# Challenges for Silicon Pixel Sensors at the XFEL

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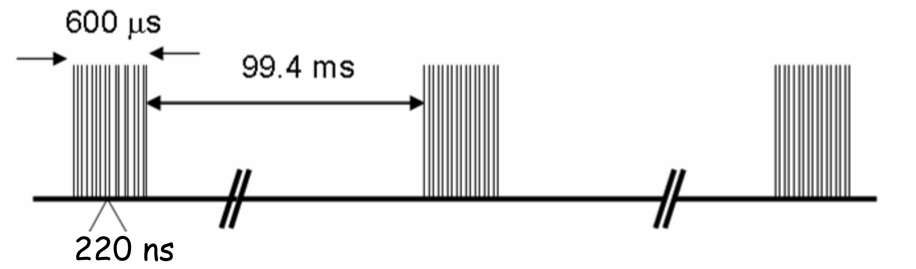
# 1. The XFEL Challenges for Pixel Sensors

- European X-FEL under construction in Hamburg → completion end 2015
- Pulse trains of e.g. 12 keV photons of 220 ns spacing and <100 fs duration



→ Pixel sensors for imaging:

- 0, 1 … $>10^5$ 12 keV photons per 200 x 200 $\mu m^2$ pixel and ~30 000 pulses/sec

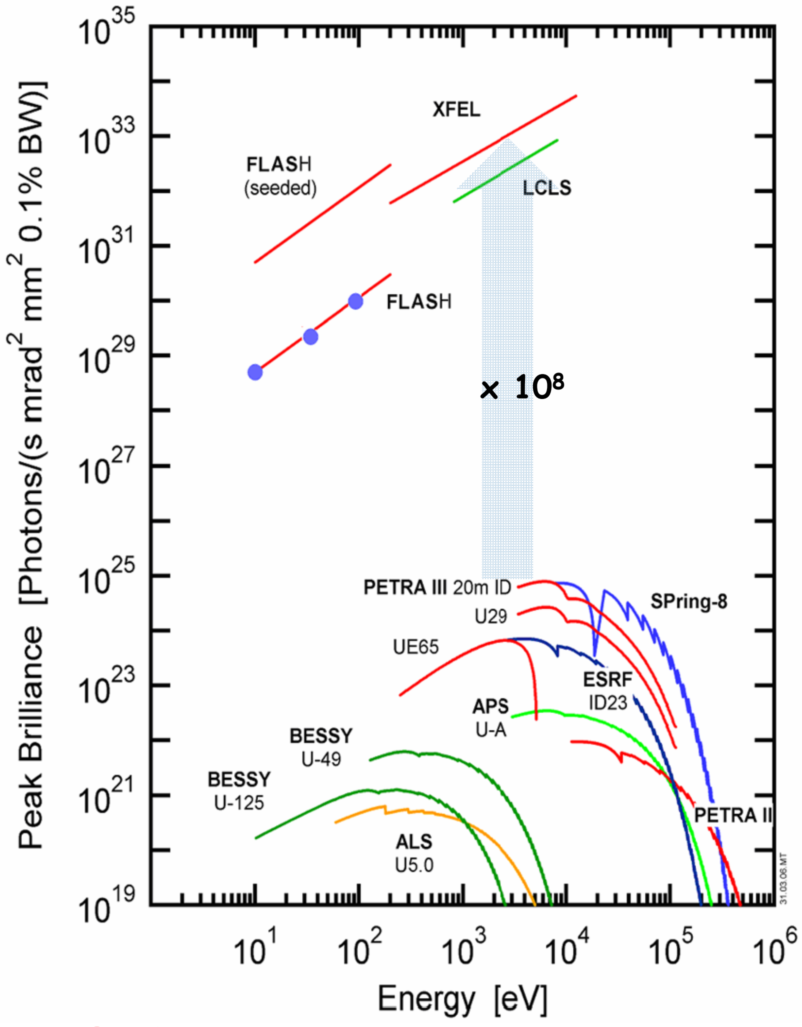
→ Radiation damage

→ Plasma effect/charge explosion

→ Charge losses

→ Pile-up from preceding pulse

**Comparison of peak brilliances of X-ray sources**



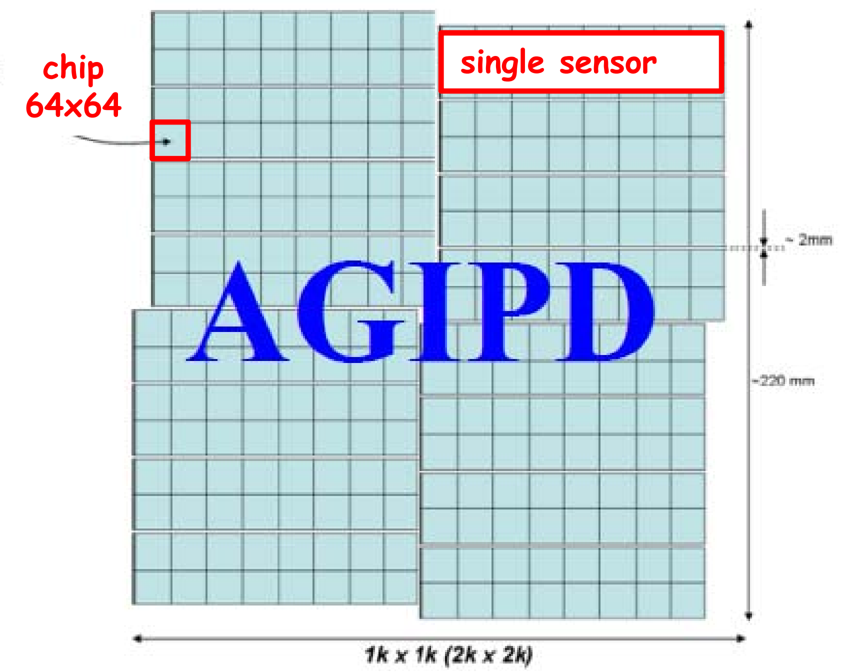
Unique XFEL features:

**Intensity x pulse duration x coherence x Å resolution**

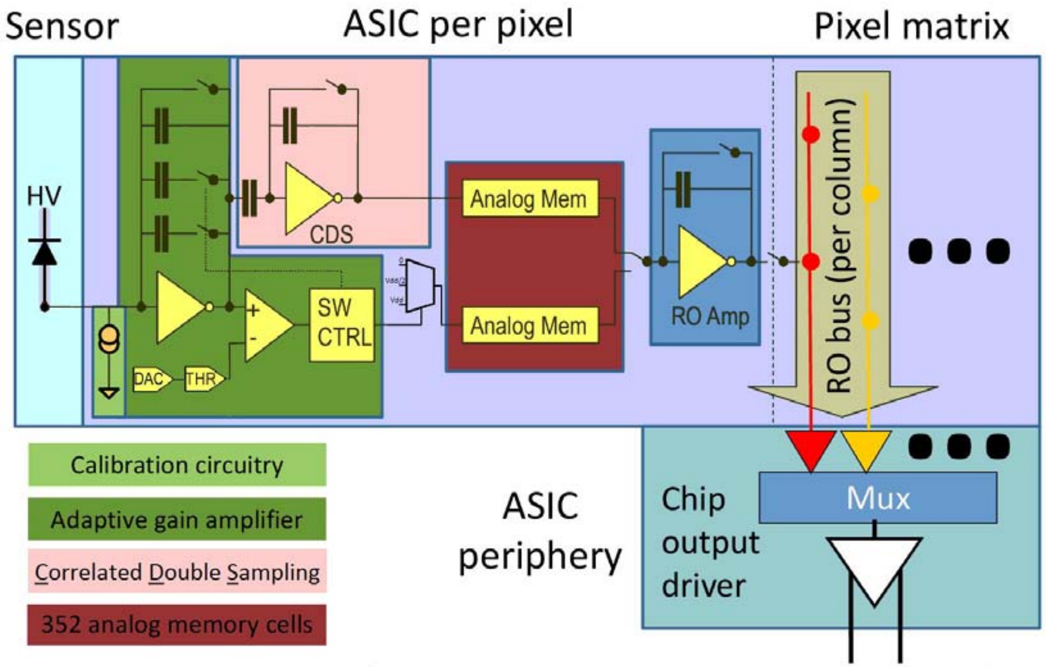
# 1. The XFEL Challenges for Pixel Sensors: AGIPD

**AGIPD = Adaptive Gain Integrating Pixel Detector (Bonn–DESY-Hamburg-PSI)**

AGIPD layout



AGIPD readout scheme



- Hybrid $p^+n$ pixel detector
- 1 Mpixels of 200 x 200 $\mu m^2$
- 500 μm thick Si

- $E_\gamma$ = 3 – 20 keV
- Dynamic range: 1 to >$10^4$ (12 keV γ's)
- Adaptive gain switching to 3 ranges
- ~ 350 stored images/pulse train
- Trigger + Fast Clear

# 2. Plasma Effect and Charge "Explosion"

**Plasma effect*):**

$10^5$ 12.4 keV γ's in (200 μm)$^2$

- → ~ $5\times10^{13}$ e-h pairs/cm$^3$
  - » n$^+$ doping of O($10^{12}$ cm$^{-3}$)
- → After ~ps a neutral e-h plasma forms, which erodes by ambi-polar diffusion
- → Once charges are separated, charge repulsion spreads charge clouds

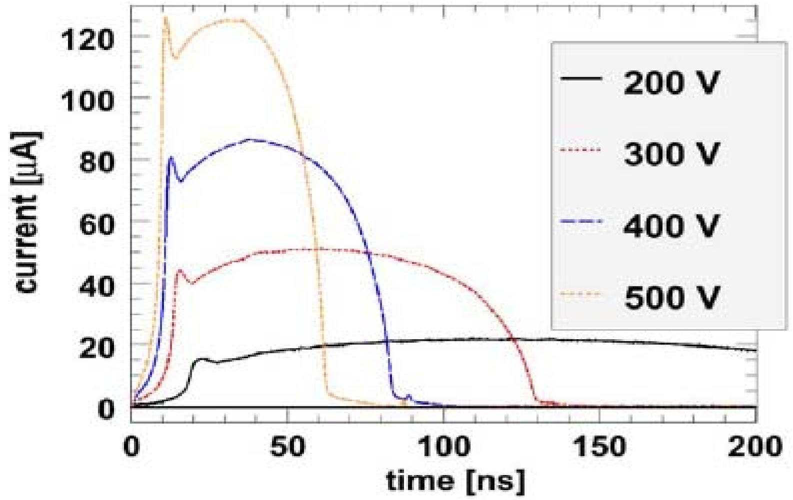
→ Delayed charge collection

→ Spread of collected charge (with a strong dependence on E-field)

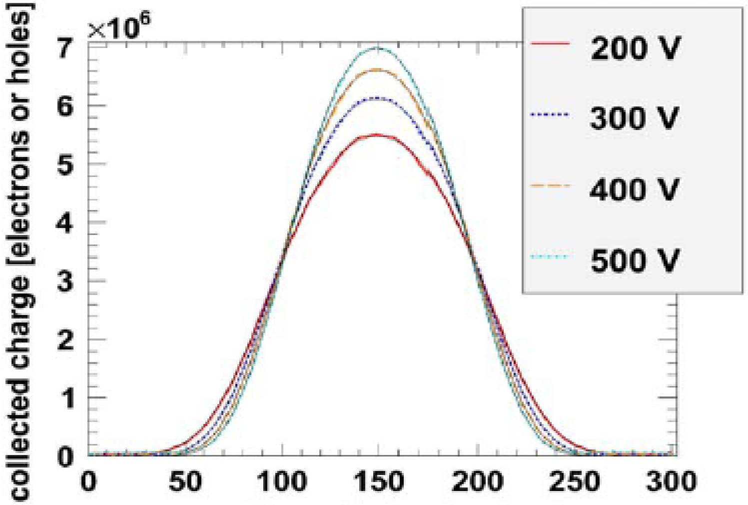
**Experiment strip-sensor:** multi-TCT with sub-ns laser with different $\lambda_{abs}$

\+ detailed simulations (WIAS-Berlin)

Current transients for 450 μm p$^+$n sensor – $V_{dep}$ = 140 V for ~ $3\times10^5$ 1 keV photons focused to Ø ~10 μm



Charge collected on strip sensor with 80 μm pitch



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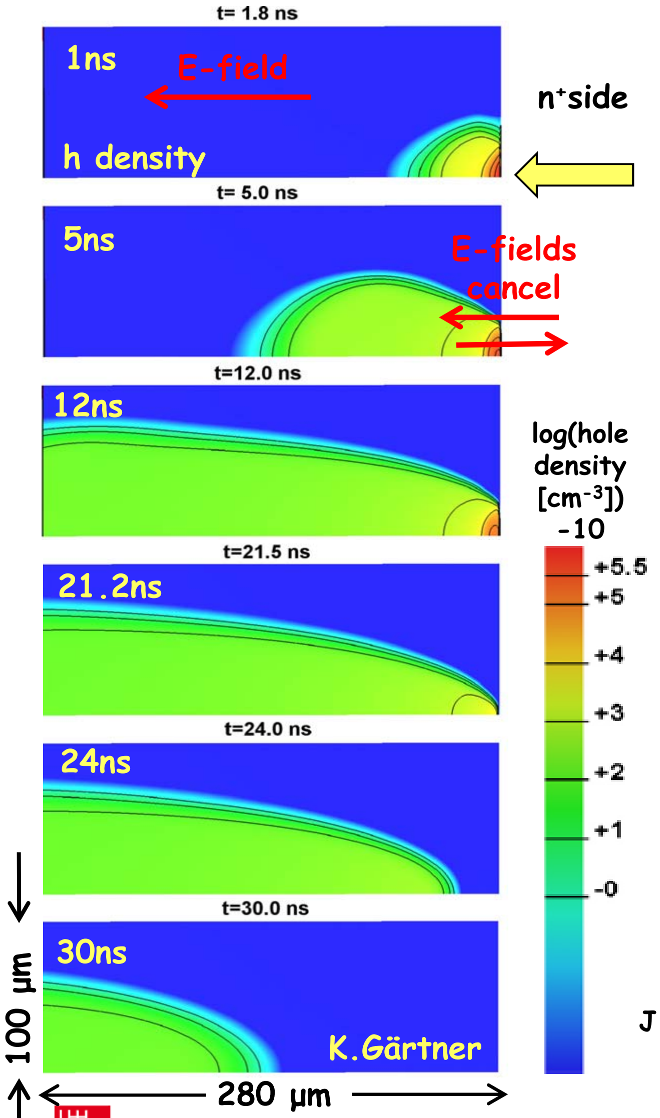
*) e-h annihilation here negligible at XFEL, not the case for ions !

