Sensor development for XFEL

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Introduction

The European *X-ray free electron laser* (XFEL) will generate ultra short, coherent extremely intense X-ray flashes. It will open up new research topics for scientists, such as mapping the atomic details of viruses, deciphering the molecular composition of cells and movies of molecular transitions.

During 3 years of XFEL operation, the 12 keV X-rays will result in a radiation exposure of the detectors of up to 1 GGy dose, which represents a major challenge.

The task is to characterize the radiation induced surface charges for different X-ray doses, study their influence on the performance of sensors, and optimize the design of sensors for the XFEL.

X-ray induced damage

X-rays produce electron-hole pairs in SiO_2 by breaking Si-O bonds. Some of the generated charge carriers recombine, but most of them either reach the top of the SiO_2, or the Si-SiO_2 interface. Once holes come close to the Si-SiO_2 interface, a fraction of them will be trapped close to the interface, and produce radiation induced positive fixed oxide charges and interface traps, which cause new energy levels distributed throughout the silicon band gap and whose occupation therefore depends on band bending.

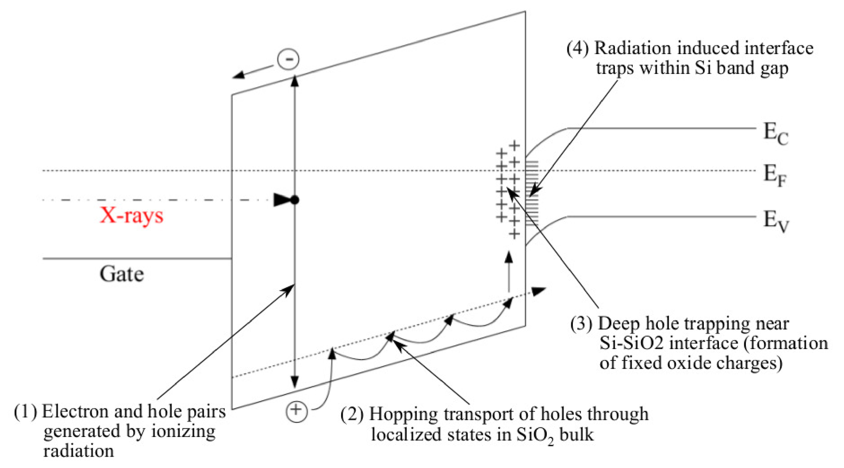


Fig 1. Formation of X-ray induced damage

Determination of concentration of defects

- *Thermally Dielectric Relaxation Current* (TDRC) → interface trap density.

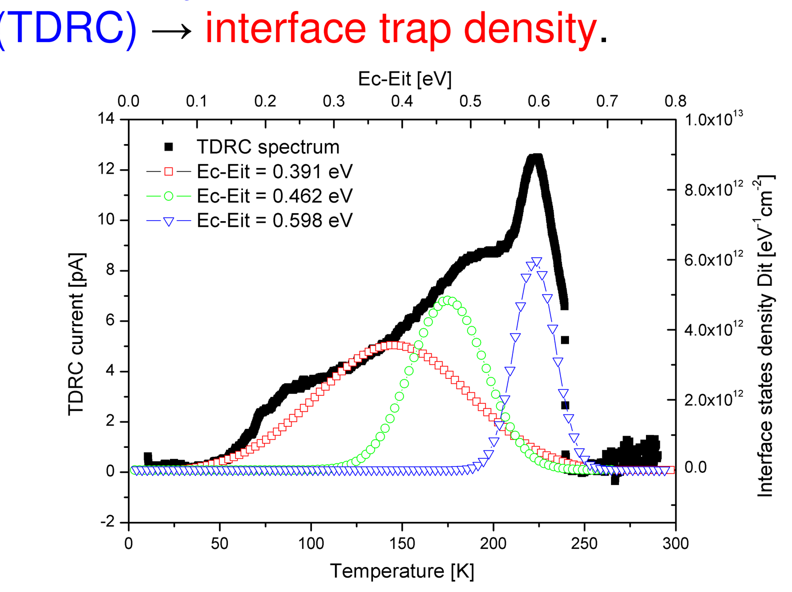


Fig 2. TDRC spectrum and calculated distribution of interface states density for 5 MGy MOS

- Fixed oxide charges and interface traps cause shift of CV curves. From shift of CV curves → fixed oxide charge density (once D_{it} distribution is known).

