Challenges for the Adaptive Gain Integrating Pixel Detector (AGIPD) design due to the high intensity photon radiation environment at the European XFEL

Julian Becker, DESY, Hamburg
Outline

• The European XFEL
  – FEL principle
  – Potential experiments
  – Detector requirements

• Radiation damage of low $E\gamma$s

• The AGIPD
  – ASIC
  – Layout

• Summary
The European XFEL

17.5 GeV linear electron accelerator producing 12.4 keV X-rays (tunable) through FEL process
unprecedented peak brilliance
user facility: common infrastructure shared by many experiments

Tunnel:
- 3.4 km long
- 12-44 m deep
Magnetic slalom structure for electrons

-> Bremsstrahlung

When path length difference = wavelength

-> microbunching and resonant emission

Same phase = coherence!

-> Self Amplified Spontaneous Emission (SASE)

Even higher amplification when external (seed) radiation is present
One possible experiment

Coherent Diffractive Imaging (CDI or CXI) using nano-crystals

Doi: 10.1126/science.1217737
Diffractive imaging

With optimal detector this can be done on individual non-reproducible objects (e.g. Cells, Viruses)
Molecular movies

Varying time delay between initiating pump (laser-) pulse and probe (XFEL-) pulse

Snapshot of chemical process on fs scale with atomic resolution

Evolution of non-equilibrium processes (e.g. phase change, alloy formation, shock wave propagation, etc.)


18.09.2012 J. Becker, VERTEX 2012
Special structure of pulse trains:

- 600 µs long pulse trains at a repetition rate of 10 Hz
- Each train consists of 2700 pulses with a separation of 220 ns
- (SASE) Each pulse consists of $\approx 10^{12}$ photons arriving <100 fs

Beam energy:

- 5 – 25 keV (depends on station)
- 12.4 keV ($\lambda$=0.1 nm) nominal design energy for AGIPD
XFEL Detector requirements

- Dynamic range: $> 10^4$ 12.4 keV photons per image
- Single photon sensitivity
- Low noise
- Radiation Hardness
- 4.5 MHz
1. High instantaneous flux
   - More charge than pixel electronics can tolerate
     • Pixel may break irrecoverably from a single shot
     • Protection measures needed
   - Distortions of local electric field in the sensor (plasma effect)
     • Influences charge collection time and point spread function
     • Requires high bias voltage to compensate

2. Total dose (up to $10^{16}$ 12.4 keV $\gamma$s = 1 GGy in 3 years of operation)
   - Charge buildup in SiO$_2$ & generation of traps at Si-SiO$_2$ interface
     • Increase of leakage currents (noise)
     • Reduction of breakdown voltages
     • Unwanted accumulation layers
     • Changes of (interpixel) capacitance

No Si-bulk damage, as beam energy is below 300 keV threshold
‘Surface’ damage in silicon

Mobile Ionic Charge, affected early stage MOS structures, not an issue today.

Oxide Trapped Charge, defects in the SiO₂ network, but difficult to communicate with free carriers.

Fixed Oxide Charge, due to the hole trapping (~ nm from interface, highly disordered region).

Interface trap, due to dangling Si-O bonds with new energy states in the forbidden band.

---


18.09.2012 J. Becker, VERTEX 2012
Factors influencing the densities of charges in the SiO\textsubscript{2}/Si\textsubscript{3}N\textsubscript{4} layers:

- dose (energy deposition in silicon dielectric layer*, not silicon bulk!)
- dose rate
- electric field in SiO\textsubscript{2} layer*
- post-irradiation conditions (e.g., time and temperature) – annealing effects*
- Si-SiO\textsubscript{2} interface properties (stoichiometry, structure, defects and doping)
- fabrication processing (oxide growth and annealing conditions)
- oxide impurities (including hydrogen, nitrogen, and sodium)
- type of ionizing radiation

* important in X-ray irradiation case, especially for surface charges (fixed oxide charges and interface traps)

Conclusions:

- \( N_{\text{ox}} \) and \( I_{\text{surface}} \) saturate with dose: typically \( N_{\text{ox}} \sim (1.5 - 4.0) \times 10^{12} \, \text{cm}^{-2} \), \( I_{\text{surface}} \sim (3 - 7) \, \mu\text{A/cm}^2 \)
- No significant differences for orientations, \( \text{SiO}_2 \) vs. \( \text{SiO}_2+\text{Si}_3\text{N}_4 \), vendors
- Saturation mechanism of \( N_{\text{ox}} \): equilibrium between hole trapping and electron recombination

18.09.2012  
J. Becker, VERTEX 2012
Conclusions:

- $N_{ox}$ and $I_{surface}$ increase for $E_{ox} > 0$
- No strong $E_{ox}$ dependence for $E_{ox} < 0$
- $p^+n$ sensor: $E_{ox} < 0 \rightarrow$ not a problem!
Influence on C/V characteristics

- $V_{\text{dep}}$ increases $\sim 10$ V after irradiation due to the presence of surface charges (not due to change of doping concentration)
- Strong frequency dependence of total capacitance observed for $V_{\text{bias}} < 300$ V

![Diagram showing capacitance characteristics before and after irradiation](image)

