Challenges for Silicon Pixel Sensors at the XFEL

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supported by and done in collaboration with
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 … >10⁵ 12 keV photons per 200 x 200 μm² 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 × pulse duration × coherence × Å resolution
1. The XFEL Challenges for Pixel Sensors: AGIPD

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

- Hybrid p+n pixel detector
- 1 Mpixels of 200 x 200 μm²
- 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
Plasma effect*):

$10^5$ 12.4 keV $\gamma$'s in $(200 \, \mu m)^2$

$\rightarrow \sim 5 \times 10^{13}$ e-h pairs/cm$^3$

$\rightarrow$ n$^+$ doping of $O(10^{12} \, \text{cm}^{-3})$

$\rightarrow$ After $\sim$ps a neutral e-h plasma forms, which erodes by ambipolar diffusion

$\rightarrow$ Once charges are separated, charge repulsion spreads charge clouds

$\rightarrow$ Delayed charge collection

$\rightarrow$ 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)

*) 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

Current transients for 450 $\mu$m p-n sensor - $V_{dep} = 140$ V
for $\sim 3 \times 10^5$ 1 keV photons focused to $\Phi \sim 10 \, \mu m$

Charge collected on strip sensor with 80 $\mu$m pitch
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: $8.2 \cdot 10^{11} \text{cm}^{-3}$

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

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 SiO₂

for 500 nm SiO₂: $4 \cdot 10^{16}$ eh/cm² for dose of 1 MGy
(compared to $10^{15}$ cm⁻² surface states)

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

Transport of free carriers

3. X-ray Induced Defects in Si Sensors

- **Transport of free carriers**
  - \( \mu_{\text{electrons}} \sim 20 \text{ cm}^2/\text{V}\cdot\text{s} \) → e's mainly escape
  - \( \nabla \mu_{\text{holes}} \sim < 10^{-5} \text{ cm}^2/\text{V}\cdot\text{s} \) → h's trapped in SiO2
    - or (mainly) at Si-SiO2 interface
      - [there are \( O(10^{15} \text{ cm}^{-2}) \) surface states !]

- **Trapping in SiO2 interface**
  - e-h pairs created by ionizing radiation

- **Effects on sensor**

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3. Damage of SiO₂ and at Si–SiO₂ Interface

**Oxide trapped charges (N_{ox}):**
- Mainly positive oxygen-vacancy defects
  - one shallow trap \( \rightarrow \) hole transport,
  - one deep trap \( E'_\gamma \approx 3 \text{ eV} \)
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} \(^\ast\)):**
Traps at interface (no barrier!)
dangling bond defects (P_b) -
\( H^+ \) released when \( h \) captured:
\[ \text{SiH} + H^+ \rightarrow (\text{Interface Trap})^+ + H_2 \]
No. limited by no. of dangling bonds

\(^\ast\) Distribution of traps in the Si bandgap:
\( D_{it} \) [1/(eV cm²)]

**Mobile ions:** not an issue anymore

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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
  → $I_{TDRC}(T) \rightarrow D_{it}(E)$
→ (Energy levels + widths + densities)$_{it}$

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

Parameterize by 3 states - not unambiguous!
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 $\rightarrow N_{ox}$

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:
- Shielded

T-dependence of $I_{surf}$

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

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 \( Si_3N_4 \)

- 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

\[ \text{Dose dependence of oxide charge density} \]

\[ \text{Dose dependence of surface current density} \]


- Equilibrium h-trapping and eh-recombination ?
- E-field effects due to oxide charges ?
\[ \Rightarrow \text{Understanding needs more studies} \]

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$_3$N$_4$

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

$V_{bias} \leq 0$: Only weak dependence

For p+n sensor: $E_{ox} < 0 \rightarrow$ no problem

$E$-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$_3$N$_4$
  
  - Described by “tunnel anneal model” [T.R. Oldham et al., 1988]