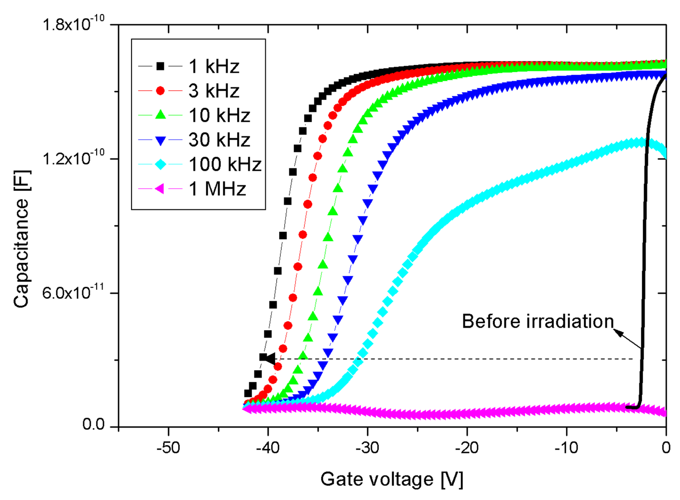


Fig 3. Capacitance-Voltage measurement

Dose dependence of concentration of defects

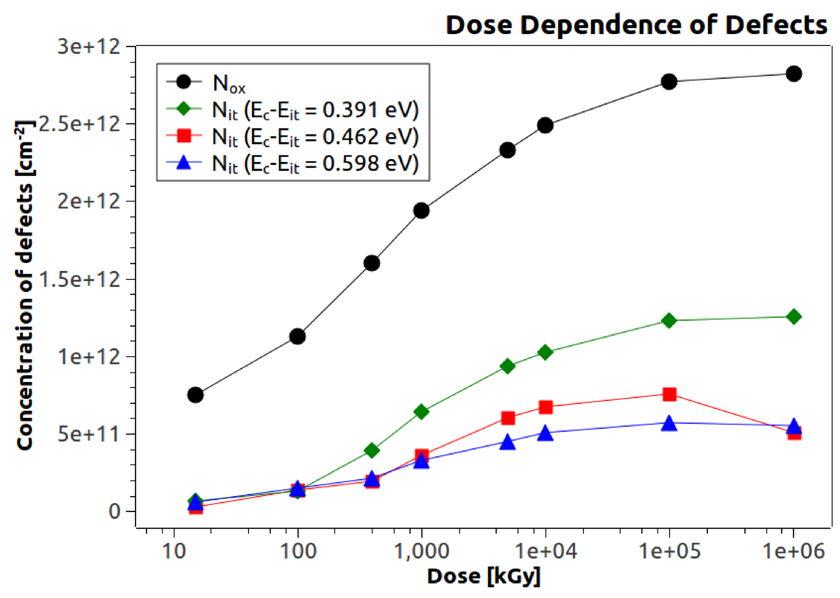
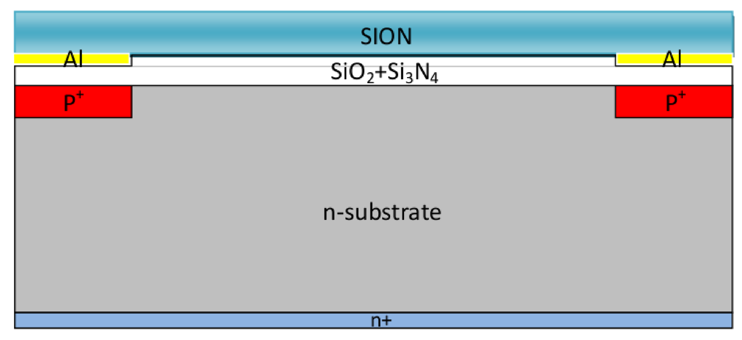


Fig 4. Dose dependence of defects

Measurements were done after annealing at 80 °C for 10 minutes:

- Density of fixed oxide charges and 3 dominant interface traps (E_c-E_{it} = 0.391 eV, 0.462 eV and 0.598 eV) saturates at dose between 10 MGy and 100 MGy.
- Saturation value of the fixed oxide charge density ~ 2.8×10^{12} cm^{-2}.
- Extracted parameters will be used in Synopsys TCAD simulation with the aim to optimize sensor design for XFEL.