J.Becker et al., NIMA 615(2009)230,
J.Becker et al., NIMA 624(2009)716

# 2. Plasma Effect and Charge "Explosion"

**Comparison simulation** (Gärtner - WIAS) **with measurements** (J.Becker):



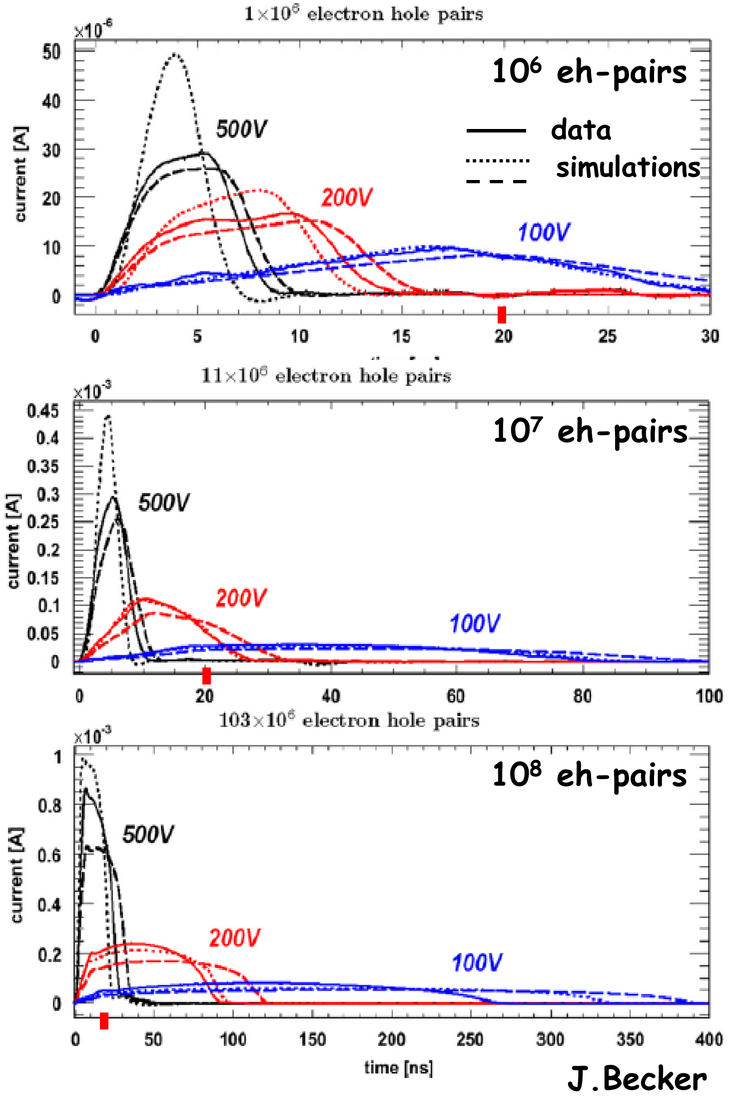
**Simulation:**
- $10^7$ eh-pairs
- $V_{bias}$ = 200 V
- n-doping: $8.2 \cdot 10^{11}$cm$^{-3}$

**Agreement with data reasonable**
(for proper mobility model)

**Big effect (in particular for high density of low-energy X-rays)**

**Program development supp. by XFEL Project**
**"Charge explosion"**
(at WIAS: K. Gärtner, at MP-HLL: R. Richter, experimental check and relevance for experiments at UNI-HH: J. Becker)

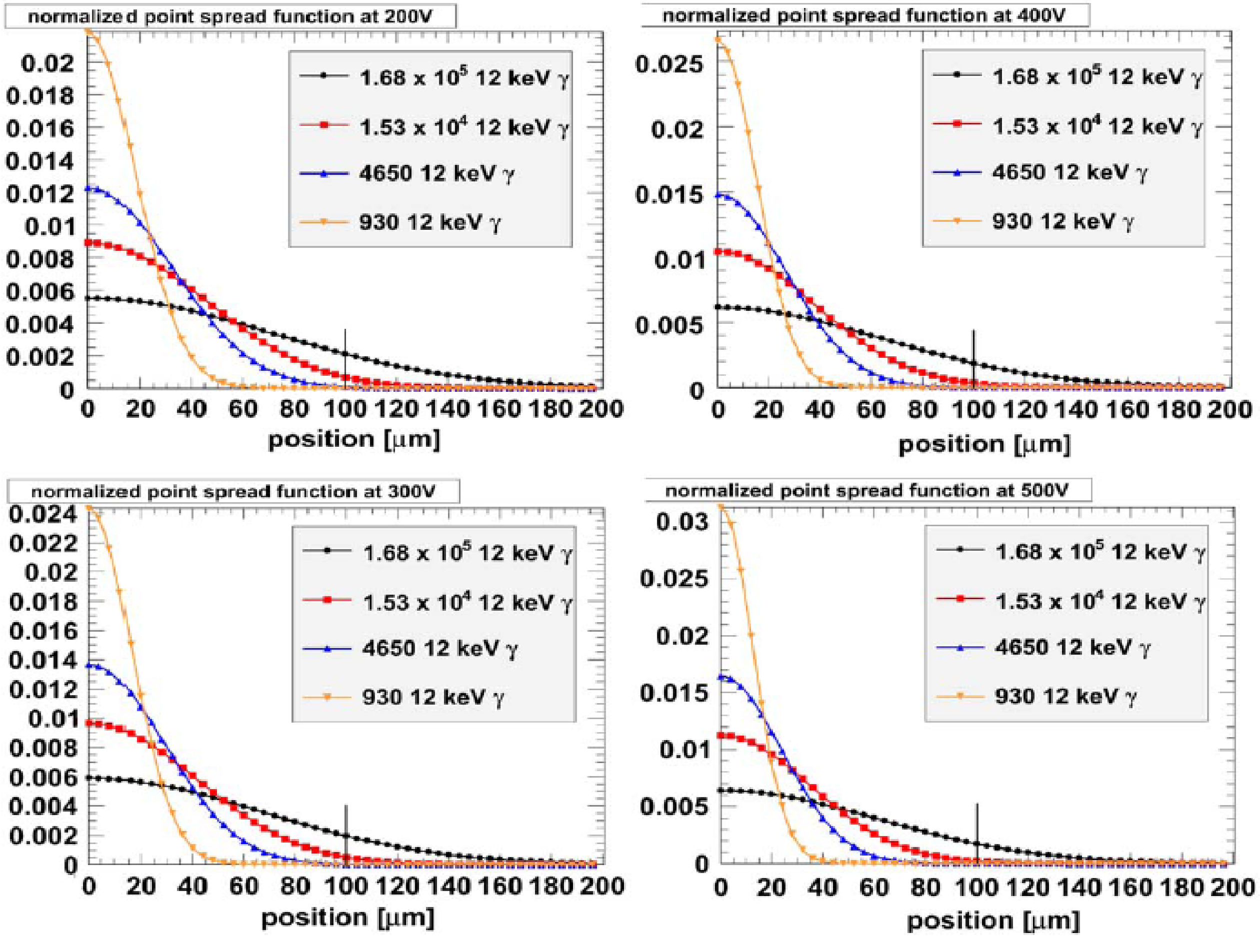
J.Becker et al., NIMA 624(2009)716



# 2. Plasma Effect and Charge "Explosion"

## Normalized point-spread functions for 12 keV γ's focused to Ø ~10 μm

J.Becker



J.Becker

**High bias voltage (>500 V) desirable to reduce influence of plasma effect** ⚠

[not shown: same conclusion if a charge collection time < 60 ns is required]

# 3. Radiation Damage

XFEL requirements: 1 GGy ($SiO_2$) for 3 years operation (non-uniform !)

Few data on X-ray damage for high-ohmic structures for such high doses

→ Work at UHH:

- Irradiate test structures from different vendors to extract "microscopic" and "macroscopic" parameters due to X-ray radiation damage
- "Understand" impact of above parameters on sensor performance, via measurements on irradiated sensors and detailed TCAD simulations
- Optimize sensor design using TCAD simulations
- Order "optimized" sensors (Aug.2012) and verify performance (early 2013)

Effects of X-ray radiation damage for $p^+n$ sensors:

- No bulk damage for $E_\gamma < 300$ keV

  → "Surface" damage: Build-up of oxide charges and Si-$SiO_2$ interface traps

    → Accumulation layers form (or increase)
    → High field regions appear reducing the breakdown voltage
    → Leakage currents increase due to interface states
    → Depletion voltage and inter-pixel capacitance increase
    → Charge losses close to the Si-$SiO_2$ interface occur (increase)

# 3. X-ray Induced Defects in Si Sensors

Generation of eh-pairs in $SiO_2$

↓

Prompt recombination of eh-pairs

↓

Transport of free carriers

↓

for 500 nm $SiO_2$: $4\cdot10^{16}$ eh/cm$^2$ for dose of 1 MGy
(compared to $10^{15}$ cm$^{-2}$ surface states)

No. eh-pairs depends on ionization density and E-field

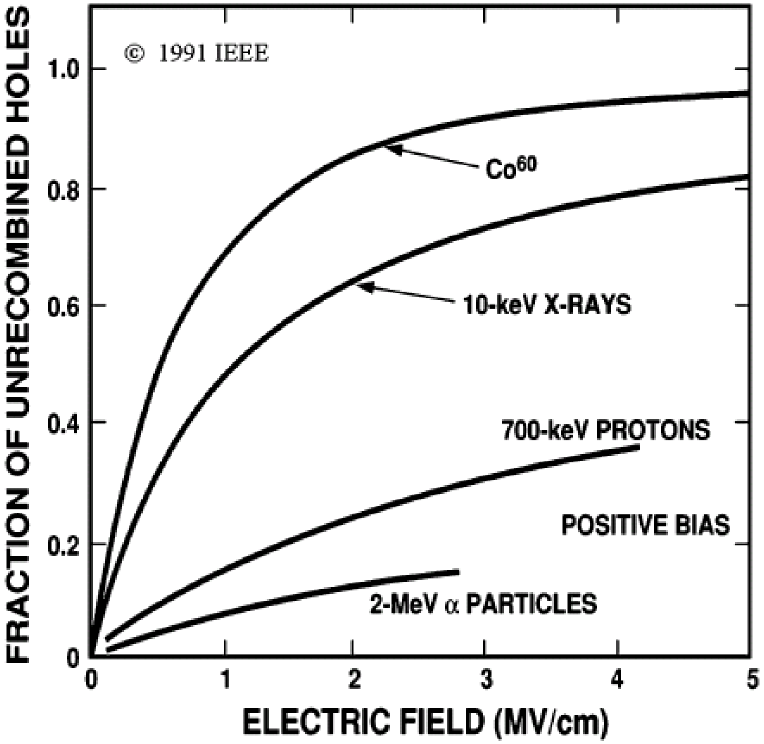


Fig. 10. Fractional yield of holes generated in $SiO_2$ as a function of electric field in the material [14], [15].

M.R. Shanefield et al., IEEE TNS 38(1991)1187

# 3. X-ray Induced Defects in Si Sensors

**Transport of free carriers**

**Trapping in $SiO_2$** | **Trapping at $Si$-$SiO_2$ interface**

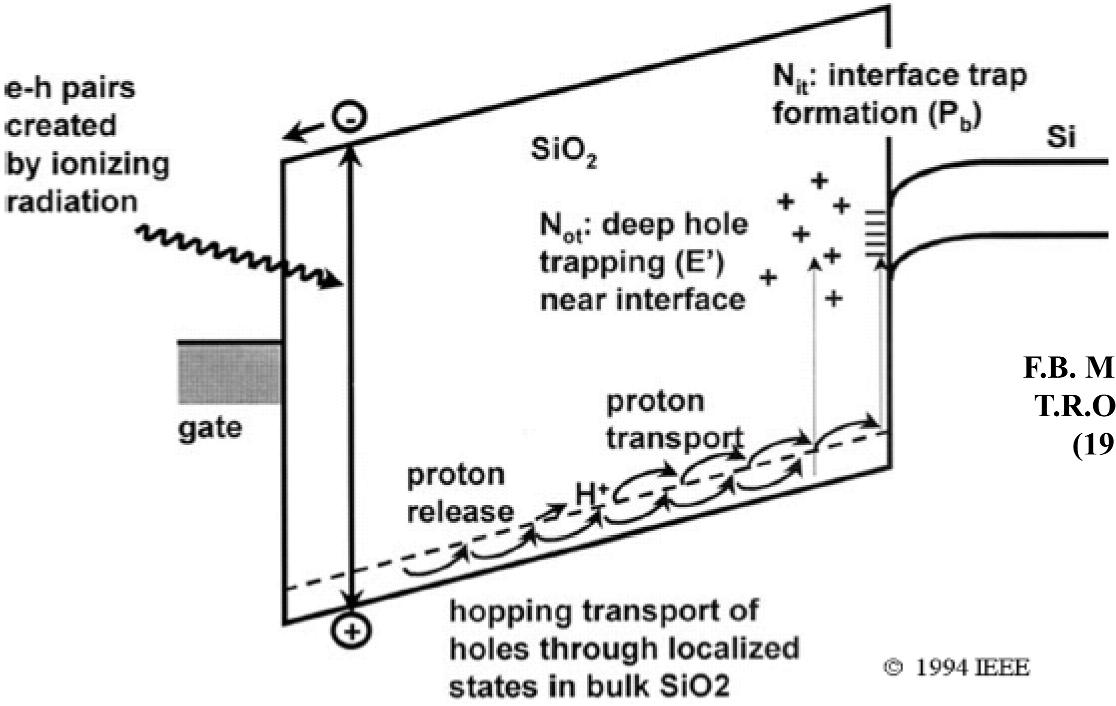
**Effects on sensor**

$\mu_{electrons}$ ~ $20\ cm^2/V{\cdot}s$ → e's mainly escape

„$\mu_{holes}$" $< 10^{-5}\ cm^2/V{\cdot}s$ → h's trapped in $SiO_2$

or (mainly) at $Si$-$SiO_2$ interface

[there are $O(10^{15}\ cm^{-2})$ surface states !]



