Detector R&D at Nikhef

Gaseous detectors & semiconductor detectors

Jan Visser
Outline

- Nikhef
- Medipix chips
- Gaseous detectors
- Semiconductor detectors
- Future developments
Detector R&D at NIKHEF

- Experiment specific
  - Atlas, LHC-b, KM3Net, etc.
- Technology driven
  - Gaseous detectors post-processed on ASICs
  - Tilable semiconductor detectors
- Focus on
  - Chip design
  - Read-out electronics
  - Mechanics
  - Cooling (CO₂)
  - Assembly of modules and systems
  - Characterising sensors, chips, systems

14 February, 2012

Jan Visser
Facilities

• Clean room
  – Probe station; wafer probing
  – Keithley; sensor characterisation (IV, CV)
  – SEM; fault analysis (dice, polish, Au coating)
  – Wire-bonder; shear and pull tester

• Lab
  – X-ray tube (60kV, pulsed)

• Future
  – X-ray tube (100kV, continuous, tuneable)
  – Laser for semiconductor tests (inject charge)
  – Cosmic-ray set-up
Test and assembly lab infrastructure

Probe station

Wire bonder

Shear / pull testing

Scanning Electron Microscope
Gas vs Semiconductors

• Gaseous detectors
  – Low material budget
  – Vectors instead of points

• Semiconductors
  – Higher stopping power
  – Proven technology
  – Strips, pixels, 3D,...

• Issues
  – Reliability
  – Radiation hardness
  – Cooling
Medipix

Courtesy of PANalytical
Medipix based hybrid detectors

- Photon counting principle (E > 4keV = 1000 e-)
- Large dynamic range
- Pixel size: 55 x 55 μm² (256 x 256 pixels)
- Active area per chip is ~ 14 x 14 mm²
- I/O periphery (wire bonded)
Medipix chips

- **Medipix1 (1µm)**
  - First attempt in late 1990s to take HEP results to other applications

- **Medipix2 (0.25µm)**
  - Started in 1999 and still going strong!
  - First commercial application at PANalytical in x-ray diffraction field

- **Timepix (0.25µm)**
  - Update of MPX2 for timing purposes in 2006

- **Medipix3 (0.13µm)**
  - New generation, solving charge sharing issues
  - Under test in 2010; a lot of progress, some issues to solve/fix
Medipix2 operation principles
Timepix operation principles

Counting mode
• Count number of events over threshold

Energy information
• Count while signal is over threshold

Arrival time
• Time from hit till close of shutter
Medipix2

Setting up the Medipix2 chip for data taking:
• Equalising pixels; i.e. same reaction to noise level
• Switching off dead pixels: up to few hundred

Threshold equalisation mask

Masked pixels
Taking data with the Medipix2 chip with a silicon sensor

Noise measurement  \(^{55}\text{Fe source} \quad ^{90}\text{Sr source} \)
Taking data with the Medipix2 chip with a silicon sensor:
- Noise hits can be suppressed
- Cosmic rays will always occur

Algorithms to remove the tracks of cosmic rays in certain imaging applications
Medipix2 versus Medipix3

**Charge sharing:**
The spectrum of a single pixel is distorted towards lower energies.

**Medipix3 readout architecture:**
Mitigating effect by summing the charge between neighbouring pixels and assigning the sum to the pixel with the highest energy deposition.

- Cluster of 4 pixels (110 x 110 μm²)
- Charge Summing
- Wider distribution due to noise summing.

![Graph showing energy distribution for single and summed pixels](image)
Chip design at NIKHEF

- **Gossipo**
  - Development of fast timing circuits for read-out of gaseous detectors

- **Kenniswerkers**
  - 2FTE from Bruco (chip design-house in Borne)
  - Development of high-speed read-out
    - From 1Gb/s to 10Gb/s
    - Test chip planned for summer 2010
  - Asynchronous read-out chips
    - Read out only those pixels that were hit, instead of all of them!
    - Compress data sample

X-ray diffraction pattern
Gas detectors on Timepix

Field strengths

- Drift region: 300 – 3kV/cm
- Amplification: 400 – 600V/50µm (80 – 120kV/cm)
Gas detectors on Timepix
• Gaseous detector
  – Start with Timepix chip
  – Build pillars (SU8) to support grid
  – Place aluminium grid on top
  – Assemble onto PCB
  – Build into system providing anode
GEM grid

- Instead of pillars with grid on top, make holes in full layer to support grid.
- To improve the gain the holes in the metal sheet were given a smaller diameter than the holes in the SU8.
Discharges

• Unavoidable in gaseous detectors
• ASICs can’t withstand these discharges
• Protection required
Discharge protection

Protection layer made of $\text{Si}_3\text{N}_4$

- only 7 µm thick
- high resistivity bulk material

Damage through pinholes

5 layers of $\text{Si}_3\text{N}_4$
Twin grid

- Twin grid to have additional tuning parameter
  - Two lower gains
  - One high gain and one low gain
  - Aim to reduce chance of discharges and possible damage
Applications