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

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

$\Rightarrow$ Annealed oxide charges:

$$\Delta N_{ox}(t) = \int_0^{x_m(t)} N_{ht}(x) \, dx$$

$\lambda$: effective tunneling time constant

$\Delta E$: distance trap level to $E_{Fermi}$

$\beta$: parameter related to barrier height

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

with $t_0(T) = t_0^* \cdot \exp\left(\frac{\Delta E}{k_B T}\right)$

$N_{ox}(t) = N_{ox}^0 \cdot (1 + t/t_0)^{-\frac{\lambda}{2\beta}}$

$\Delta E = E_{ht}(SiO_2) - E_{Fermi}(Si) = 0.91$ eV

$E_{ht}(SiO_2) \sim 6$ eV - compatible with existing data

$\Rightarrow$ 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

- $\text{cI}_\text{S} \ \langle 111 \rangle$ with $\sim350 \ \text{nm} \ \text{SiO}_2 + 50 \ \text{nm} \ \text{Si}_3\text{N}_4$

$\text{J. Zhang et al., arXiv:1210.0427(2012)}$

![Graph showing TDRC signal vs temperature](image_url)
3. Annealing of $J_{\text{surf}}$

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$_3$N$_4$

- Described by “two reaction model” \[ \text{[M.L. Reed 1987]} \]

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

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

Message: $N_{\text{ox}}$ and $J_{\text{surf}}$ 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)

\[
\text{p}^+ \text{ on n Si strip sensor:}
\begin{align*}
&\text{\langle100\rangle n-substrate} \\
&\text{High resistivity: 2 - 5 kΩ\cdot cm} \\
&\text{Thickness: 285 ± 10 μm} \\
&\text{Active area: 0.62 cm}^2 \\
&\text{“Oxide”: 300 nm SiO}_2 + 50 \text{ nm Si}_3\text{N}_4 \\
&\text{Strip length: 7.8 mm} \\
&\text{Strip pitch: 80 μm} \\
&\text{Strip number: 98}
\end{align*}
\]

X-ray irradiation environments:
- @DESY DORIS III beamline F4
- Typical energy is 12 keV
- Dose rate in SiO\(_2\): 200 kGy/s
- \textit{Doses: 1 MGy}
- \textit{Irradiated sensors:}
  - \textit{sensor 1: irradiated without bias}
  - \textit{sensor 2: irradiated with 35 V bias}
AC-coupled CIS sensor:

**Total Leakage Current**

- Measurement for 0 MGy
- Measurement for 1 MGy
- Measurement for 10 MGy
- Simulation for 0 MGy
- Simulation for 1 MGy
- Simulation for 10 MGy

**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**

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Robert Klanner - Univ. of Hamburg - Jour
AC-coupled CIS sensor:

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

Effects of $N_{\text{ox}} \rightarrow$ increase of electrons in accumulation layer
- Step in $1/C^2$ when undepleted regions below $\text{SiO}_2$ separate
- Voltage required to deplete entire sensor depends on $N_{\text{ox}}$

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

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

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 irradiation

J. Schwandt
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 $\mu$m below SiO$_2$
- Charges spread in ps over acc. layer
- Time to reach equilibrium after losses 10-100 $\mu$s $\gg$ 220 ns

\textbf{Charge losses no problem}

\textbf{Side remark:}

TCT with focused light and few $\mu$m 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 ($\rightarrow$ 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 $\mu$m 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:

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

Time constant changes by factor $\approx 50$ between $\approx 30\%$ and $\approx 45\%$ RH
4. Charge Losses and Surface Boundary Conditions

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

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

**TCAD Simulation**

(non-irradiated strip sensor)

- "humid" $E_T = 0$ on surface
  - No accumulation layer
  - Potential low below $\text{SiO}_2$
  $\rightarrow$ moderate E-fields at corners of $p^+$ implants

- "dry" $Q = 0$ on surface
  - Accumulation layer
  - Potential high below $\text{SiO}_2$
  $\rightarrow$ High E-fields at corners of $p^+$ implants

$\rightarrow$ Low breakdown voltage

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

Has to be understood for sensor design

Work with producers to solve this (well known by experts) problem?