© 1994 IEEE

F.B. McLean,
T.R.Oldham
(1987)

# 3. Damage of $SiO_2$ and at Si-$SiO_2$ Interface

**Mobile ions:** not an issue anymore

⊕**Oxide trapped charges ($N_{ox}$):**
- Mainly **positive** oxygen-vacancy defects
  (one shallow trap → hole transport,
  + one deep trap $E'_\gamma$ @~3 eV)

saturation: h-trapping = eh-recombination

⊕**Border oxide traps ("add" to $N_{ox}$):**

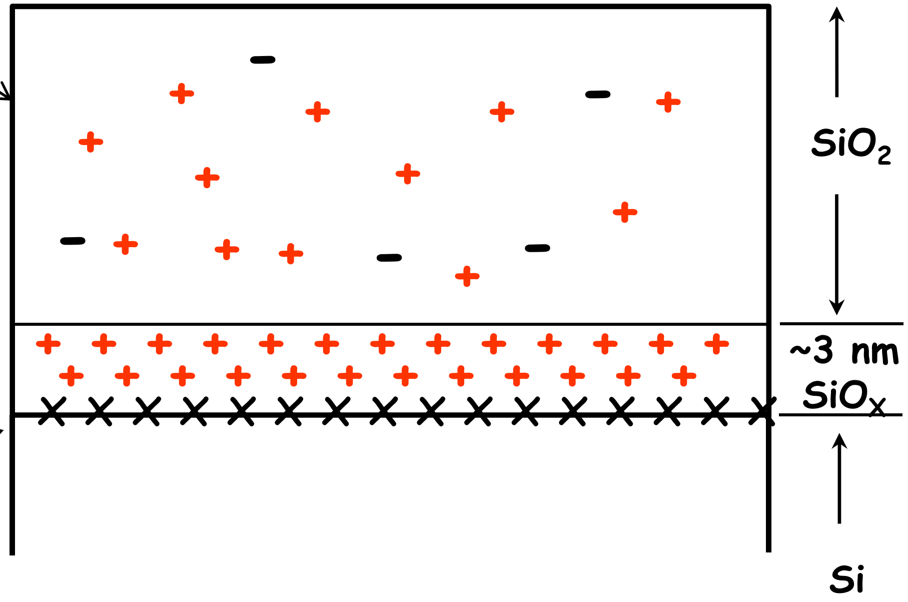
**Positive** $E'_\gamma$ defect can exchange charge with Si depending on Fermi-level on time scales 0.01 s to seconds

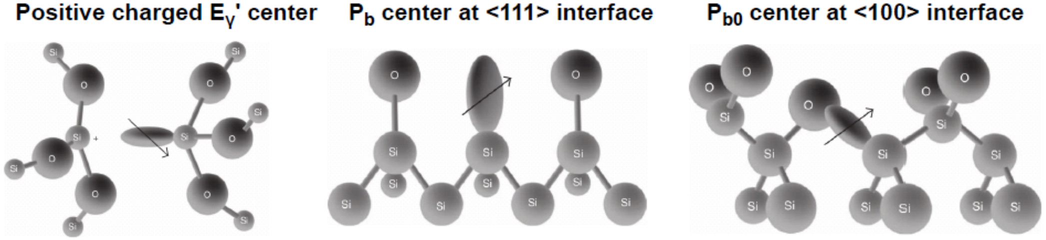
⊗**Interface traps ($D_{it}$*)):**

Traps at interface (no barrier !)
dangling bond defects ($P_b$) –
$H^+$ released when *h* captured:

$$SiH + H^+ \rightarrow (Interface\ Trap)^+ + H_2$$

No. limited by no. of dangling bonds




Positive charged $E_\gamma'$ center
$P_b$ center at <111> interface
$P_{b0}$ center at <100> interface

* from D. M. Fleetwood's book "Defects in Microelectronic Materials and Devices"

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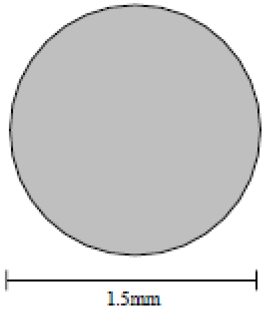
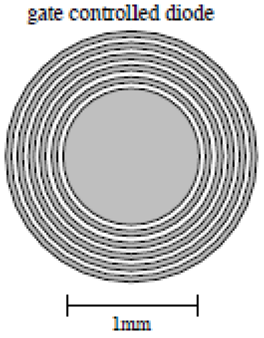
*) **Distribution of traps in the Si bandgap: $D_{it}$ [1/(eV·cm²)]**

# 3. Characterization of Microscopic Defects: $D_{it}$

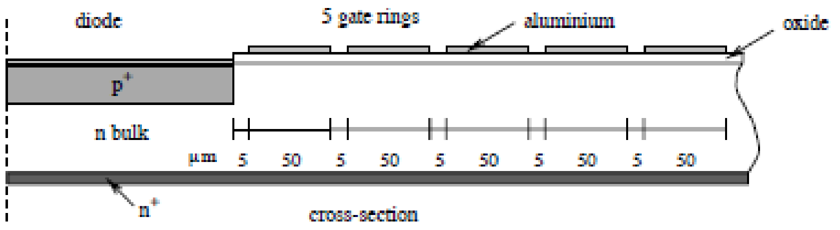
**Test structures** (diff. vendors + crystal orientations, oxide thickness, + … )

**MOS Capacitor "MOS-C"**





**Gate Controlled Diode "GCD"**



## TDRC: Properties of interface traps

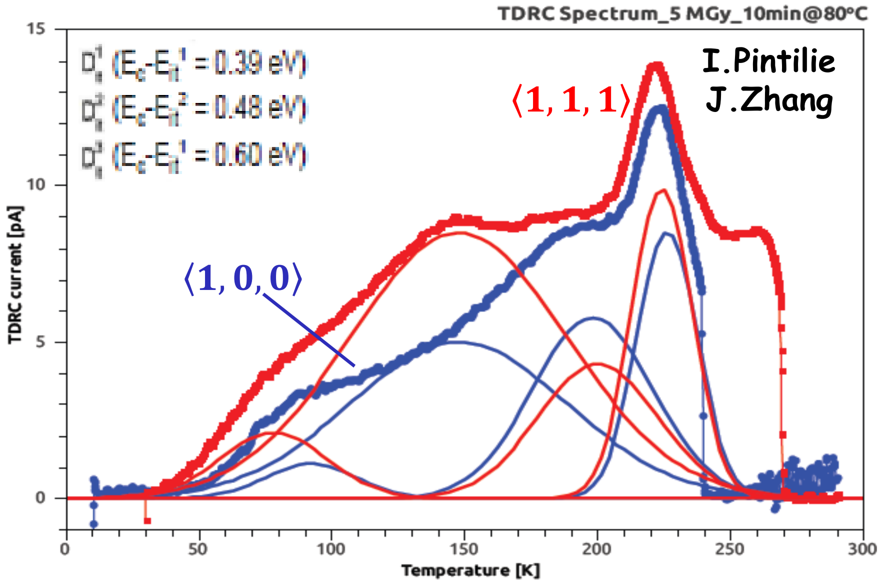
**(Thermal Dielectric Relaxation Current)**

- Bias MOS-C in e-accumulation
  → fill interface traps with electrons
- Cool to 10 K → freeze e in traps
- Bias to inversion and heat up to 290 K

→ $I_{TDRC}$ due to release of trapped e's

→ $I_{TDRC}(T)$ → $D_{it}(E)$ *)

→ $(\text{Energy levels + widths + densities})_{it}$



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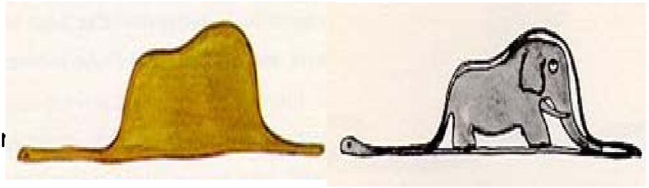
Parameterize by 3 states - not unambiguous !



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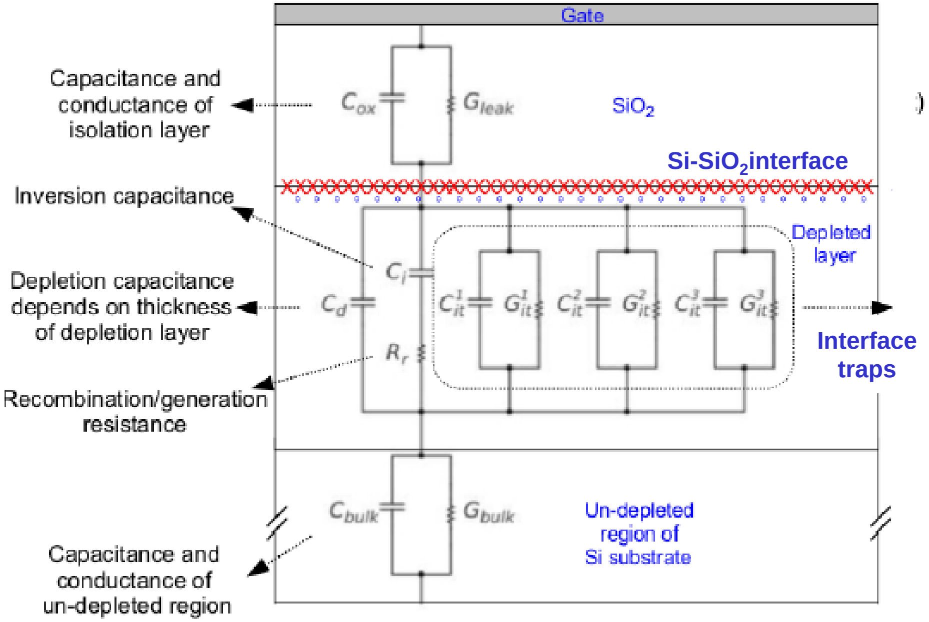
*) Temperature T → $E_c - E_{it}$ (T dependence of Fermi level)

# 3. Characterization of Microscopic Defects: $N_{ox}$

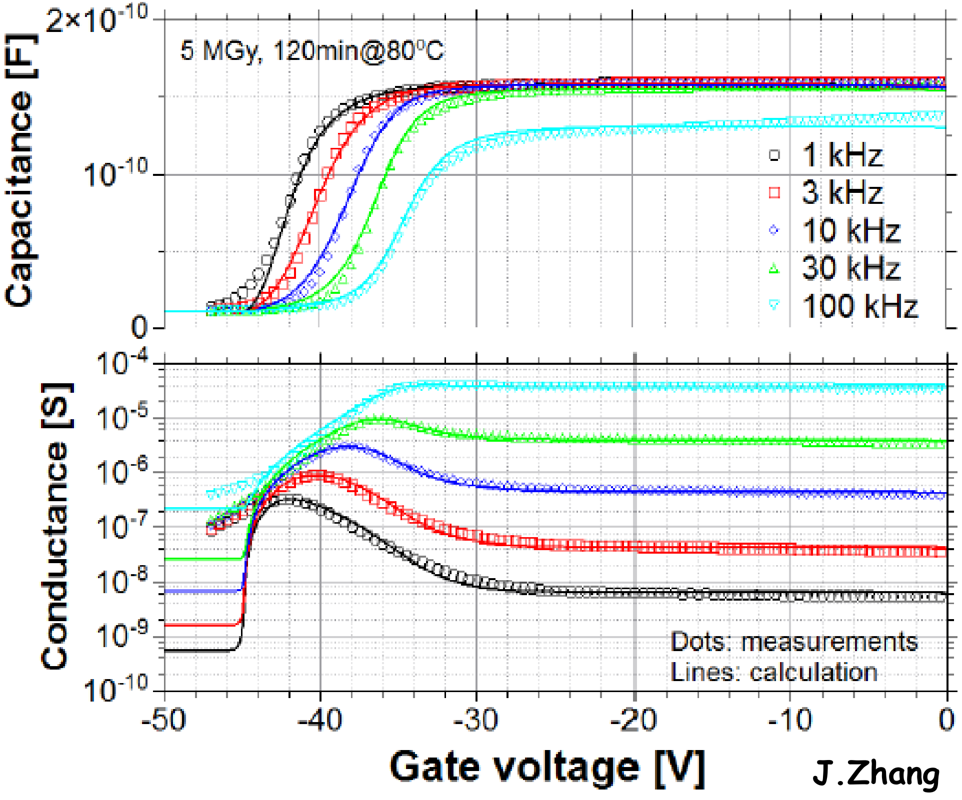
## C/G-V curves for CMOS-C:

- $D_{it}(E)$ allows calculation of C/G-V curves as function of frequency (assuming values for trap cross sections)
- Oxide charge density $N_{ox}$ just shifts curves along the V-axis → $N_{ox}$

Model for MOS capacitor



C/G-V measurement on irradiated MOS capacitor



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**Fair description of a large amount of data**

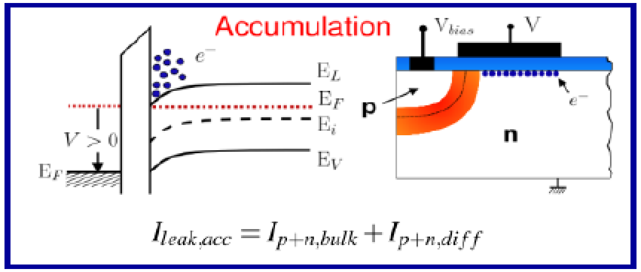
For details and (some of) the experimental complications, see: J.Zhang et al., JSR19/3(2012)340,

# 3. Characterization of Macroscopic Effects: $J_{surf}$

## Surface current density from GCD:

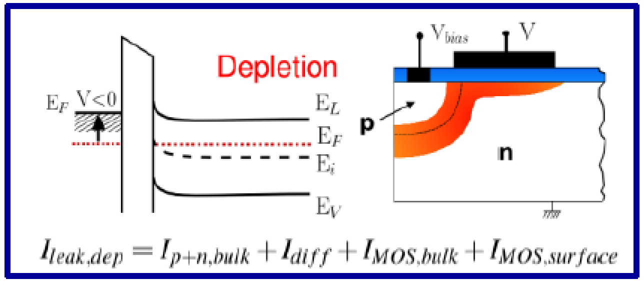
- Measure I-V curve
- $J_{surf}$ dominated by mid-gap traps

E-field at Si-SiO$_2$ interface:



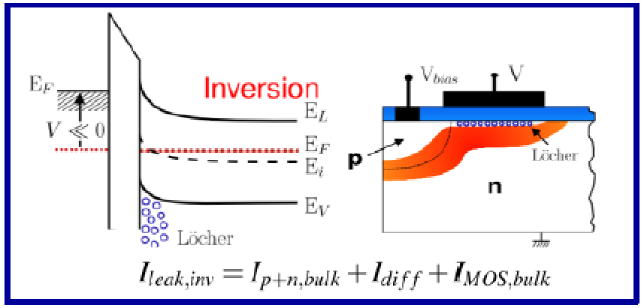
$$I_{leak,acc} = I_{p+n,bulk} + I_{p+n,diff}$$

shielded



$$I_{leak,dep} = I_{p+n,bulk} + I_{diff} + I_{MOS,bulk} + I_{MOS,surface}$$

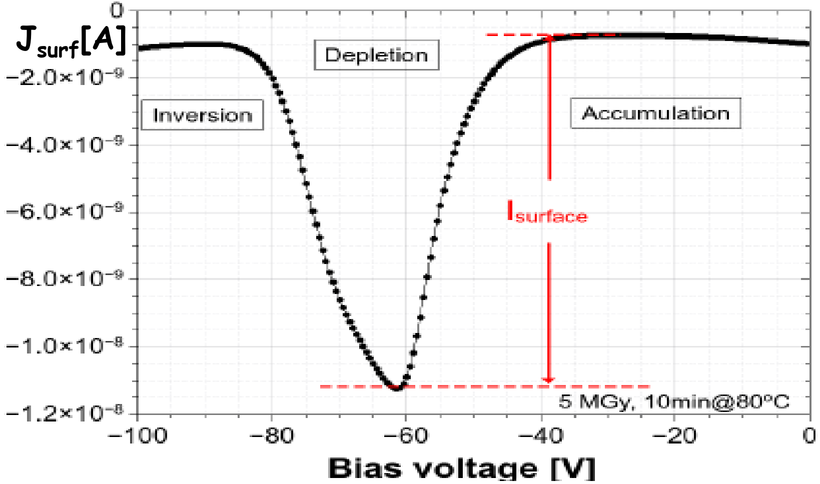
non zero



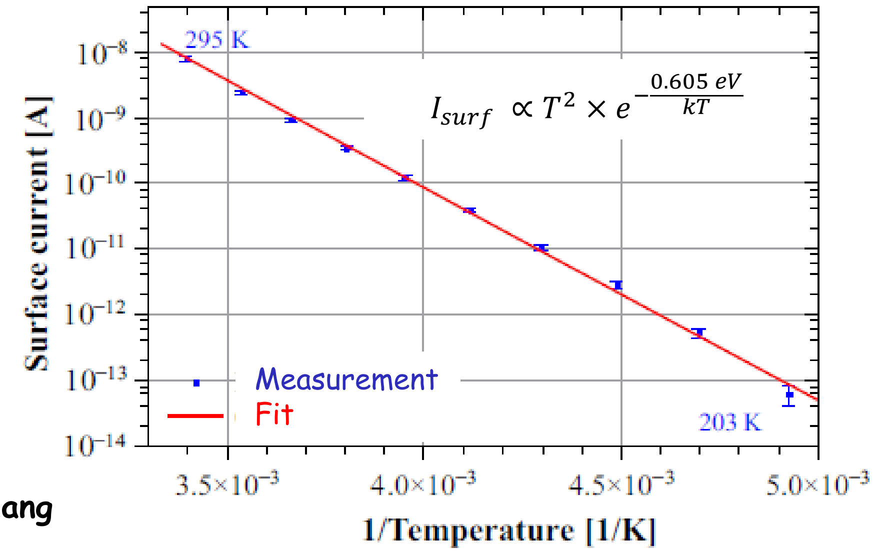
$$I_{leak,inv} = I_{p+n,bulk} + I_{diff} + I_{MOS,bulk}$$

