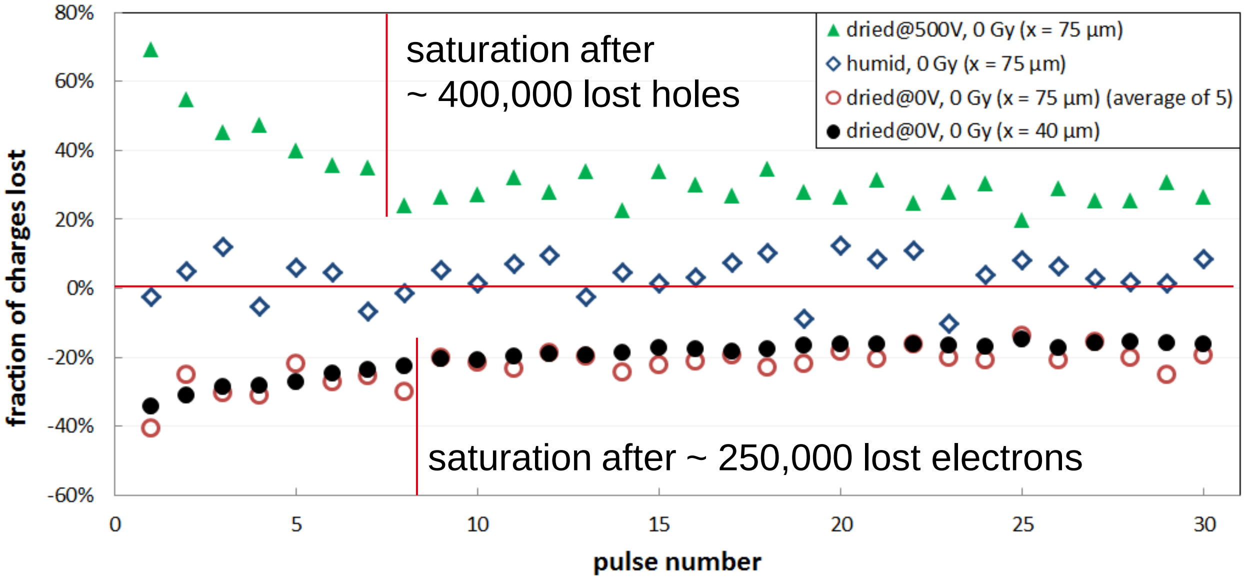
Saturation of charge losses







pulse spacing: $t_1 = 50$ ns, $t_2 = 1$ ms, ~ 100,000 eh pairs generated

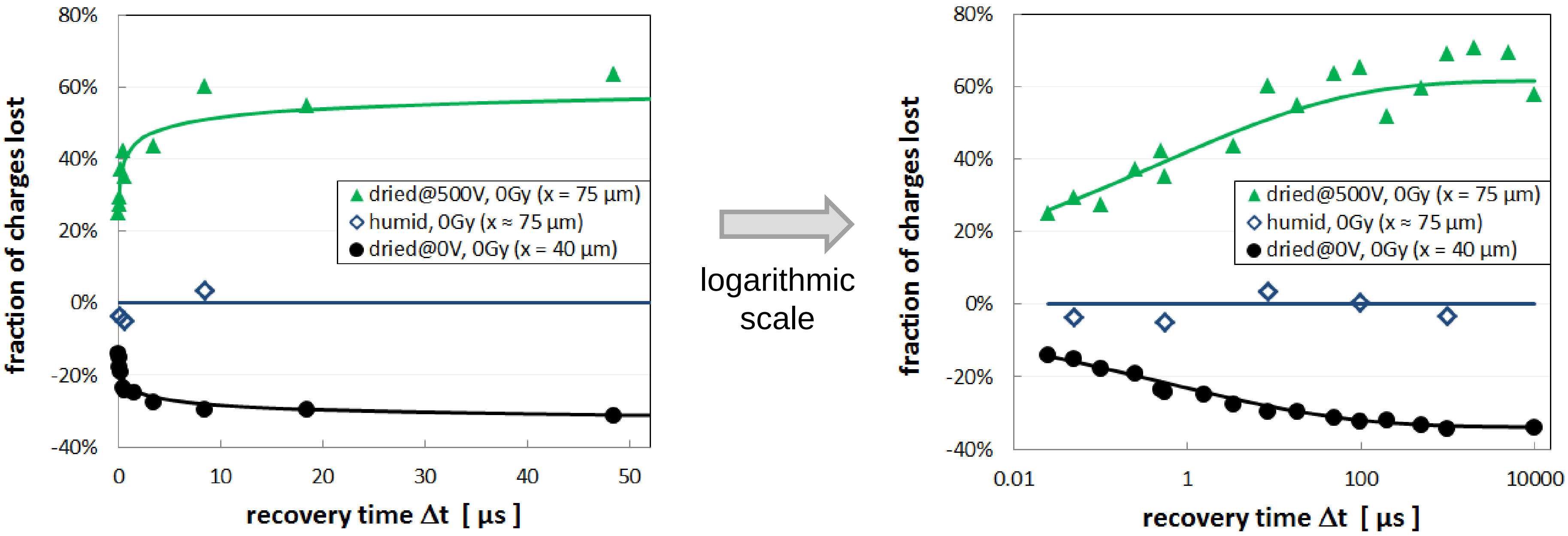


saturation after ~ 400,000 lost holes

saturation after ~ 250,000 lost electrons

Lost holes ⇒ reduction of further hole losses (potential increase)
No losses ⇒ no change (potential remains the same)
Lost electrons ⇒ reduction of further electron losses (potential decrease)

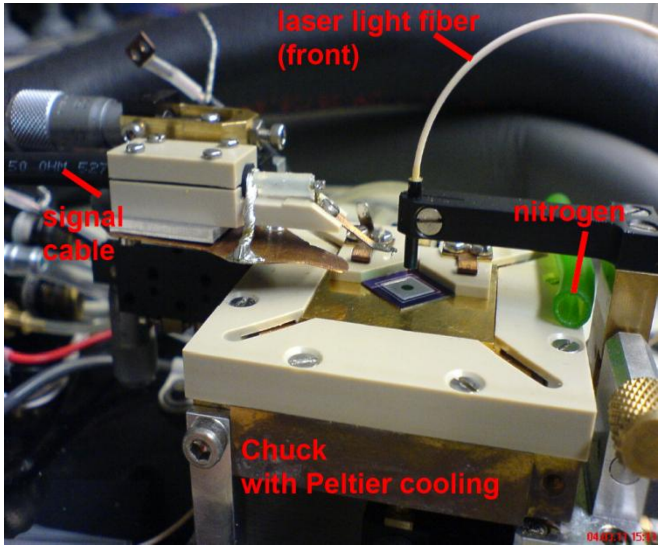
Recovery of charge losses

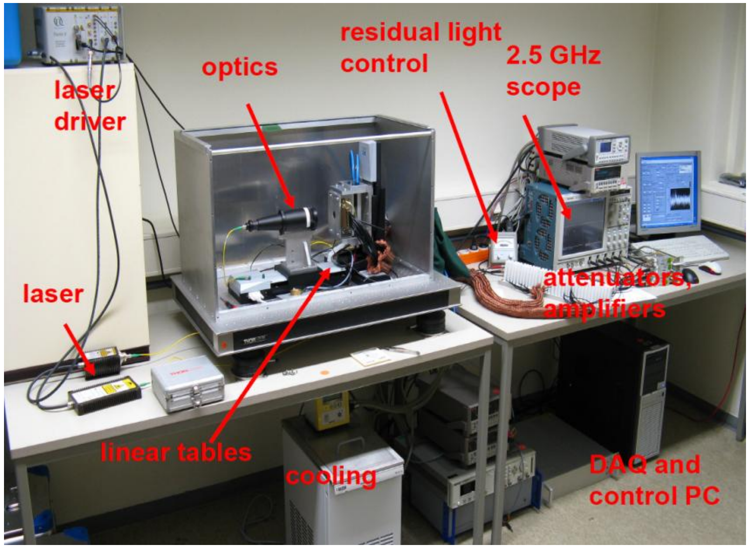


- after ≳ 50 µs : charge losses fully recovered
- for shorter recovery times: less charge losses
- large fraction of charge losses recover < 1 µs

Charge collection measurements
Transient current technique (TCT)

Transient-Current-Technique (TCT): time-resolved current pulses are recorded I(t)





<u>TCT setup for pad diodes</u>

(TCT Setup 4)

front contact: needle

red and infrared lasers

Peltier cooling, dry air

digital oscilloscopes

<u>multi channel TCT</u>

used for strip sensors

front contacts: wire bonds

position scans (µm precision)