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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.
## 5. AGIPD Sensor: Specifications

Sensor specifications *(based on science and feasibility)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>mechanical thickness</td>
<td>$500 \pm 20 , \mu m$</td>
<td>mounting tolerances, X-ray conv. efficiency</td>
</tr>
<tr>
<td>flatness (sensors after cutting)</td>
<td>$&lt; 20 , \mu m$</td>
<td>bump bonding, <em>value to be discussed</em> <em>(v. t. b. d.)</em></td>
</tr>
<tr>
<td>distance pixel edges to cut edges</td>
<td>$1200 , \mu m$</td>
<td>dead space for science</td>
</tr>
<tr>
<td>n doping</td>
<td>$3-8 , k\Omega \cdot cm$</td>
<td>depletion voltage, sideway depletion at edges</td>
</tr>
<tr>
<td>dead layer n*-side</td>
<td>$&lt; 0.5 , \mu m Al, &lt; 1 , \mu m n^* Si$</td>
<td>minimize, but no compromise on breakdown</td>
</tr>
<tr>
<td>doping non-uniformity</td>
<td>$&lt; 10%$</td>
<td>distortions in charge collection</td>
</tr>
<tr>
<td>pixel dimensions</td>
<td>$200 , \mu m \times 200 , \mu m$</td>
<td>see sensors design</td>
</tr>
<tr>
<td>nominal operating voltage</td>
<td>$500 , V$</td>
<td></td>
</tr>
<tr>
<td><strong>breakdown voltage</strong></td>
<td>$&gt; 900 , V$</td>
<td>Sensor should operate stably at $&gt; 900 , V$, high voltage options for high photon density: mounting, pulse shape, dead space at edges</td>
</tr>
<tr>
<td>coupling type</td>
<td>DC</td>
<td></td>
</tr>
<tr>
<td>inter-pixel capacitance@500V</td>
<td>$500 , \text{fF}$</td>
<td>noise, cross-talk</td>
</tr>
<tr>
<td>total dark current sensor@500V</td>
<td>$50 , \mu A$</td>
<td>power</td>
</tr>
<tr>
<td>max. dark current/pixel@500V</td>
<td>$50 , \text{nA}$</td>
<td>noise, operation of read-out ASIC</td>
</tr>
<tr>
<td>max. dark current CCR@500V</td>
<td>$20 , \mu A$</td>
<td></td>
</tr>
</tbody>
</table>
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

5. AGIPD Sensor: Optimization Strategy

- Performance to be optimized:
  - Pixel:
    1. Breakdown
    2. Surface current
    3. Inter-pixel capacitance
  - Guard-rings: 1. $V_{\text{bias}}$ (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)

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):

**Strong dose dependence:**
($V_{bd}$ $\sim$400V for $N_{ox} < 10^{11}$cm$^{-2}$)

**Sudden decrease in $V_{bd}$:**
- Si below Al overhang gets depleted $\rightarrow$ voltage drop over larger region $\rightarrow$ $E$ 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 - $V_{bd}$ $\sim$ 70 V (0 GR) can be reached
5. Guard Ring Optimization: 15 Guard Rings vs. $V_{bd}$

**Optimize GR layout**

1 gap (0 GR) $\rightarrow V_{bd} \sim 70$ V  
$\rightarrow$ for $V_{bd} \sim 1000$ 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 $\mu$m
- Width implantation window CCR: 90 $\mu$m
- Al overhang CCR: 5 $\mu$m
- Gap CCR to 1st guard ring (GR): 12 $\mu$m
- Width of implantation window GR 25 $\mu$m
  - Al overhang left (towards pixel) of GR 1, 2, ... 15: 2, 3, ... 16 $\mu$m
  - Al overhang right (away from pixel) of GR 1 – 15: 5 $\mu$m
- Gap between GR 1-2, 2-3, ... 14-15: 12, 13.5, ... 33 $\mu$m
- Distance pixel to cut edge: 1.2 mm

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

GDS printout: J. Schwandt and J. Zhang  
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