shielded

I-V measurement on irradiated GCD



T-dependence of $I_{surf}$



$$I_{surf} \propto T^2 \times e^{-\frac{0.605\ eV}{kT}}$$

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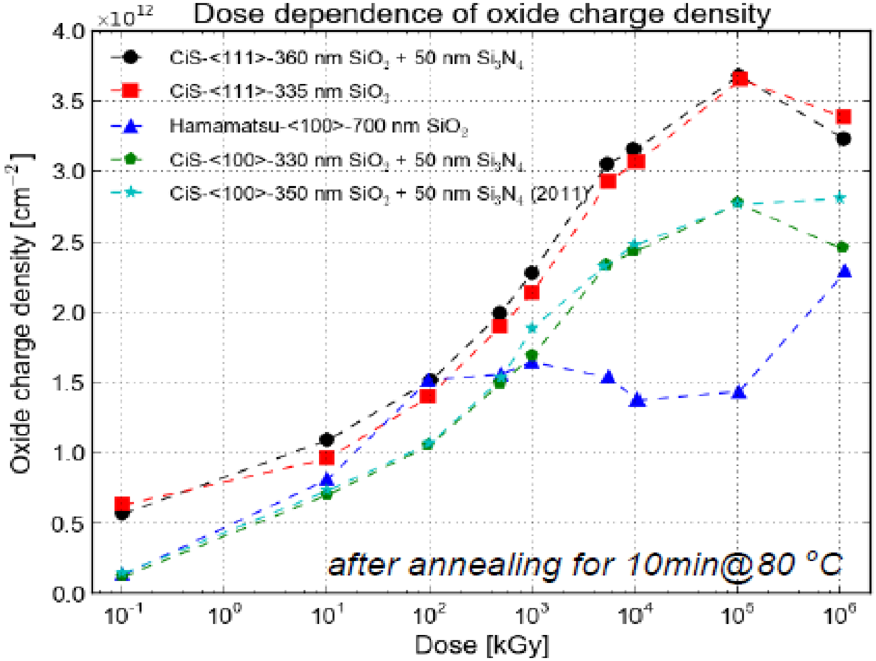
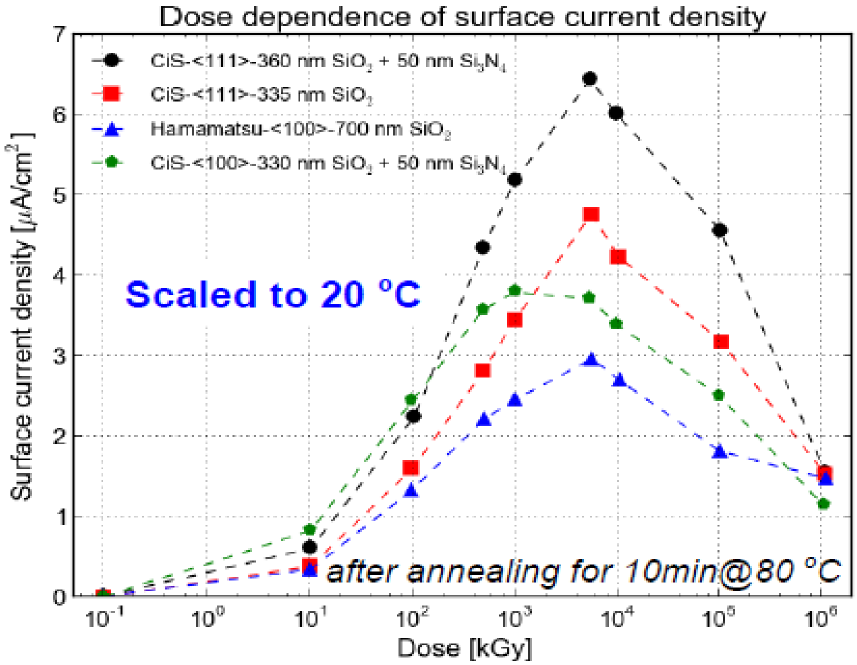
# 3. Summary: Dose Dependence of $N_{ox}$ and $J_{surf}$

**Vendors**: **CiS, Hamamatsu, Canberra**; **Crystal orientations**: **<111>,<100>;**
**Insulator**: **$SiO_2$ (335-700 nm), with and without additional 50 nm $Si_3N_4$**





J.Zhang et al., arXiv:1210.0427(2012)

- **Results reproducible (after some annealing)**
- **Spread of about a factor 2**
- **$N_{ox}$ saturates for ~1 – 10 MGy**
- **$J_{surf}$ peaks at 1-10 MGy, then decreases**

- **Equilibrium h-trapping and eh-recombination ?**
- **E-field effects due to oxide charges ?**

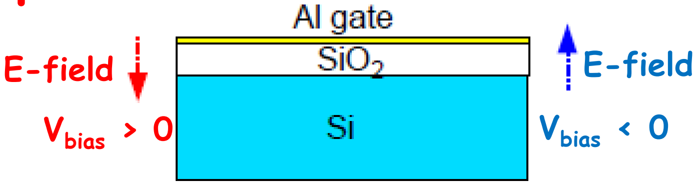
**→ Understanding needs more studies**

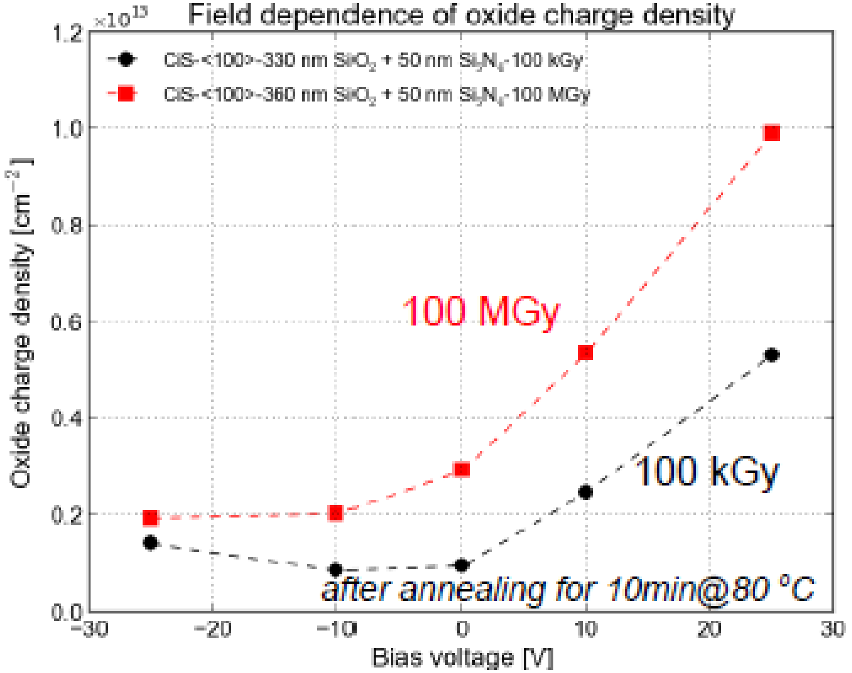
**X-ray radiation damage saturates !!!**

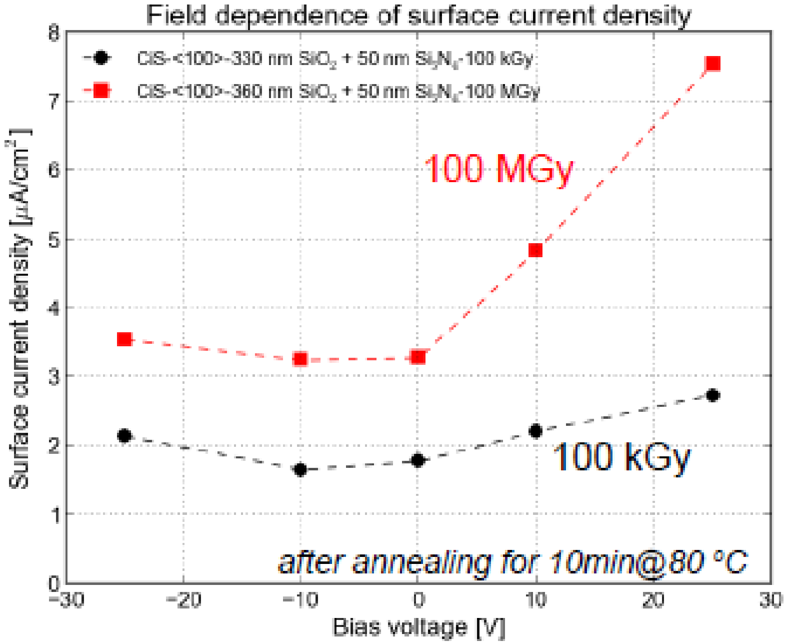
# 3. E-Field Dependence of $N_{ox}$ and $J_{surf}$

## Irradiation MOS-C and GCD with bias applied

- CiS <100> with ~350 nm $SiO_2$ + 50 nm $Si_3N_4$







$V_{bias}$ > 0: Increase of $N_{ox}$ and $I_{surf}$

$V_{bias}$ ≤ 0: Only weak dependence

For $p^+n$ sensor: $E_{ox}$ < 0 → no problem

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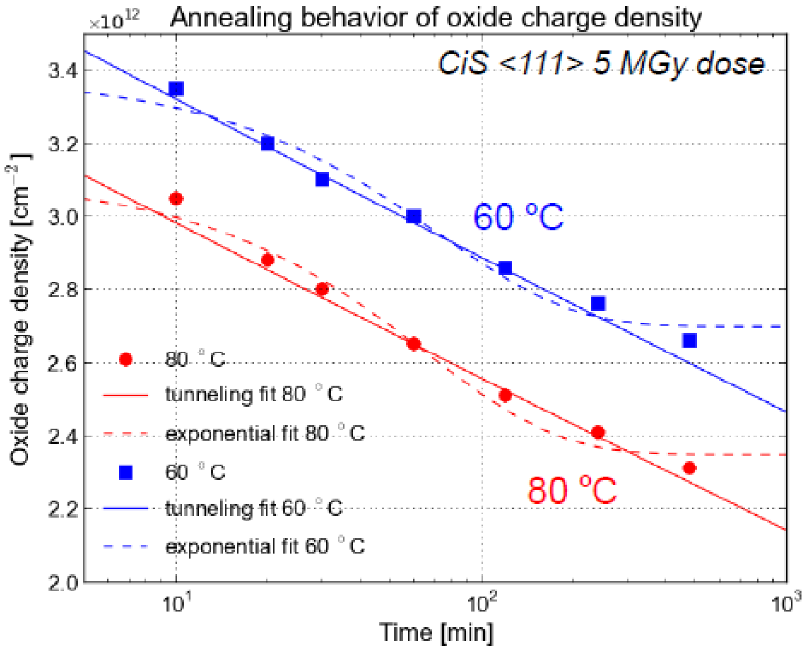
**E-field in oxide is not a problem for $N_{ox}$ and $J_{surf}$**

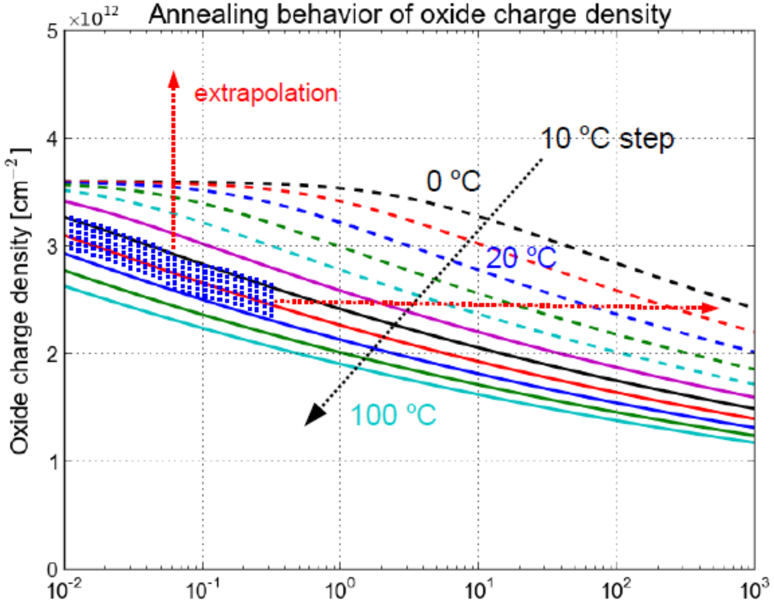
# 3. Annealing of $N_{ox}$

## MOS-C and GCD irradiated to 5 MGy and annealed at 60 and 80°C

- CiS <111> with ~350 nm $SiO_2$ + 50 nm $Si_3N_4$

J.Zhang et al., arXiv:1210.0427(2012)





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- Described by "tunnel anneal model" [T.R. Oldham et al., 1988]

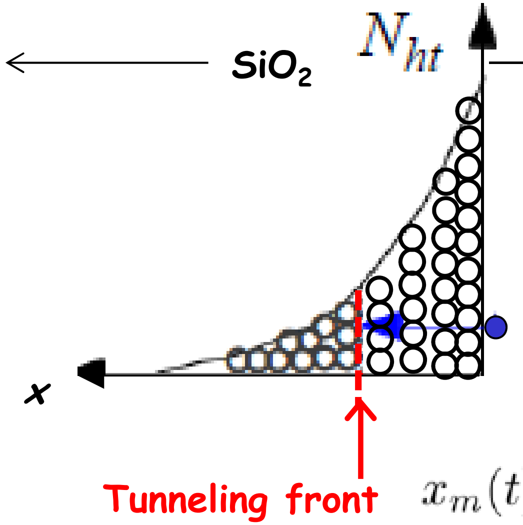
$$N_{ox}(t) = N_{ox}^0 \cdot (1 + t/t_0)^{-\frac{\lambda}{2\beta}} \quad \text{with} \quad t_0(T) = t_0^* \cdot \exp\left(\frac{\Delta E}{k_B T}\right)$$