Influence on electric properties of segmented sensors



Device under investigation:

- Thickness: 285 µm • Orientation: <100>
- Pitch: 80 µm • Gap: 62 µm
- Oxide: 200 / 300 nm SiO_2 + 50 nm Si_3N_4
- Coupling: AC • Doping: 8×10^{11} cm^{-3}

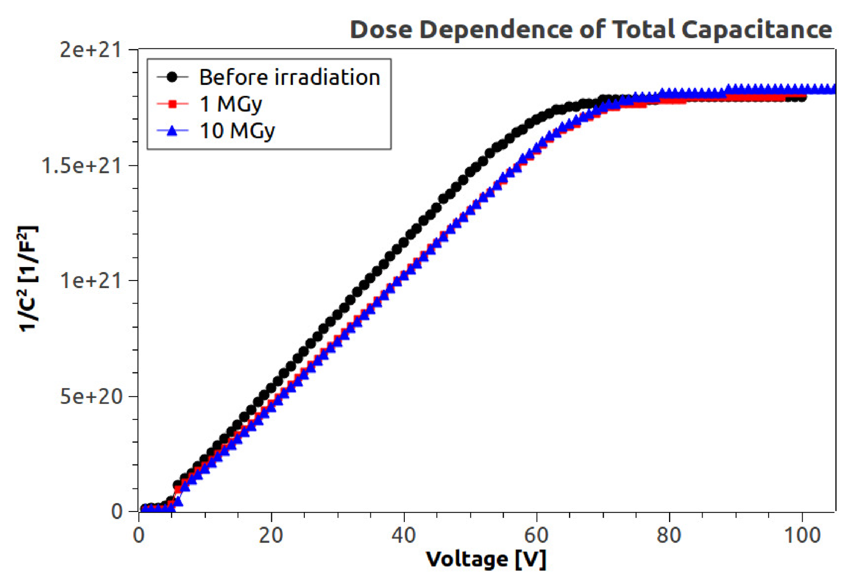


Fig 5. Capacitance-voltage curves of a p⁺n microstrip sensor

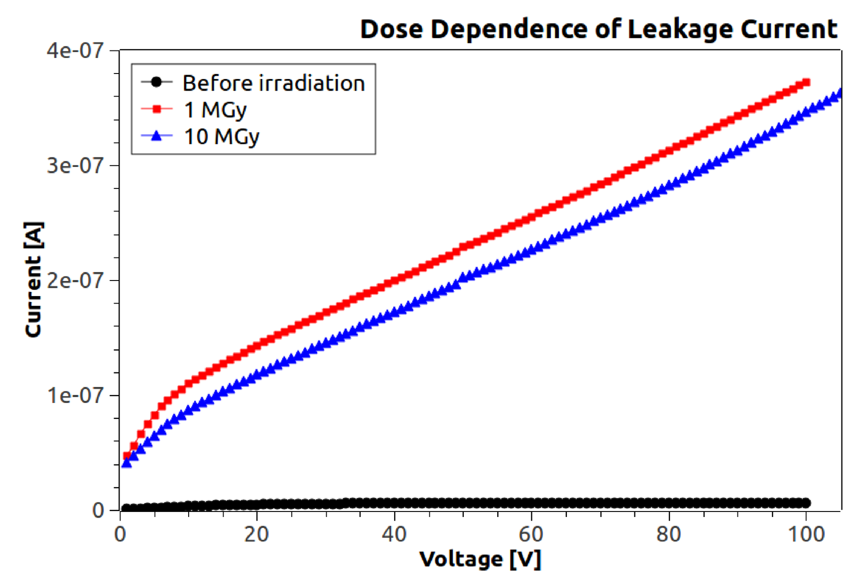


Fig 6. Leakage current-voltage curves of a p⁺n microstrip sensor

- Full depletion voltage V_{dep} changes with irradiations.
- Leakage current $I_{leakage}$ "linearly" increases with bias voltage and no saturation is observed even above full depletion voltage. $I_{leakage}$ depends on interface trap density N_{it} and depleted area A_{dep} at the Si-SiO_2 interface.

