Development of semiconductor radiation detectors at Helsinki Institute of Physics (HIP)

University of Helsinki Physics campus
www.hip.fi

Micronova Nanofabrication Center
www.micronova.fi

Construction site of CERN CMS Detector in late 1990's, Cessy, France
Silicon detector R&D at HIP

http://research.hip.fi/hwp/cmsupg/

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Outline

Who are we?
Our activities – CMS experiment upgrade and detector R&D
  Compact Muon Solenoid (CMS) experiment at CERN LHC
  Radiation hardness challenge
  Detector processing at Micronova

What Silicon detector is good for radiation safety, monitoring, dosimetry etc.

The CMS Tracker implements 25000 silicon strip sensors covering an area of 210m². Connected to 75000 APV chips, one has to control 9600000 electronic readout channels, needing about 26 million microbonds.
On-going activities of HIP CMS group -Phase I pixel upgrade

- LHC experiments are investigating very rare elementary particle decay events
- Proton beams are colliding at 40MHz rate
- Luminosity (proportional to intensity) is constantly increasing → amount of collision data increases.
- We must replace our current analog CMOS ASIC read-out chips (ROC) with more efficient digital ROCs.
- Simultaneously, we must improve radiation hardness of our Si detectors

The pixel detector contains 65 million pixels, allowing it to track the paths of particles emerging from the collision with extreme accuracy. It is also the closest detector to the beam pipe, with cylindrical layers at 4cm, 7cm and 11cm and disks at either end, and so will be vital in reconstructing the tracks of very short-lived particles. Thus, extreme radiation hardness is required. In coming few years the pixel Detector will be upgraded 65M pixels > 120M pixels. 
On-going activities of HIP CMS group - Phase I pixel upgrade

- Finland has committed to deliver in-kind 50% on pixel modules of CMS Layer3.
- 4000 read-out ASICs will be Flip-Chip bonded in Micronova resulting in >16M channels
- Simultaneously, we have launched internal R&D for next generation pixel sensors utilizing potential of ALD technology.
Radiation hardness challenge

- Constant Luminosity increase is foreseen after the 1st phase of the LHC
- Extensive R&D is required because

1. Leakage current ($I_{\text{leak}}$) increases 10 X
   - Increased heat dissipation
   - Increased shot noise

2. Full depletion voltage ($V_{\text{fd}}$) will be >1000V
   
   This is a threshold when detector is not anymore operational

3. Trapping will limit the Charge Collection efficiency (CCE).
   - CCE at $1 \times 10^{15} \text{ cm}^{-2}$ $\approx 50\%$ (strip layers of HL-LHC Tracker)
   - CCE at $1 \times 10^{16} \text{ cm}^{-2}$ $\approx 10-20\%$ (pixel layers of HL-LHC Tracker)
Trapping of signal into radiation defects
HIP AC-coupled pixel sensor

Basic wafer layout similar as current CMS pixel:
Three large (2x8 ROC) sensors + 8 single chip sensors

- Biasing via WNx thin film resistors
  - Easy process: room temperature sputter deposition + RT wet/plasma etching
  - Poly-Si resistor = 2 implants + high temp poly CVD + high temp activation
- Coupling insulator ALD Al$_2$O$_3$
- No p-spray or p-stop
HIP AC-coupled pixel sensor II

First batch processed in 2013
How particle detectors could be applied in nuclear safety?

- Silicon detector can detect:
  - Charged particles
  - Photons < 10-15keV
  - Visible light 300nm-1100nm

- Silicon detector cannot detect:
  - Neutrons
  - High energy photons > 20keV
  - Light >1100nm

- Silicon detectors can be:
  - Very cost effective, i.e. one chip can cost ~cup of coffee → detector can be disposable
  - Read-out e.g. 40 MHz → short exposure time
  - Very sensitive, e.g. single photon counting
  - Radiation hard, can stand in LHC 10 yrs
  - Very good spatial resolution. Typically in particle tracking application ≈ 5-10μm
Neutron detection with silicon

- In principle, Si is ineffective for neutrons.
- Si detector is, however, very sensitive for radiation damage caused by neutrons.
- There is well-known linear dependence of Si detector leakage current \( I_{\text{leak}} \) on radiation dose expressed in terms of 1 MeV neutron equivalent fluence.
  - Dependence is linear over almost 6 order of magnitude
  - \( I_{\text{leak}} \) can be measured by ~100pA accuracy
  - By differential measurement from two detectors having different areas (or several Si diodes connected parallel) one can compensate environmental effects (such as temperature dependence) from the measurement

\[
I_{\text{leak}}(T, t) = \alpha \Phi_{\text{eq}} V
\]
X-ray dosimetry

• In the future each radiotherapy patient must possess personal dosimetry history
• Si diode has Quantum Efficiency $\approx 1\%$ for photons of 5-15 MeV
• Under therapeutic X-ray beam Si diode
  - Is practically transparent towards to patient.
  - Induces a signal $>100\times$ of background ($I_{\text{leak}}$)
  - Signal/sensitivity degrades only after $\sim50k$ Gy
  - If read-out by charge amplifier (standard in HEP electronics) in pulse counting mode, accuracy of $\approx 0.1\%$ rather easily achievable.
  - Is not temperature depended.
  - Si diode can be processed to be very small (e.g. for Intra Operational IORT use)
  - 100% of volume is active in fully depleted Si diode $\rightarrow$ no angular dependence of dosimetric measurement.
Photon detectors

- Cross-talk between pixels is a challenge in photon detectors.
- Absorption of X-rays depends on the $Z$-number of the material.

$$Z_{\text{Si}}=14 \quad Z_{\text{W}}=74$$

$$\frac{74^4}{14^4} \approx 1000$$

Illuminated side of CMS pixel detector with Al metal grid (design of PSI)
Summary

• HIP has long tradition in detector development
• Activities include e.g. mask design, device simulation and design, semiconductor processing at Micronova Center, characterization, irradiation campaigns and tests on full system modules with appropriate read-out electronics and DAQ.
• Main focus is the Upgrade of Si detectors in CMS experiment and application of ALD grown thin films for radiation detectors.
• Silicon detectors can be produced in large quantities → relatively low unit price
• Si detectors are fast (signal rise-time <1ns, signal transit time ≈ 15ns), radiation hard (stand LHC particle radiation 5-10 yrs), very good position resolution and Signal-to-Noise ratio (typically >40)