$1/\lambda$ … width of hole trap distr. in $SiO_2$
$t_0(T)$ … tunneling time constant
$\beta$ … related to tunnel-barrier height
$\Delta E$ … $E_{trap}$ - $E_{Fermi}$

# 3. Annealing of $N_{ox}$

**"Tunnel anneal" model: How to obtain a non-exponential t-dependence?**

T.R.Oldham et al., IEEE Trans.NS-33/6(1986)1203 – (with some modification by J.Zhang/R.Klanner)



Hole trap distribution:

$$N_{ht}(x) = \lambda \cdot N_{ox}^0 \cdot \exp(-\lambda \cdot x)$$

Electrons tunnel and anneal hole traps

→ Annealed oxide charges: $\Delta N_{ox}(t) = \int_0^{x_m(t)} N_{ht}(x)\mathrm{d}x$

$t_0$: effective tunneling time constant

$$x_m(t) = \frac{1}{2\beta} \cdot \ln\left(\frac{t+t_0}{t_0}\right)$$

$t_0(T) = t_0^* \cdot \exp\left(\frac{\Delta E}{k_B T}\right)$ $\Delta E$ ... distance trap level to $E_{Fermi}$

$\beta$: parameter related to barrier height

$$\rightarrow \quad N_{ox}(t) = N_{ox}^0 \cdot (1 + t/t_0)^{-\frac{\lambda}{2\beta}} \quad \text{with} \quad t_0(T) = t_0^* \cdot \exp\left(\frac{\Delta E}{k_B T}\right)$$

| $N_{ox}^0$ [cm$^{-2}$] | $\lambda/2\beta$ | $t_0^*$ [s] | $\Delta E$ [eV] |
|---|---|---|---|
| $3.6 \times 10^{12}$ | 0.070 | $5.4 \times 10^{-12}$ | 0.91 |

| T [°C] | 80 | 60 | 20 |
|---|---|---|---|
| $t_0$ [s] | 48 | 290 | 21710 |

J.Zhang

$\Delta E = E_{ht}(\mathrm{SiO_2}) - E_{Fermi}(\mathrm{Si})$ = 0.91 eV ➡ $E_{ht}(\mathrm{SiO_2}) \sim 6$ eV – compatible with existing data

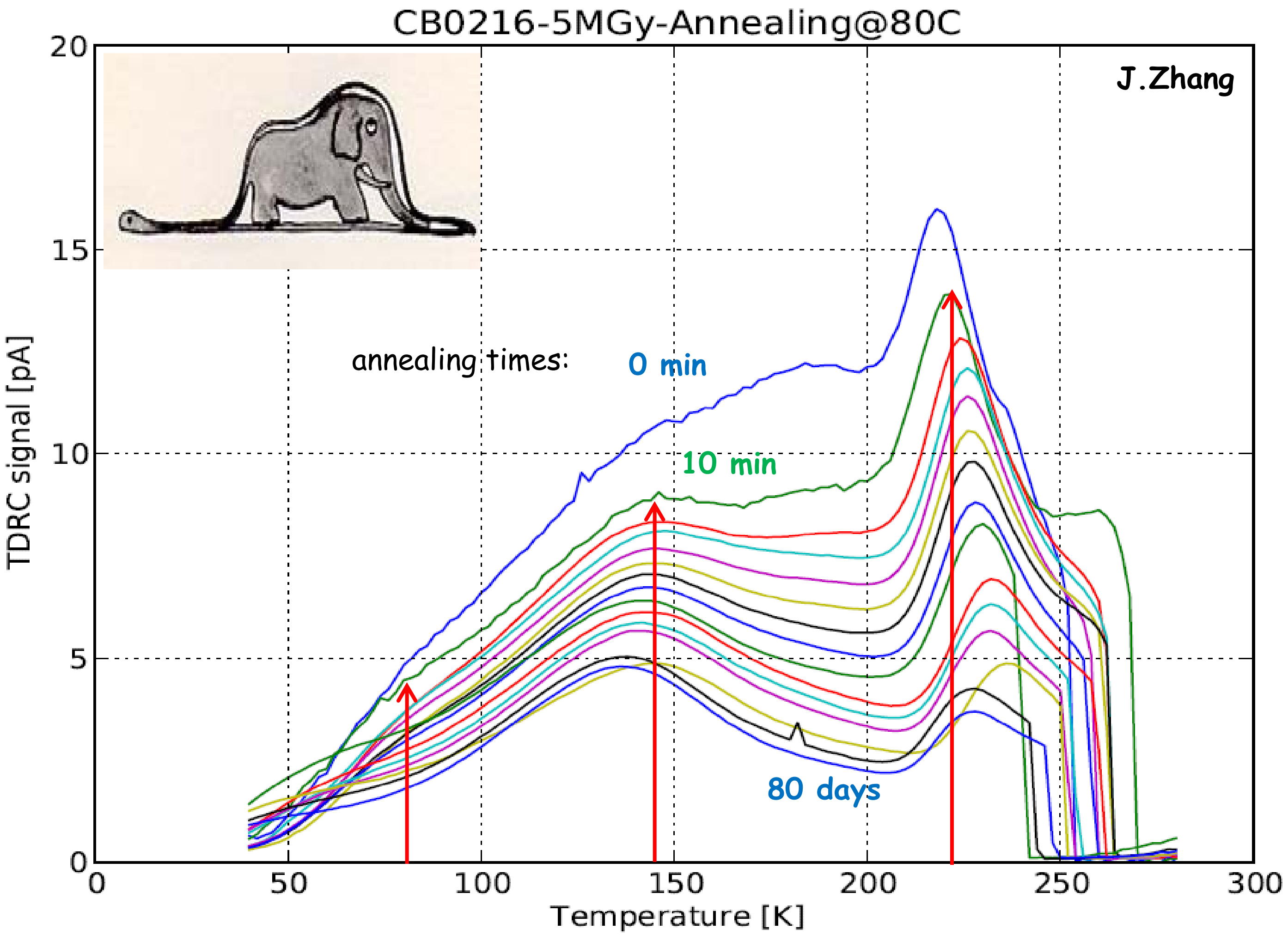
**→ Slow $N_{ox}$ annealing: At 20°C <50% annealing in 3 years (assuming model is correct!)**

# 3. Annealing of $N_{it}$ – Microscopic View

## GCD irradiated to 5 MGy and annealed 80°C

- CiS <111> with ~350 nm $SiO_2$ + 50 nm $Si_3N_4$

J.Zhang et al., arXiv:1210.0427(2012)

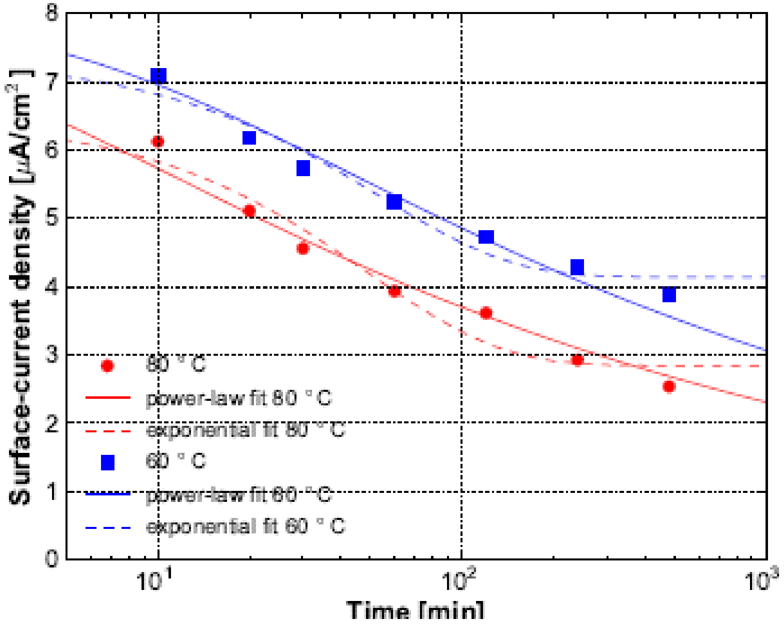


# 3. Annealing of $J_{surf}$

## MOS-C and GCD irradiated to 5 MGy and annealed at 60 and 80°C

- CiS <111> with ~350 nm $SiO_2$ + 50 nm $Si_3N_4$

J.Zhang et al., arXiv:1210.0427(2012)



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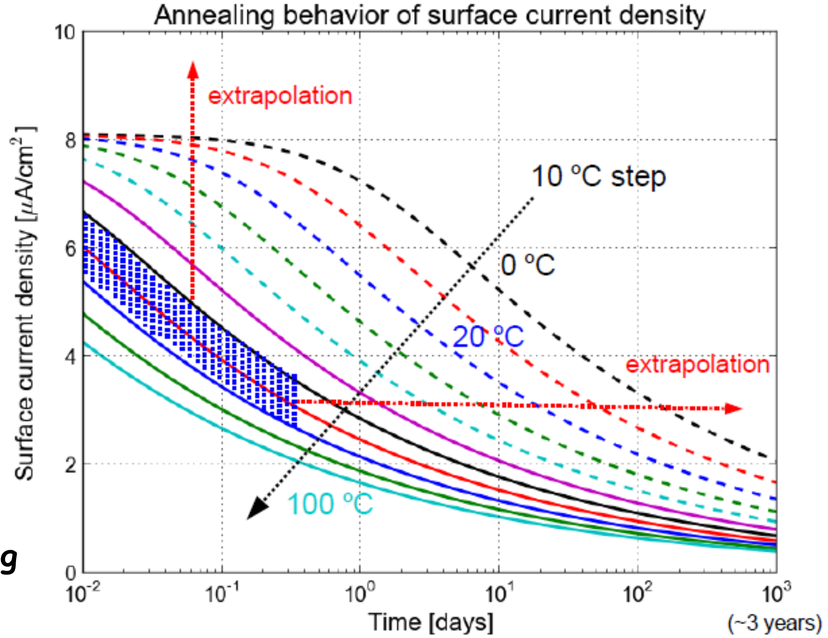


- Described by "two reaction model" [M.L. Reed 1987]

$$I_{surface}(t) = I^0_{surface} \cdot (1 + t/t_1)^{-\eta} \quad \text{with} \quad t_1(T) = t_1^* \cdot \exp\left(\frac{E_a}{k_B T}\right)$$

$\eta = k_1/2k_2$
Dangl. bonds: $\frac{d}{dt}[\mathrm{Si}\cdot] = -k_1[\mathrm{Si}\cdot][\mathrm{H}]$
$H_2$ formation: $\frac{d}{dt}[\mathrm{H}] = -2k_2[\mathrm{H}][\mathrm{H}]$
$t_1(T)$ … characteristic time constant
$E_a$ … activation energy

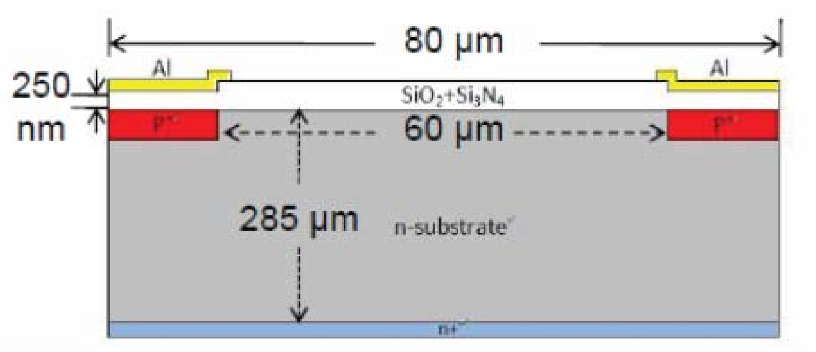
→ Fast annealing: At 20°C ~50% annealing in 5 days (assuming model is correct!)

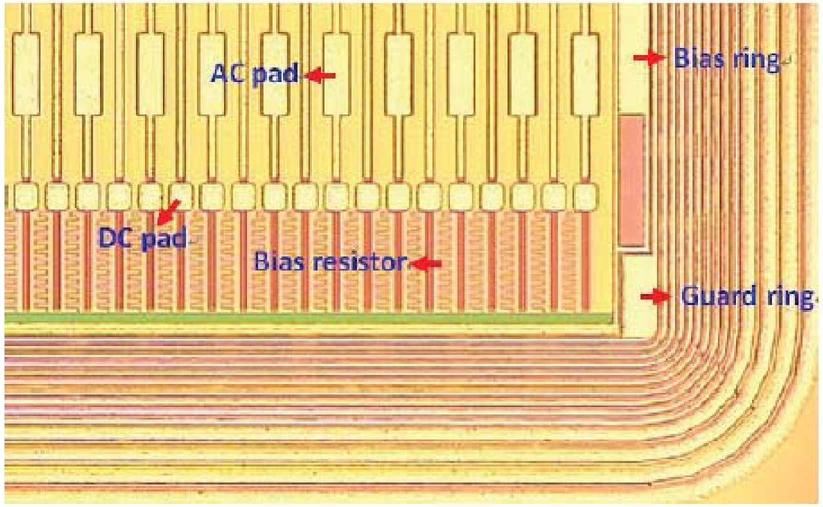
**Message: $N_{ox}$ and $J_{surf}$ anneal with time**

# 3. Impact of Radiation Damage on Sensors

## Sensors irradiated:

- AC coupled from CIS (80 µm pitch)
- DC coupled from Hamamatsu (50 µm pitch)





**$p^+$ on n Si strip sensor:**

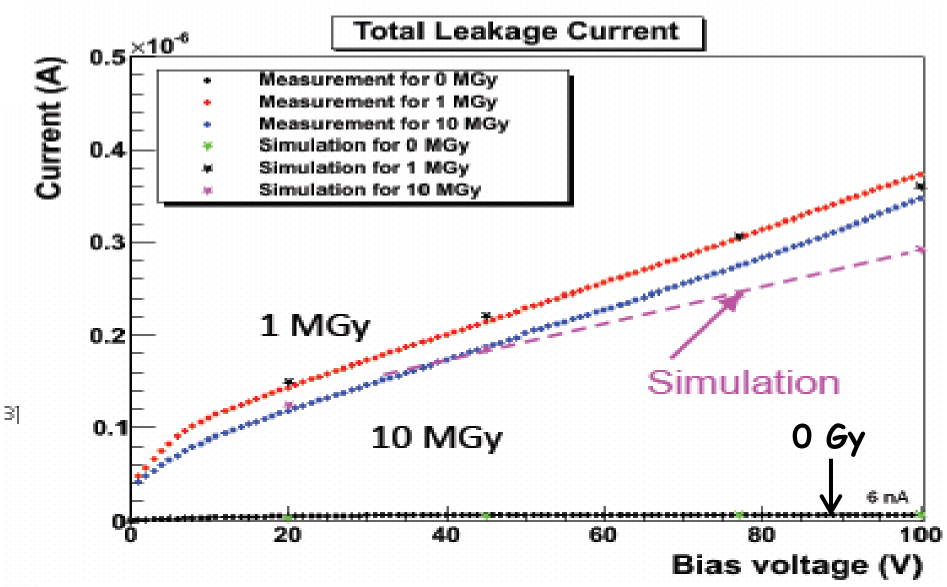
- <100> n-substrate
- High resistivity: 2 - 5 kΩ·cm
- Thickness: 285 ±10 µm
- Active area: 0.62 $cm^2$
- "Oxide": 300 nm $SiO_2$+50 nm $Si_3N_4$
- Strip length: 7.8 mm
- Strip pitch: 80 µm
- Strip number: 98