• High energy physics
  – Tracking

• Polapix
  – Detect polarised x-rays
    – e.g. from black holes
  – Future satellite mission

• Xenon
  – Position sensitive Xe TPC
  – WIMP-nucleon cross-section
  – Direct Dark Matter Search
Photosensitive GridPix

InGrid with CsI on Al anode
UV light 200-400 nm
UV well absorbed by fingerprint

Univ. Twente and Weizmann institute

14 February, 2012
Gaseous detectors status & future

Status
• Tracks can be constructed really well
• Resolution in agreement with simulations
• Protection layer big step forward

Future
• Construction
  • Investigate different materials for more robustness
  • Make larger area for ILC-TPC
• Tests
  • Tests at Nikhef (source and cosmics)
  • Test beam at DESY and CERN (GeV particles)
Semiconductor Detectors
Medipix2 Hybrid detector

• Hybrid medipix pixel detectors advantages
  – Photon counting
  – No electronic noise (> 4keV)
  – High sensitivity, large dynamic range and low contrast detectability;
    • Possible dose reduction
  – Better than many detectors in use in many fields
  – High speed imaging and readout

• Issues
  – Radiation hardness (Synchrotron applications)
  – Small! (1.4cm x 1.4cm)
  – Periphery on one side

• Solutions
  – Current design (0.13µm) very radiation tolerant
  – Make them bigger!
Large Area Detectors

RELAXD: high Resolution Large area X-ray detector

Technologies:

• Edgeless sensor technology (Canberra)
• Through Silicon Vias and Ball-Grid-Array (IMEC)
• Ceramic printed circuit board (Nikhef)
• 1 Gbit/s ethernet data transmission (Nikhef)
• CO₂-cooling (Nikhef)
• Product development (PANalytical)
1. Reduce the dead area around the sensor ➞ edgeless sensors.
2. Decrease the Medipix periphery ➞ design & dicing.
3. Through-Silicon-Vias ➞ replacement of wire bonds.
Reduction of edge induced currents

Suppression: Guard Ring vs. Stop Ring
TecPlot – visualisation

Hole current density as a function of the surface recombination at the edge
(Changing parameter: electron and hole recombination velocity)

No stop ring

50 µm wide stop ring
Dicing methods

Traditional blade dicing

Stealth dicing (laser)

Deep Reactive Ion Etching

14 February, 2012
Jan Visser
Dicing techniques results

Standard dicing

Stealth dicing

DRIE dicing
51 edgeless samples

40% of them showed an acceptable leakage current density in the active area

45% of the sensors with p+ SR showed leakage current reduction due to bias on the SR
Through-Silicon-Vias

- Bonding device wafer face down on temporary carrier
- Thinning down to 50-100µm
- Annular silicon DRIE stopping on oxide
- Dielectric polymer fill of annular trenches
- Dielectric opening at the top surface
- DRIE/wet etching of center Si block + RIE of oxide
- Seed layer deposition and Cu electroplating
Printed circuit boards

Board requirements

- Through-silicon-via chips are thinned
  - Thermal expansion coefficients play a role!
  - Ceramic close to silicon in thermal behaviour
  - Looking into stablcor multi layer boards
- Vacuum applications for low energy ion or electron detection
  - Ceramic is vacuum compatible
  - Liquid crystal polymer coated FR4 works well

14 February, 2012
Jan Visser
Hybrid detector challenges

Status

• Edgeless sensors under development
  – Need to position with 10µm precision
  – Dicing accuracy crucial (both sensor and ASIC)
  – Design sensor with four chips underneath with identical pixels

• Hybridisation
  – Periphery obstacle to full tiling possibility
  – Pitch adjustment between sensor and ASIC still an issue
Hybrid detectors future

Separate functionality

• **Sensors**
  – Precisely diced edgeless
  – Uniform pixel matrix

• **Hybridisation**
  – Get rid of periphery
  – Separate analogue and digital
    (select optimal technology)
  – Thinned ASICs
  – Through-wafer-vias
  – Ball-grid-array
  – Wafer to wafer bonding

Gb ethernet

14 February, 2012
Jan Visser
Medical x-ray application

Interventional x-ray imaging
- large area
- little gaps
- efficient detection of ~100keV x-rays

Hidralon
- Collaboration with Philips Healthcare in Best
- Development of CdTe detectors with minimal edge
Sensor materials

• Silicon
  • Relatively light material
  • Abundant in good quality
  • Works well for
    • Tracking purposes
    • Low energetic X-rays $< 20\text{keV}$
    • “Transparent” for high energetic X-rays 20-120keV

• Alternatives
  • Cadmium Zinc Telluride
  • Gallium Arsenide

• Challenges
  • Good material scarce and difficult to make
  • Small wafers
  • Nasty materials; brittle and poisonous
Sensor materials

Absorption efficiency vs. X-ray photon energy (keV)

- Si
- CdZnTe
- GaAs
MARS: **Medipix All Resolution System**

**Spectroscopic mode:** up to 8 thresholds (7 energy windows)

Images emulated with multiple exposures of mouse by Medipix2

**Phase Contrast Angiography on mouse:**
- **GREEN:** Calcium – bone
- **RED:** Iodine contrast in blood vessels
- **PURPLE:** Barium in the lungs