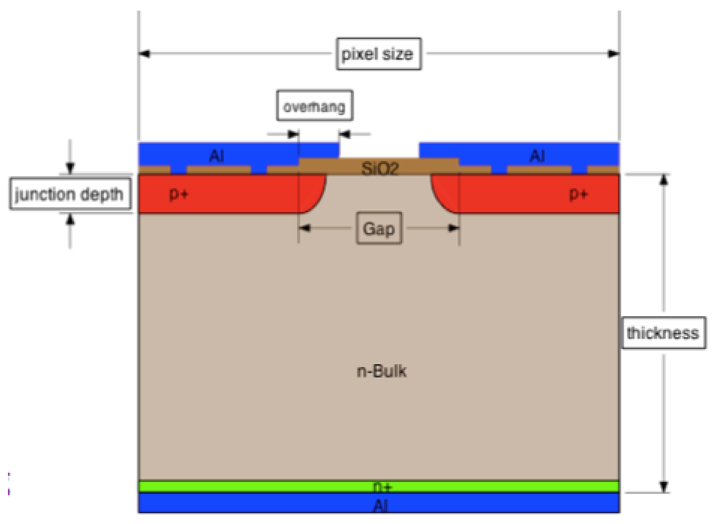
Optimization of sensor design

One of the detectors under development for the XFEL is the Adaptive Gain Integrating Pixel Detector (AGIPD), which consists of a classical hybrid pixel array with readout ASICs bump-bonded to a silicon sensor with pixels of 200 × 200 µm². The expected dynamic range, from single photon counting to 10^5 12 keV photons/pixel/pulse, is a challenge for the design of silicon sensors and front end electronics.

AGIPD-Sensorparameter:

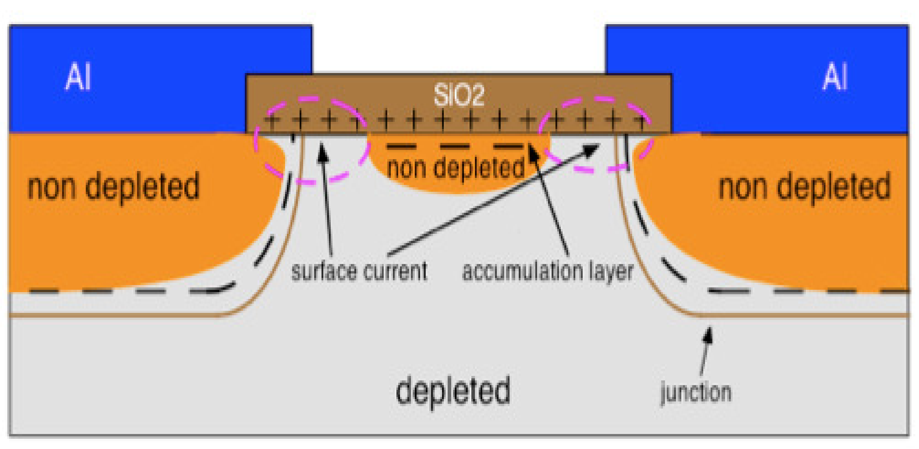
Parameter	Specification
thickness	500µm
pixel size	200µm x 200µm
type	p+ n
resistivity	~5kΩ·cm
V_fd	< 200V
V_op	500V
C_int	< 0.5pF
I_leak	< 10 nA/pixel

Parameter to optimize:
-Gap
-Metal overhang
-Curvature at edges
-Guardring structure