**X-ray irradiation environments:**

- @DESY DORIS III beamline F4
- Typical energy is 12 keV
- Dose rate in $SiO_2$: 200 kGy/s
- ***Doses: 1 MGy***
- ***Irradiated sensors:***
  - ***sensor 1: irradiated without bias***
  - ***sensor 2: irradiated with 35 V bias***

# 3. Impact of Radiation Damage on Sensors: $I_{dark}$

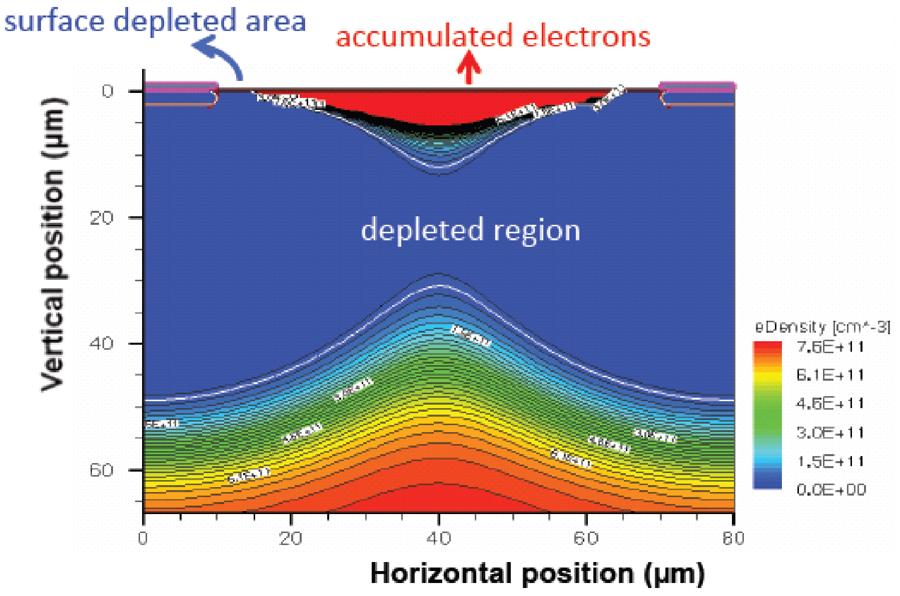
## AC-coupled CIS sensor:



**Interface current ($D_{it}$) dominates**

- Current from depleted interface (E-field)
- Interface area changes with $V_{bias}$
  - → seen by X-ray users
    - → minimize depleted interface area
    - (→ minimize gap between implants/Al)

**Important for sensor optimization**



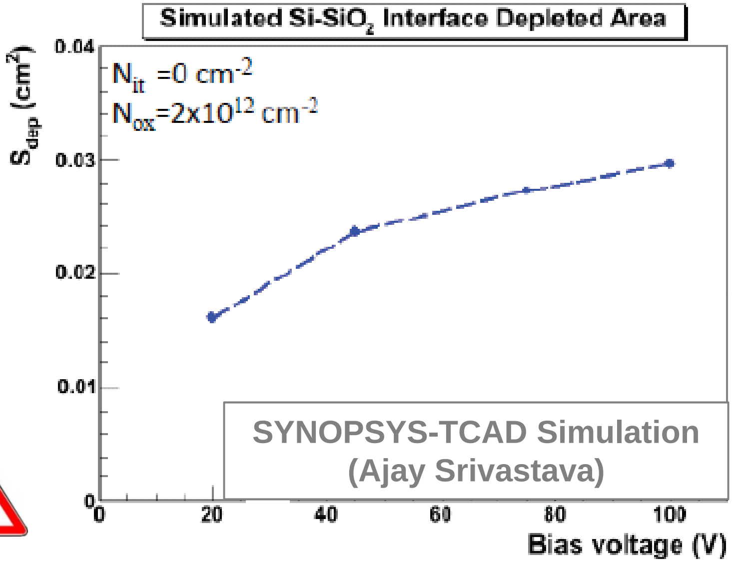
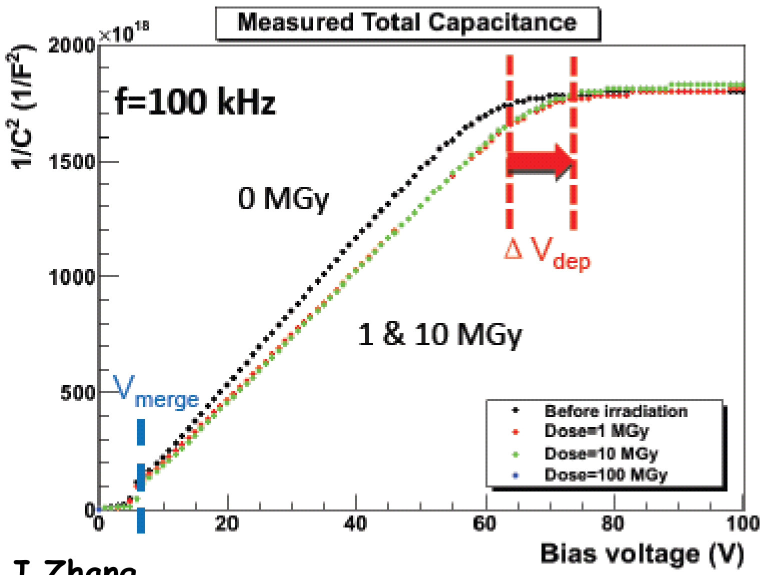


Fig 8. Simulated Si-SiO$_2$ interface depleted area

# 3. Impact of Radiation Damage on Sensors: $V_{depl}$

## AC-coupled CIS sensor:

For pad sensor $C = \frac{\varepsilon \cdot \varepsilon_0 \cdot A}{w_{depletion}} \rightarrow \frac{1}{C^2} \sim V$ up to depletion, then C = constant



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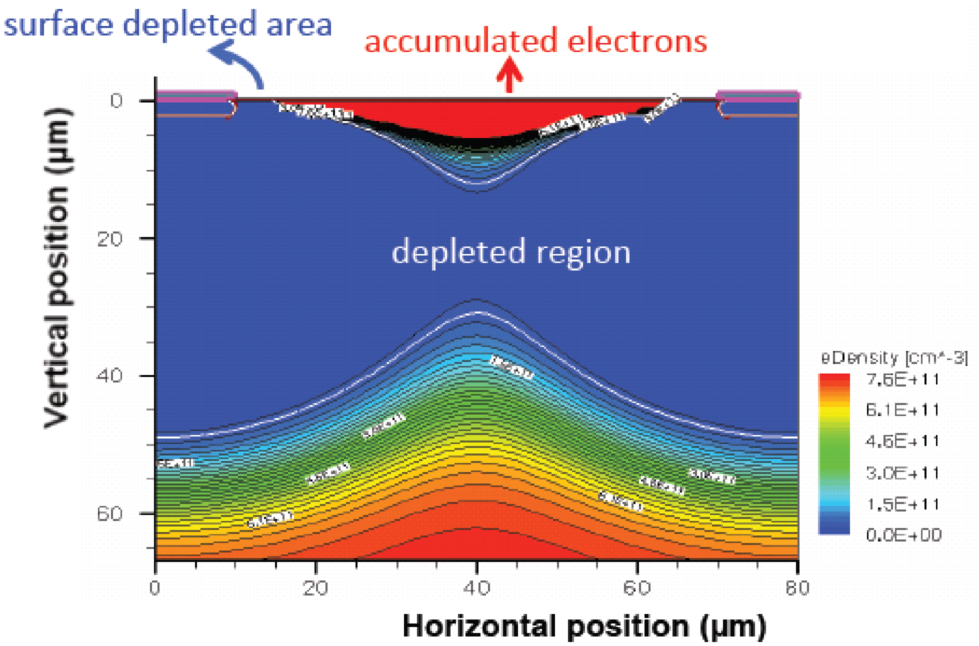


Effects of $N_{ox}$ → increase of electrons in accumulation layer

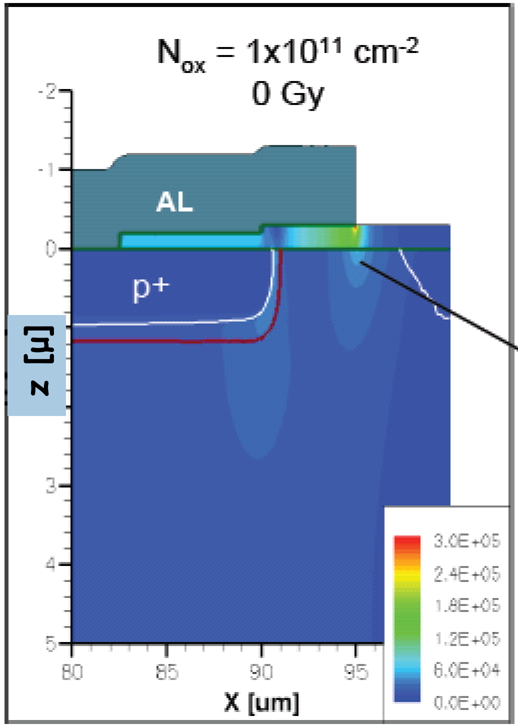
- Step in $1/C^2$ when undepleted regions below $SiO_2$ separate
- Voltage required to deplete entire sensor depends on $N_{ox}$

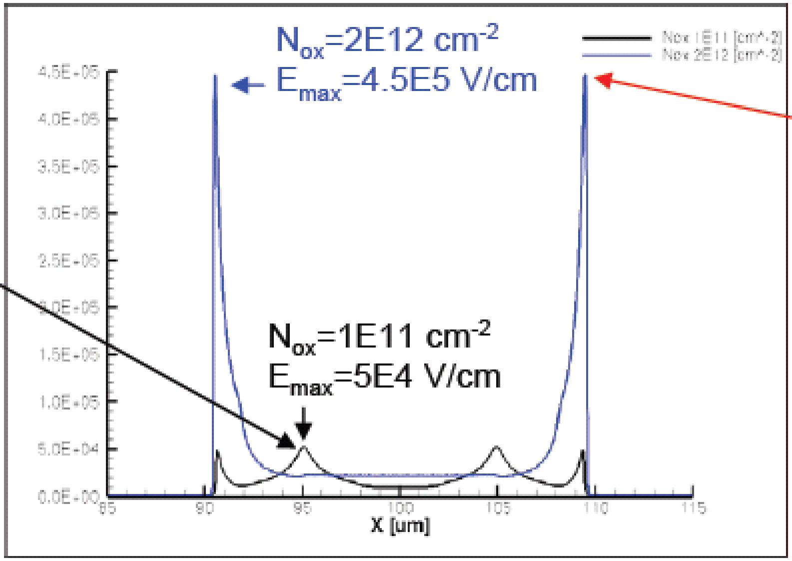
**No significant impact – however, good to know**

# 3. Impact of Radiation Damage on Sensors: $V_{bd}$

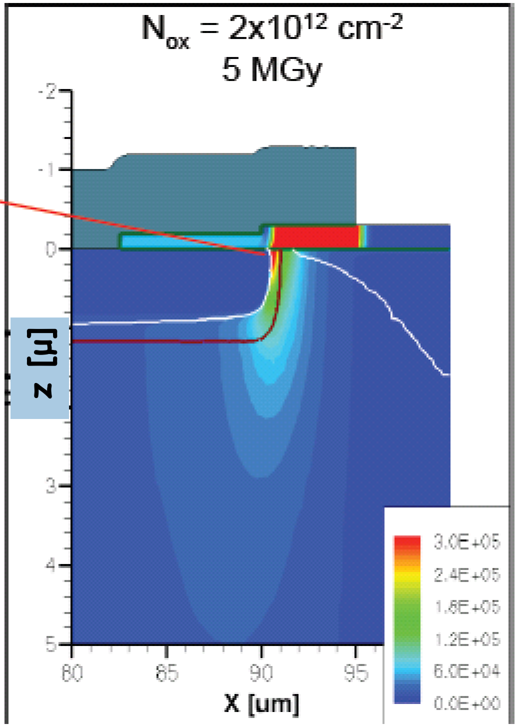
**Simulations 2-dim [x,z and r,z] and 3-dim**

**$N_{ox}$ → accumulation layer → changes curvature $p^+$-depletion → changes E-field**





E-field 100 nm below the interface



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**Breakdown ($V_{bd}$) depends on $N_{ox}$,$t_{ox}$,$p^+$-implant, Al-overhang, potential on top of sensor (passivation layer), technology, etc.**

**Major challenge to reach $V_{bd}$ > 500 V after irradition** ⚠

# 4. Charge Losses close to Si-SiO$_2$ Interface

**Worry:** Do charges trapped at interface cause pile-up ?

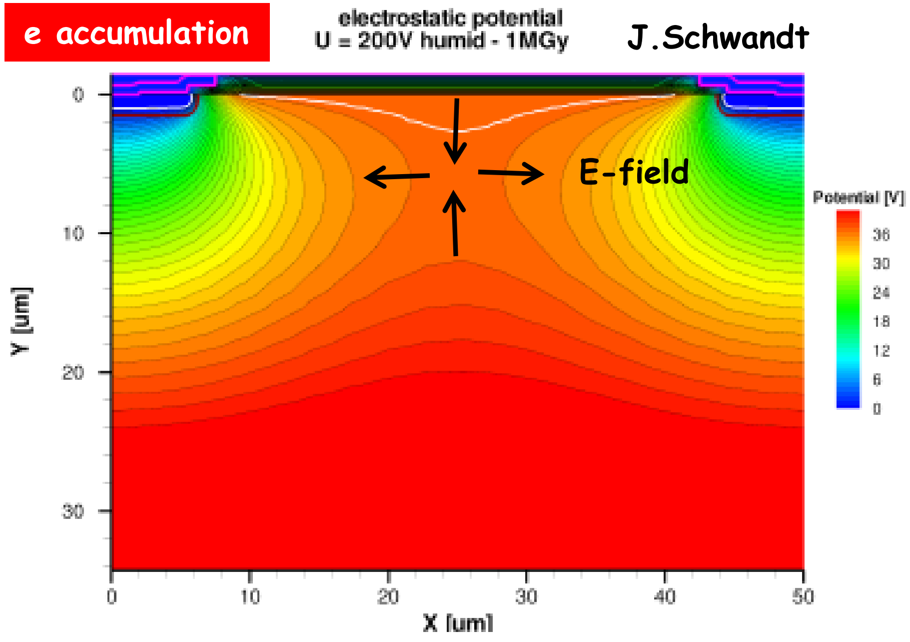
Positive Charges (N$_{ox}$, D$_{it}$)