**Total Capacitance (in series)**

- Before irradiation
- 1 MGy
- 10 MGy

**Total Capacitance after 10 MGy (in series)**

- 1 kHz
- 3 kHz
- 10 kHz
- 30 kHz
- 100 kHz

$V_{\text{merge}}$ for $f = 100$ kHz (after 60 min @ 80°C)

$\Delta V_{\text{dep}}$
Influence on I/V characteristics

- Leakage current: $I_{\text{leakage}} = I_{\text{bulk}} + I_{\text{surface}}$

- Increase of $I_{\text{leakage}}$ after irradiation $\leftarrow$ interface trap density $N_{\text{it}}$
- "Linear" increase of $I_{\text{leakage}}$ with bias voltage $\leftarrow$ depleted area $A_{\text{dep}}$ at Si-SiO$_2$ interface
- Decrease of $I_{\text{leakage}}$ with irradiation dose $\leftarrow$ result of competition between $N_{\text{it}}$ and $A_{\text{dep}}$
- For irradiation under bias, $I_{\text{leakage}}$ larger by $\sim 100$ nA

18.09.2012 J. Becker, VERTEX 2012
The AGIPD

- **Adaptive Gain Integrating Pixel Detector**
- Hybrid pixel detector for the European XFEL
- $(200 \, \mu m)^2$ pixels and $500 \, \mu m$ silicon sensor
- Collaboration of DESY, PSI, Univ. Hamburg and Univ. Bonn
- Uses IBM 130 nm technology for ASIC
- 1 of 3 detector projects for XFEL (LPD, DSSC)
### XFEL challenges

#### XFEL provides

- Simultaneous deposition of all photons
  - $10^{12}$ X-ray photons <100 fs

#### Challenges

- Single photon counting not possible
- Dynamic range: $10^4$ photons/pixel with single photon sensitivity

#### Approach

- Charge integration
- Dynamic gain switching
  - 3 gain stages
  - Single photon sensitivity in highest gain (300 e$^-$ ENC)

#### Additional Challenges

- High number of bunches
  - 2700 bunches per train (600 µs)
- Reading out of single frames during pulse train impossible
- Analog memory in the pixel using the $\approx\!350$ storage cells per pixel

18.09.2012 J. Becker, VERTEX 2012
ASIC design of a \((200 \, \mu m)^2\) pixel

Sensor

ASIC per pixel

Pixel matrix

- Calibration circuitry
- Adaptive gain amplifier
- 352 analog memory cells

Analog Mem

Differential

CDS

SW CTRL

THR

DAC

Analog Mem

RO Amp

Chip output driver

Mux

RO bus (per column)
Radiation damage to the ASIC

- Shielded by 500 µm thick silicon sensor.
- Only ~10% of the maximum dose in ASIC
- Remains functional up to 10 MGy
- After annealing the ASIC is functional beyond 100 MGy

Most problematic issue: deterioration of analog performance
- Increase of ENC (only minor -> can be handled)
- Signal droop in storage cell (can be compensated by cooling)
Imaging with AGIPD testchips

Images courtesy to:
D. Greiffenberg, PSI
U. Trunk, DESY
From single chips to modules

- Module layout based on successful LAMBDA design
- 2x8 chips on LTCC carrier board
- Thermal vias (Ag) for improved cooling

Radiograph of pinecones

Images courtesy of D. Pennicard
**Specifications:**

- 200 x 200 µm² pixel size
- 500 µm silicon sensor
- Hole for direct beam

→ 1 chip: 64 x 64 pixels
→ 1 module: 8 x 2 chips

- 4 quadrants
- 4 modules per quadrant
- 1 Mpixel, upgradable to 4 Mpix
Summary

- European XFEL poses unique rad. hardness challenge
- Rad. hard AGIPD test chips demonstrated
  - Verified functionality
  - Imaging capability demonstrated
  - Dynamic gain switching
  - About 300 $e^{-}$ noise
  - 352 storage cells
## Acknowledgements

**AGIPD Collaboration**

<table>
<thead>
<tr>
<th>DESY</th>
<th>PSI</th>
<th>Univ. Bonn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Julian Becker</td>
<td>Roberto Dinapoli</td>
<td>Marcus Gronewald</td>
</tr>
<tr>
<td>Laura Bianco</td>
<td>Dominic Greiffenberg</td>
<td>Hans Krueeger</td>
</tr>
<tr>
<td>Peter Goettlicher</td>
<td>Beat Henrich</td>
<td></td>
</tr>
<tr>
<td>Heinz Graafsma</td>
<td>Aldo Mozzanica</td>
<td></td>
</tr>
<tr>
<td>Helmut Hirsemann</td>
<td>Bernd Schmitt</td>
<td></td>
</tr>
<tr>
<td>Stefanie Jack</td>
<td>Xintian Shi</td>
<td></td>
</tr>
<tr>
<td>Sabine Lange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alessandro Marras</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulrich Trunk</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Univ. Hamburg**

<table>
<thead>
<tr>
<th></th>
<th>Robert Klanner</th>
<th>Joern Schwandt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Jiaguo Zhang</td>
</tr>
</tbody>
</table>
BACKUP
Unprecedented brightness -> unprecedented dose

Conservative estimate of the total dose:

- $10^{16}$ 12.4 keV photons in 3 years
- $\approx 1$ GGy at entry window
- $\approx 100$ MGy at pixel implants and ASIC

More details in the talk of Jiaguo Zhang later this session