Oxide charge effects in p-n sensors

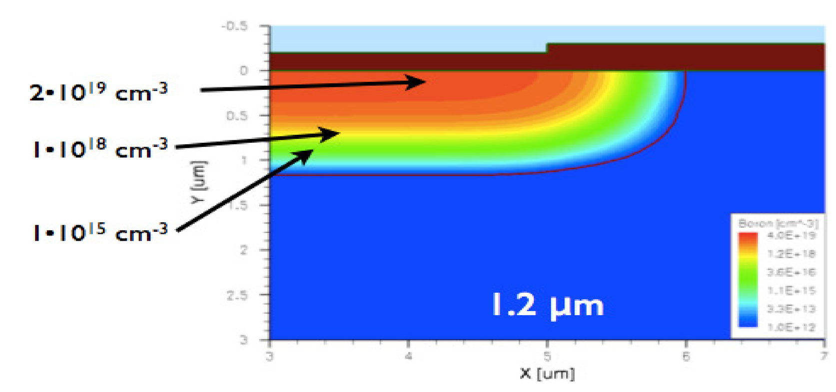
Sharp corner depletion region bondary
→ high electric field
Negatively charged accumulation layer
→ not fully depleted surface
→ high electric field (over short path)
→ charge loss
Surface current ∝ depleted area A_{dep} at the Si-SiO_2 interface



For simulation we need:
1. Oxide charge density distribution
2. Energy distribution of interface states
3. Oxide thichness
4. Realistic doping profile