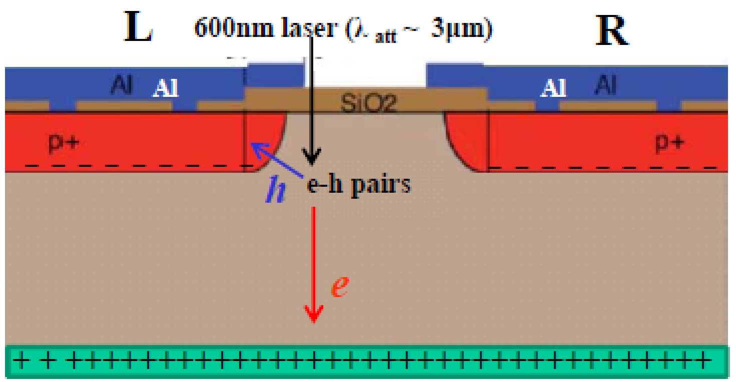
→ e-accumulation + potential minimum

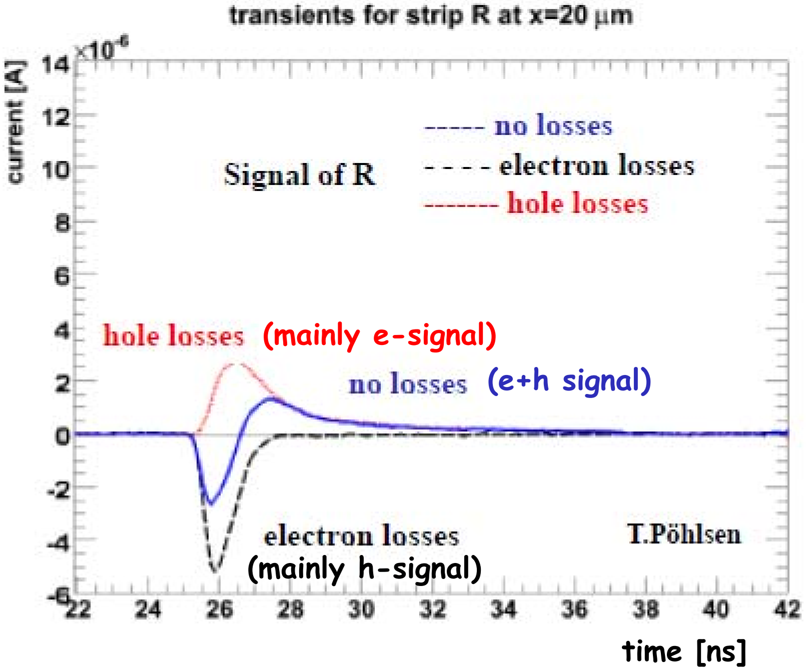
→ Charges stored ("lost")

p$^+$n strip sensor: 50µm pitch, N$_{eff}$=10$^{12}$cm$^{-2}$

**Experiment:** TCT (Transient Current Technique)







→ Significant charge losses observed

# 4. Charge Losses close to Si-SiO$_2$ interface

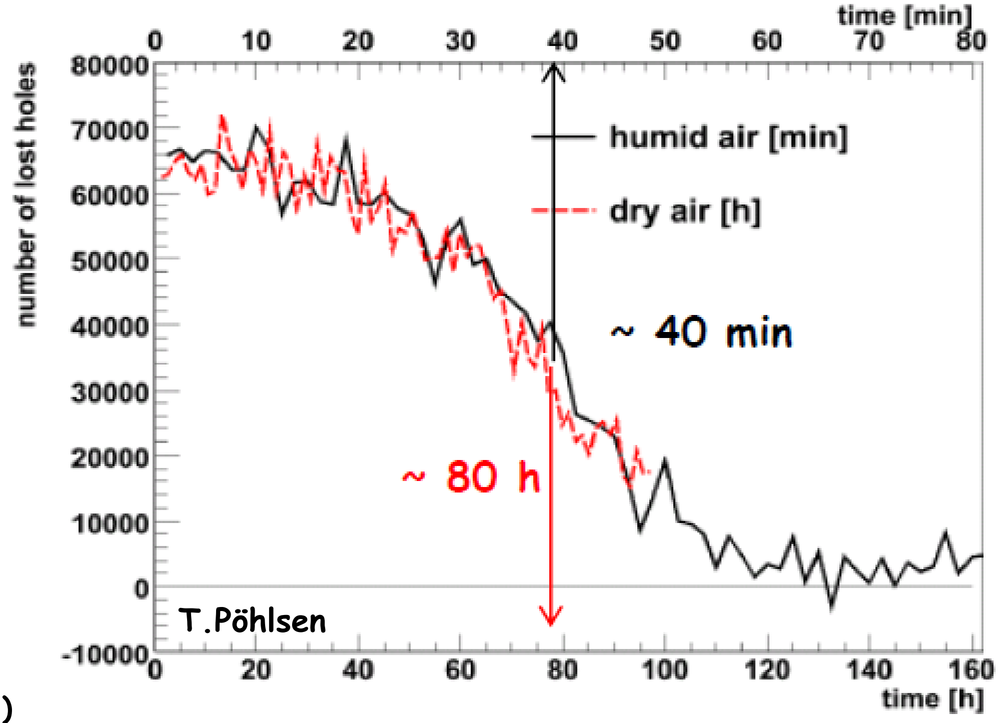
- Losses limited to few µm below SiO$_2$
- Charges spread in ps over acc. layer
- Time to reach equilibrium after losses 10-100 µs » 220 ns

**Charge losses no problem** ☺

**Side remark:**

TCT with focused light and few µm penetration:

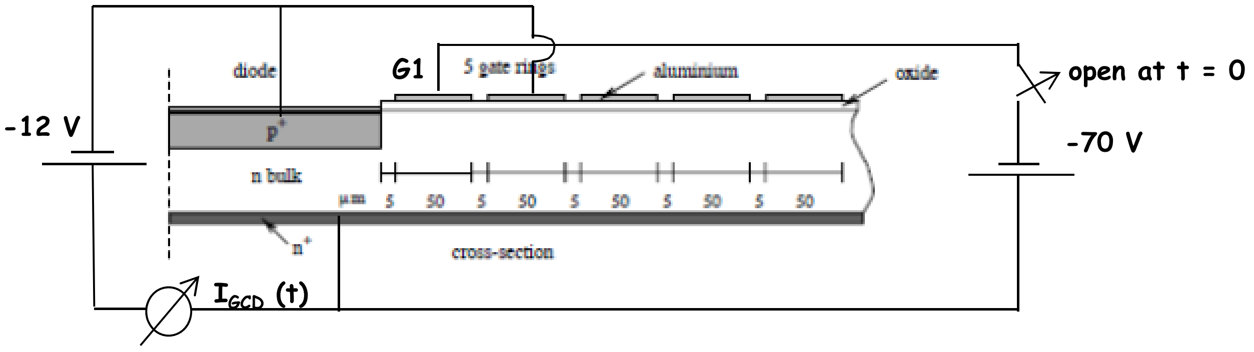
- An excellent tool to study the dependence of accum.layers on radiation damage and the (time/ humidity dependent) boundary conditions on the sensor surface
- It is observed that charge losses depend on time, with constants strongly correlated with humidity (→ surface conductivity ???)
- Time constants differ by factor 120


Hole losses vs. time after changing bias voltage from 500 V to 200 V; $p^+n$ strip sensor, 50 µm pitch, 0 Gy. 600 nm laser, 100k eh-pairs injected

T.Pöhlsen et al., arXiv:1207.6538(2012), (subm. to NIM-A)

# 4'. Surface Conductivity and Steady-State

**Another way to measure the time dependence of surface potentials:**



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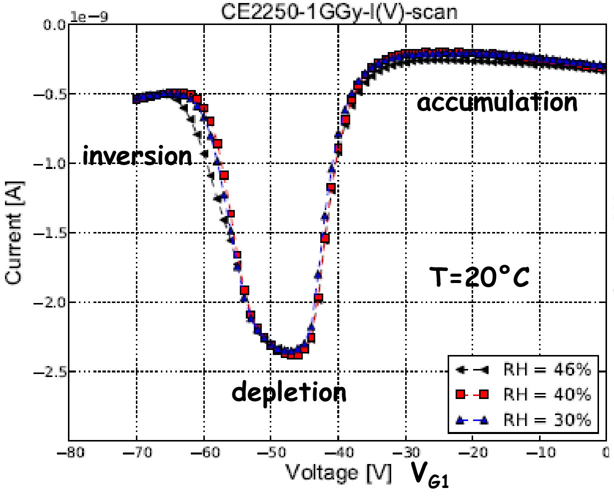
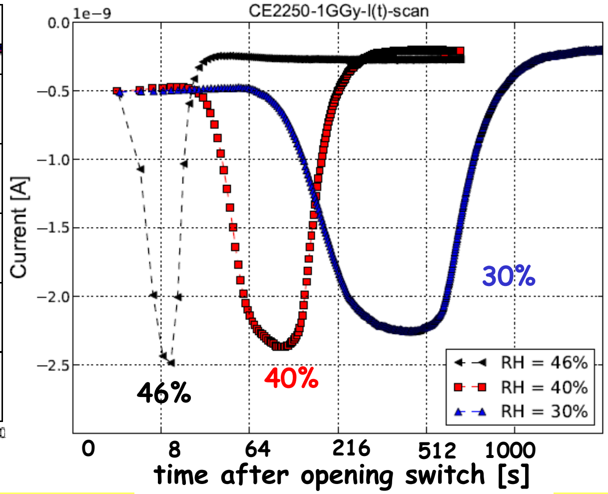
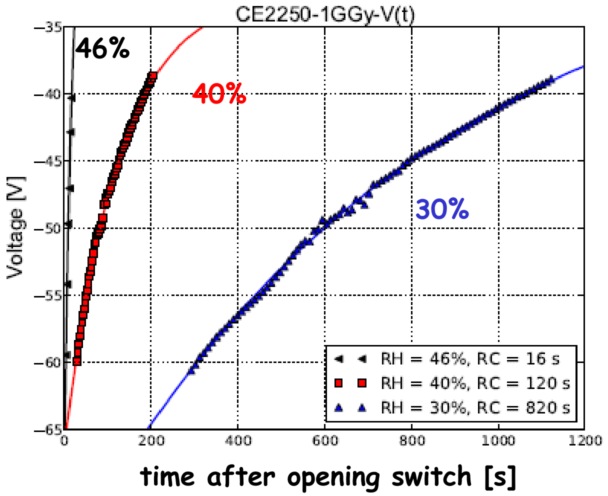
$I_{GCD}/V_{G1}$ curve for gate controlled diode



$I_{GCD}(t)$ for different relative humidities



$V_{G1}(t)$ for different relative humidities

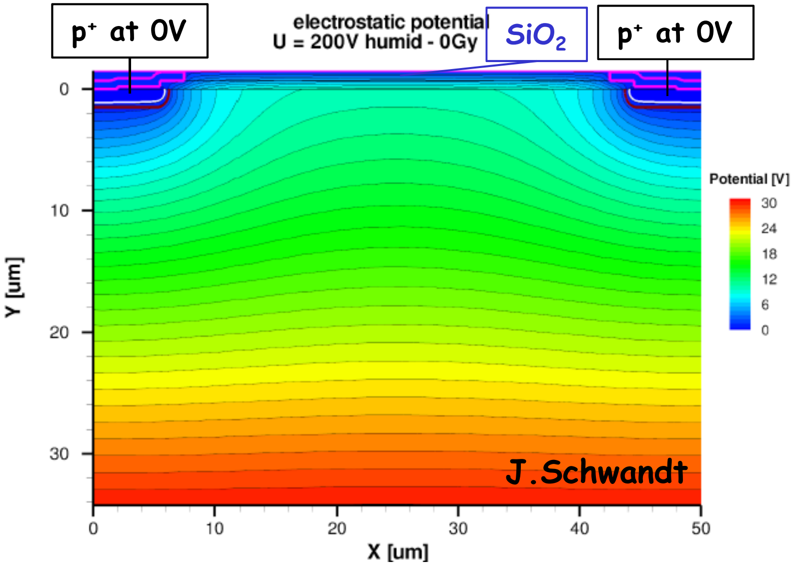


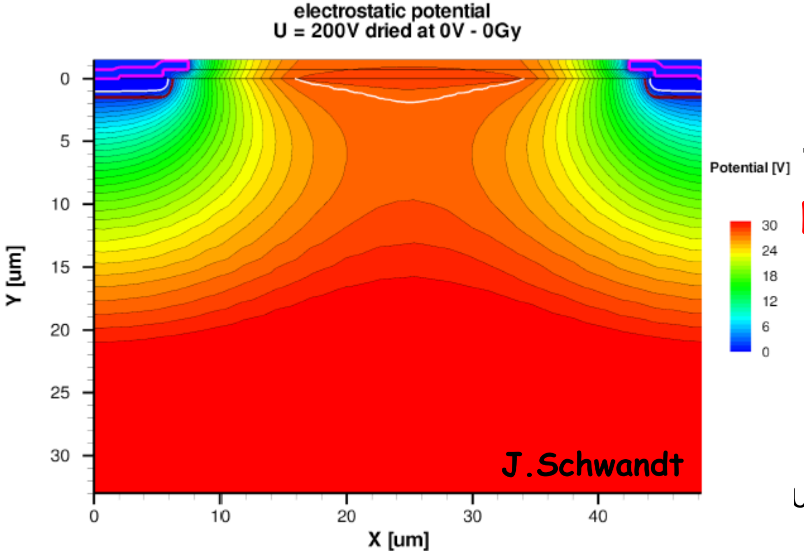
**Time constant changes by factor ~50 between ~30% and ~45% RH**

# 4. Charge Losses and Surface Boundary Conditions

## Do we care what happens on the surface (passivation) of the sensor?

**ATLAS test sensor: $V_{breakdown}$ depends on humidity!**





TCAD Simulation
(non-irradiated strip sensor)

**"humid"** $E_T = 0$ on surface
- No accumulation layer
- Potential low below $SiO_2$

→ moderate E-fields at corners of p⁺ implants

**"dry"** $Q = 0$ on surface
- Accumulation layer
- Potential high below $SiO_2$

→ High E-fields at corners of p⁺ implants

→ Low breakdown voltage

**NB: Vacuum = very dry !!**

F.G. Hartjes NIMA 552(2005)168

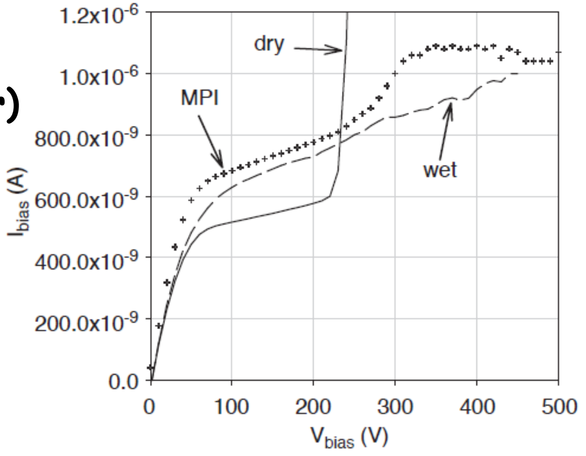


Fig. 3. Example of the breakdown behaviour in a wet (45% < RH < 50%) and in a dry (RH < 5%)atmosphere.