14 February, 2012

Jan Visser
Medipix projects summary

- **Medipix3**
  - Test new features
  - Read-out 1Gb/s (10gb/s)

- **Timepix2**
  - Next generation with improved timing
  - Data driven read-out

- **Photon detection**
  - Photocathode + MCP’s + TPX

- **Ion or electron detection**
  - MCP’s + MPX or TPX @ Amolf, Leiden, TUT

Advance with Medipix in LEEM (Leiden)
Gaseous detector summary

• Gridpix
  – Post-processing structures on TPX chips
  – Signal formation studies
  – Position resolution
  – Simulations

• Gridpix projects
  – Gossip for Atlas tracking
  – TPC for vertexing at ILC
  – Xenon; GridPix as a single electron detector in bi-phase Xenon filled WIMP search experiments
  – Polapix; measuring polarisation of x-rays in space
Semiconductors summary

• **Relaxd**
  – Edgeless silicon sensor
  – Through-silicon-vias
  – 1Gb/s read-out

• **Hidralon**
  – Edgeless CdZnTe sensors
  – Simulations
  – 10Gb/s read-out
3D view of discharge current
Edgeless sensors

• Characterisation
  – Example of dicing techniques:
  – Standard with blade results in chipping: stay mm’s from edge
  – Deep Reactive Ion Etching (DRIE); possible 50-100 micron from edge
  – Stealth Dicing works well for MPX chips, try on sensors

Standard dicing  DRIE dicing
Mouse pelvis and surrounding soft tissue structures demonstrates extremely high contrast of images taken by Medipix2.

Even structure of overlaying hair is seen through at the side of mouse’s body.

Thanks to the Czech Technical University in Prague.
Computed Tomography reconstruction

Thanks to the University of Canterbury, Christchurch, NZ

**GREEN:** Calcium - bone
**BROWN:** Iodine contrast in the stomach
**YELLOW:** Intestine
Ball-Grid-Array

- 5-10 µm Cu
- 5 µm of polymer
- 500 µm Si wafer
- 100 µm Si wafer
- 5 µm of BCB
- 3-5 µm of Ni, 500 nm Au
- 400 µm (80% of the ball size)
- 500 µm
XFEL Experiments

• Coherent imaging of “small things” (structure)
• Photon Correlation Spectroscopy (time evolution)
• Pump-Probe diffraction (non-equilibrium states)
• Small Quantum systems
• Warm dense matter (“plasmas”)
• Unexpected effects

Physics for AMOLF, Rijnhuizen, Bio-medical, Pharma, ...

But Detector R&D compatible with HEP-ILC !!
HPAD: a pixel detector for XFEL

- 1Mpixel: 1024´1024 pixel
- 4 Quadrants to allow beam hole
- 32 modules for 256´128 pixel
- 8 ASIC's/module: 64´64pixel
-pixel: 200µm´200µm

**Module:**
size: ~ 51.2´25.6mm²
pixels: 32K

**XFEL Current first dates for:**
- 1st beam injector ~ end. 2012
- 1st beam Linac ~ end. 2013
- 1st SASE(1) at 0.2nm ~ end. 2014
Module mechanics

Each interface has to fit behind active area: no depth limitation
Separate PCB constructions for low-EMI analogue and high dense digital
Heat per module: 40W

Principle quite similar to our RELAXD module! ➔
Hidralon

• **General**
  – New generation of CMOS imagers;
    e.g. automotive and entertainment industry
  – Large European project (Catrene)

• **Nikhef**
  – Collaboration with
    • Philips Healthcare in Best
  – Development of Cadmium-Telluride detectors
    with minimal edge
  – Aim is to efficiently detect X-rays with an energy
    between 30 and 120keV in a tiled area, ultimately 20x30cm²
  – First CdTe has arrived, mount on MPX chips for testing in 2010
Interventional x-ray imaging requires large area with little gaps and efficient detection of ~100keV x-rays
Characteristics

Characteristics:

• Direct X-ray conversion in semiconductor sensor
• Photon counting within given energy region ($E_\gamma > 4$ keV)
• High maximum count rates
• High sensitivity, large dynamic range and low contrast detectability;
• potential dose reduction
• Noise-free
• No sensitivity to dark currents
• High speed imaging and readout

Limitation:

Larger area coverage is needed. Enlargement of the chip size, however, leads to a degradation of the production yield. The solution is TILING.

3-side buttable $\rightarrow$ limits the Medipix2 tiling possibilities to 2*N array configuration.
Medipix2 Hybrid detector

Characteristics:

• Direct X-ray conversion in semiconductor sensor
• Photon counting within given energy region ($E_{\gamma} > 4 \text{ keV}$)
  • No sensitivity to dark currents
  • Noise-free
• High maximum count rates
• High sensitivity, large dynamic range and low contrast detectability;
  • Potential dose reduction
• High speed imaging and readout