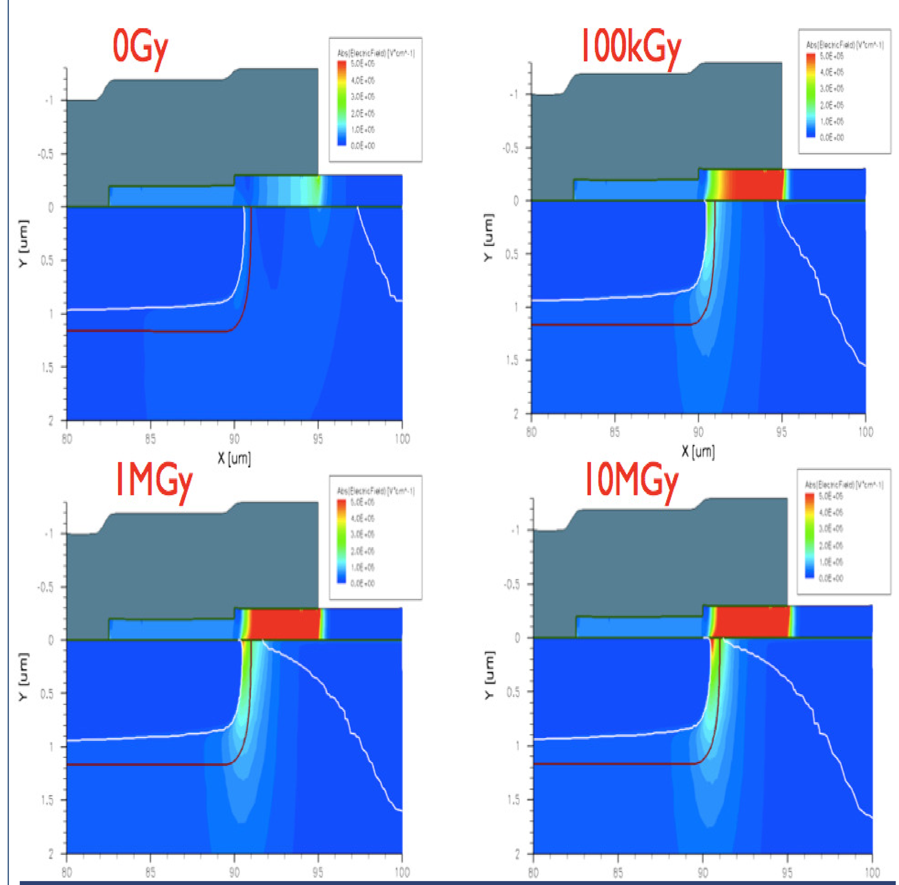
Doping profile

Boron profile from process simulation



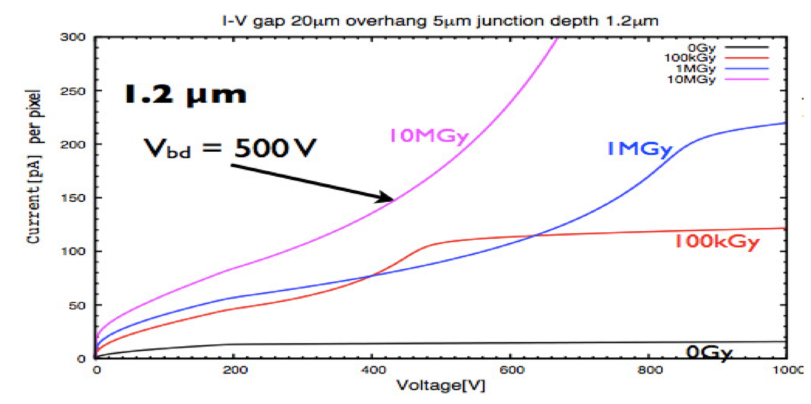
E-field vs. dose

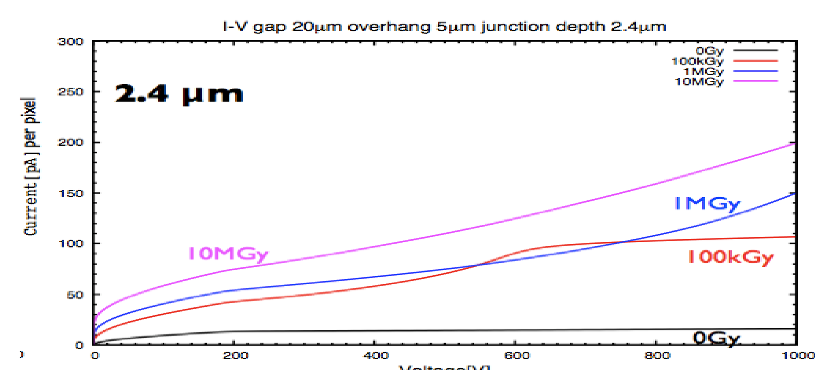
- Oxide thickness: 300 µm • Gap: 20 µm
- Metal overhang: 5 µm • Voltage: 500 V



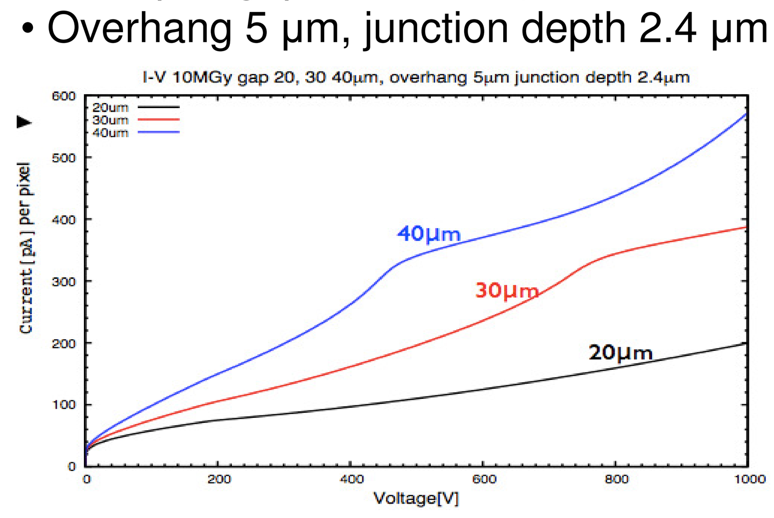
I-V vs. dose

- Example: gap 20 µm • Overhang 5 µm
- Junction depth: 1.2 µm vs. 2.4 µm





- Example: gap 20, 30, 40 µm
- Overhang 5 µm, junction depth 2.4 µm



- 2.4 µm junction: no breakdown up to 1000 V

Conclusions

- The density of fixed oxide charges and interface traps saturates at high dose.
- X-ray induced surface damage causes shift of full depletion voltage and increase of leakage current in p⁺n segmented detectors.
- Deep junction and small gap show better performance.