**Has to be understood for sensor design
Work with producers to solve this (well known by experts) problem ?**

# 5. AGIPD Sensor: Specifications

## Sensor specifications (based on science and feasibility)

| Parameter | Value | Comments |
|---|---|---|
| mechanical thickness | 500±20 µm | mounting tolerances, X-ray conv. efficiency |
| flatness (sensors after cutting) | < 20 µm | bump bonding,:*value to be discussed (v. t. b. d.)* |
| distance pixel edges to cut edges | 1200 µm | dead space for science |
| n doping | 3-8 kΩ·cm | depletion voltage, sideway depletion at edges |
| dead layer $n^+$-side | < 0.5 µm Al , < 1 µm $n^+$ Si | minimize, but no compromise on breakdown |
| doping non-uniformity | < 10% | distortions in charge collection |
| pixel dimensions | 200 µm x 200 µm | see sensors design |
| nominal operating voltage | 500 V | |
| breakdown voltage | > 900 V | Sensor should operate stably at > 900 V, high voltage options for high photon density: mounting, pulse shape, dead space at edges |
| coupling type | DC | |
| inter-pixel capacitance@500V | 500 fF | noise, cross-talk |
| total dark current sensor@500V | 50 µA | power |
| max. dark current/pixel@500V | 50 nA | noise, operation of read-out ASIC |
| max. dark current CCR@500V | 20 µA | |

# 5. AGIPD Sensor: Optimization

## Optimization using TCAD

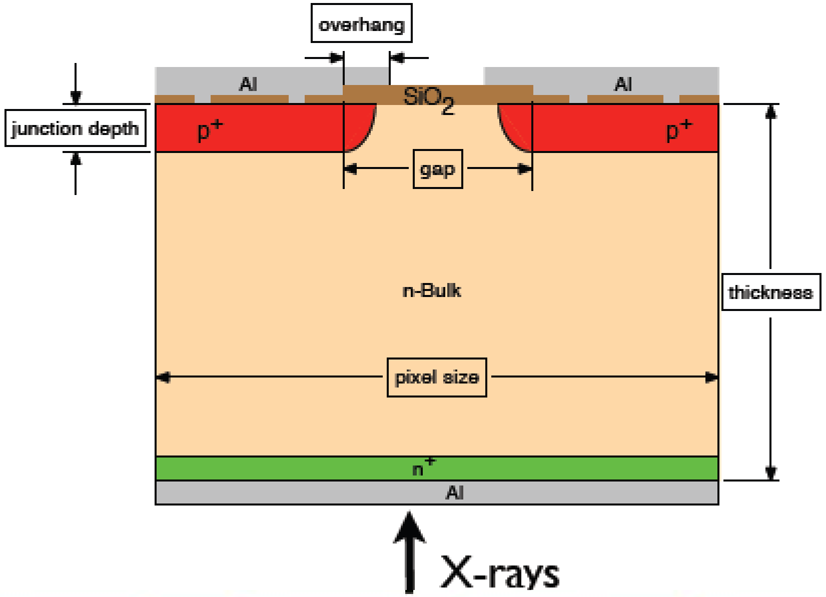
**with radiation damage parameters**

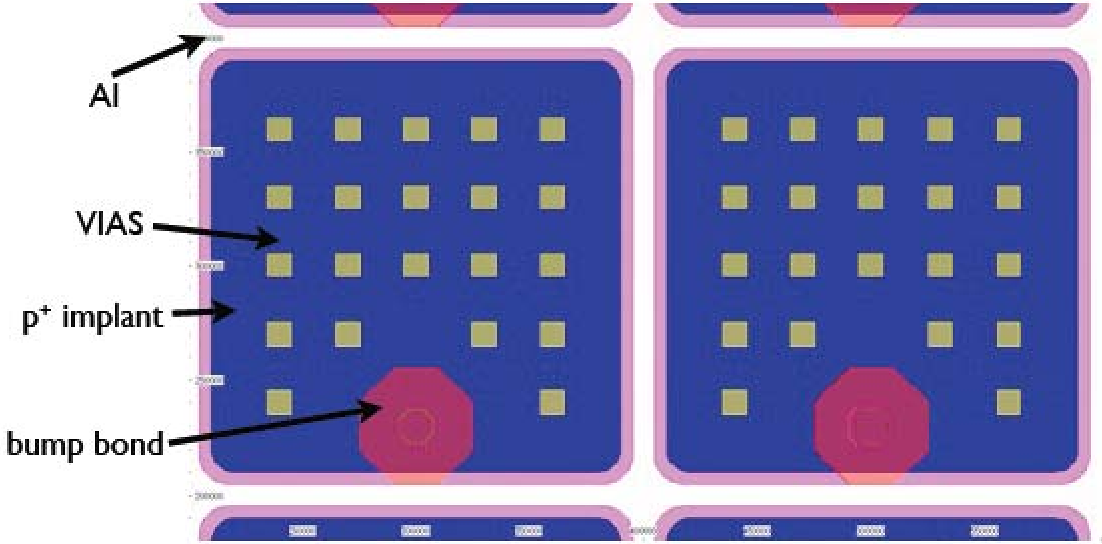
**Performance parameters optimized**

- Breakdown voltage
- Dark current
- Inter-pixel capacitance
- Dead space

1. Pixel:
   - Gap
   - Al overhang
   - Radius of implant and Al at corners
2. Guard-ring structure + sensor edge
   - Number of rings
   - Implantation width
   - Spacing
   - Al overhangs
   - Radii
   - Scribe line
3. Process parameter:
   - Junction depth
   - Oxide thickness
   - Overall passivation

J.Schwandt et al., arXiv:1210.0430(2012)





# 5. AGIPD Sensor: Optimization Strategy

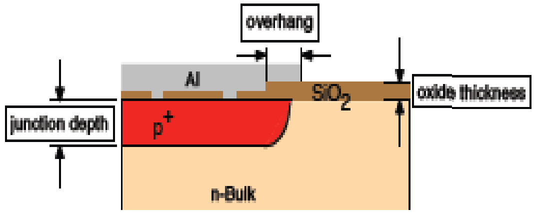
- Performance to be optimized:
  - Pixel:
    1. Breakdown
    2. Surface current
    3. Inter-pixel capacitance
  - Guard-rings:
    1. $V_{bias}$ (1000 V?) over 1.2 mm for doses between 0 and 1 GGy ( nonuniform )
    2. Bulk not depleted at scribe line ( no leakage current from the edge )
- Strategy of guard-ring (GR) optimization ( 2D simulations in (x,y) and (r,z) coordinates ):
  - 0 GR: Study breakdown behavior of 0 GR ( CCR only ) for different oxide charges as function of oxide thickness and Al overhang
  - Estimate number of floating GRs for 1000 V
  - Vary spacing between rings, implant width and overhang to achieve maximum $V_{bd}$ ≈ equal electric field
  - Minimize space required
- Strategy of pixel optimization ( 2D „strip sensor“ calculation used ):
  - Optimize oxide thickness, Al overhang, gap and implantation depth with respect to breakdown voltage, dark current and capacitance
  - Extrapolation of dark current and capacitances to „3D values“
  - Check breakdown voltage + dark current with 3D simulation ( only 1/4 pixel used due to grid size )

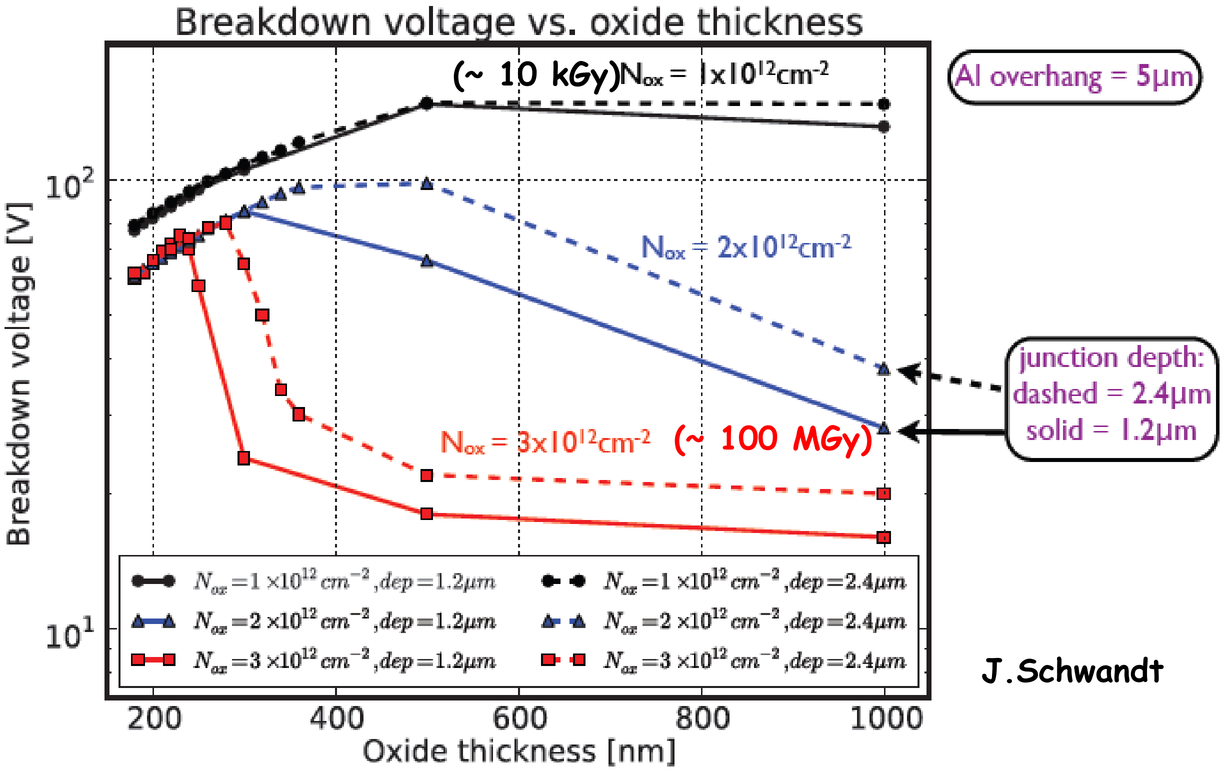
**J.Schwandt et al., arXiv:1210.0430(2012)**

**Discuss only guard ring optimization due to lack of time**

# 5. Guard Ring Optimization: 0 GR $V_{bd}$ vs. $d_{ox}$ and $d_{p+}$

**2-D (x,y) simulations** (for 0 guard ring - GR):





J.Schwandt

**Strong dose dependence:**

($V_{bd}$ ~400V for $N_{ox} < 10^{11} cm^{-2}$)

**Sudden decrease in $V_{bd}$:**

- Si below Al overhang gets depleted → voltage drop over larger region → E smaller for a given (high) $N_{ox}$: $V_{bd}$ increases with ↓ $d_{oxide}$ and ↑ $p^+$-implant depth

**For high radiation damage optimization is very different than for unirradiated sensor – $V_{bd}$ ~ 70 V (0 GR) can be reached**

# 5. Guard Ring Optimization: 15 Guard Rings vs. $V_{bd}$

## Optimize GR layout

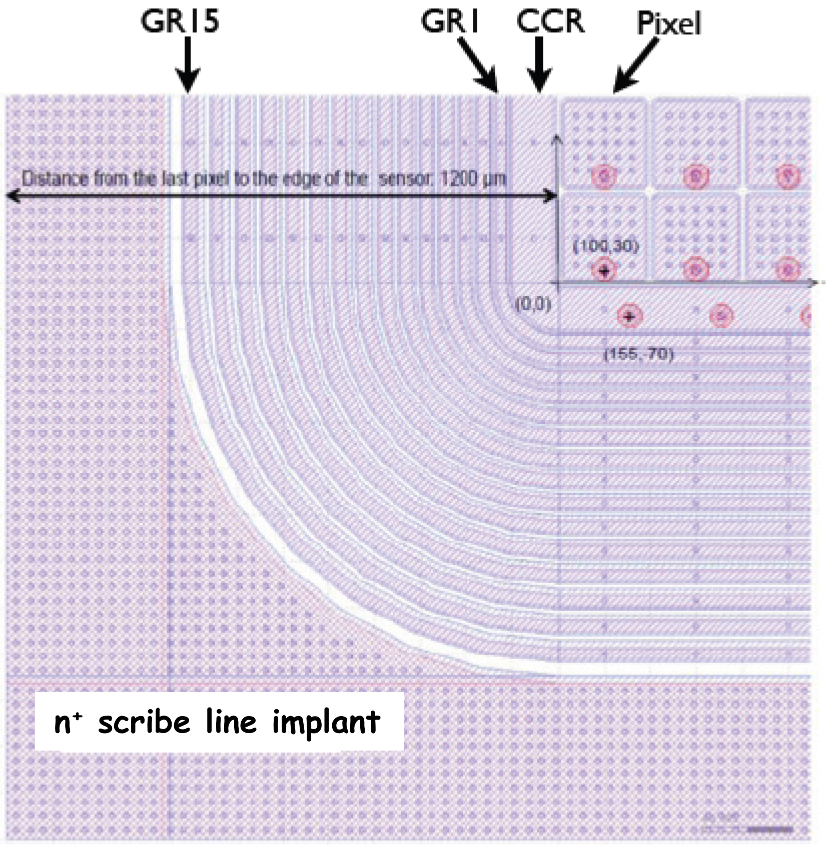
1 gap (0 GR) → $V_{bd}$ ~70 V
→ for $V_{bd}$ ~ 1000 V need 16 gaps (15 GR)

Optimize spacing, width implant, Al overhang for equal max. E-field and minimal space

\+ Assure that depletion region does not touch cut edge (critical for low $N_{ox}$ !)

## Result:

- Gap pixel to CCR: 20 µm
- Width implantation window CCR: 90 µm
- Al overhang CCR: 5 µm
- Gap CCR to 1st guard ring (GR): 12 µm
- Width of implantation window GR 25 µm
- Al overhang left (towards pixel) of GR 1, 2, … 15: 2, 3, … 16 µm
- Al overhang right (away from pixel) of GR 1 – 15: 5 µm
- Gap between GR 1-2, 2-3, … 14-15: 12, 13.5, … 33 µm
- **Distance pixel to cut edge: 1.2 mm**



GDS printout: J.Schwandt and J.Zhang
J.Schwandt et al., arXiv:1210.0430(2012)

**Optimized pixel and guard ring layout meets all specifications**

# 6. Summary

**Challenges for pixel sensors at E-XFEL have been studied at UHH:**

- Plasma effect
- Charge losses close to Si-$SiO_2$ interface – surface effects
- Pile-up
- Radiation damage

**Sensor optimized using TCAD with radiation damage implemented**

- Design optimization depends on dose
- 15 guard rings needed for $V_{bd}$ O(1000 V)
- Layout + technological parameters found which meet specifications

**Sensor ordered → delivery early 2013**

**Comment:** Compared to bulk damage little efforts in the detector community on the study of X-ray damage for sensors (and there have been surprises in the past !)

Many thanks to UNI-Hamburg- + AGIPD-colleagues + sponsors

# The End