The High-Voltage Monolithic Active Pixel Sensor for the Mu3e Experiment

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Outline

• The decay $\mu \rightarrow eee$

• The Mu3e Experiment
  • The Mu3e Pixel Detector based on HV-MAPS
  • Results from Test Beam at DESY 2013/2014
Motivation

• The Mu3e experiment searches for:
  
  • Lepton flavor violation in the decay of $\mu^+ \rightarrow e^+e^+e^-$ with a sensitivity of $\text{BR} < 10^{-16}$
  
  • Four orders of magnitude improvement over the most stringent limit to date
  
  • In the SM, the decay is suppressed to unobservable levels ($\text{BR} < 10^{-54}$)
  
  • Any observed signal event is a clear signature of new phenomena beyond the SM
Motivation

• The experiment allows to test models involving new particles

• Supersymmetry

• Extended Higgs models

• Heavy vector bosons

Supersymmetry

LFV at tree level
Signal and Backgrounds

- Decay signature: Muon decays at rest
- Two positrons and an electron
- Opposite curvature in magnetic field
- Coincident in time, originating from same vertex

- Momentum conservation: $|\vec{p}_{\text{tot}}| = |\Sigma \vec{p}_i| = 0$

- Energy conservation: $E_{\text{tot}} = \Sigma E_i = m_\mu c^2$

- Individual energies are below 53 MeV
Signal and Backgrounds

• Internal Conversion (Radiative muon decay)

• Combinatorials

Precise timing, good momentum and vertex resolution required

\[ \sigma_p < 0.3 \text{ MeV}, \quad \sigma_t < 100 \text{ ps} \]
Mu3e Experiment

- To achieve sensitivity goal:
  - $10^9$ muon decays/s
  - excellent vertex resolution
  - excellent time resolution

- Low $p_T < 53$ MeV/c decay product, track resolution dominated by multiple scattering.

- High granularity Si-based tracking detector made of HV-MAPS
HV-MAPS

- HV-MAPS as a particle detector
- Based on 180 nm HV-CMOS technology
  - Fast charge collection (<100 ps) via drift, results in high radiation tolerance
  - Thinning to < 50 μm
  - Power consumption ~ 7.5 μW/pixel
- Relatively cheap due to use of commercial process
HV-MAPS

- Low doped deep N-well as signal collecting region
- Depleted p-n junction as a sensor ~ 9 μm
- The charge collected by drift ~625 e in depleted region using Sr\textsuperscript{90} as a source
- Entire pixel electronics CMOS transistors inside the deep N-well
- Integrated readout electronics
- N-well are in matrix, depleted zones overlapped ~ 100% fill factor
MUPIX4

- Features: AMS 180nm process
- Pixel Matrix: 40x32 pixels, 80x92 μm² (pixel size) Active area: 9.4 mm²
- Moderate substrate resistivity ~10 Ω cm
- Designed by Ivan Peric (U. Heidelberg Institute for Computer Science (ZITI))
- Analog part: Small pixel capacitance
  Temperature tolerance
- Digital part: Zero suppression
  Mostly Ready
  Feature: pixel address problem in half column
  Fixed in MUPIX6 using inverters
HV-MAPS: Integrated readout electronics

**Concept:** Each pixel has its own read out (RO) cell placed on the chip periphery.

- **Hit flag**
- **RAM/ROM**
- **Priority scan logic**
- **Time stamp**
- **Data bus**
- **Comparator and Thr tune DAC**
- **Read**

**Readout cell function:**
- **Time stamp**
- **Hit data**
- **Priority logic**
- **Binary Suppressed read out**

**RO cell size is 7μm x 40 μm in 180nm AMS process (with comparator and threshold tune DAC)**
Test Beam set up at DESY

- DESY Test Beam set up
  - Beam-line T22
  - 1 GeV to 6 GeV electrons
  - EUDET Telescope
  - MUPIX4 prototype
Test Beam Results
Result: Time Resolution : 17 ns (Sensor and DAQ)
External Gray counter at 100 MHz

Result: Resolution given by pixel size
Measured track residuals:
RMS x = 28 μm, RMS y = 29 μm
Result: First working prototype
Efficiency > 99% for untuned DAC

Result: Rotated chip with 45 degree angle, higher efficiency
Conclusion

• Mu3e experiment aims for $\mu^+ \rightarrow e^+e^+e^-$ with sensitivity of $\text{BR} < 10^{-16}$

• HV-MAPS has been implemented for fast charge collection efficiency, radiation hardness and minimum material

• Looking forward to integrate full digital electronics in the Mu3e pixel prototype by end of this year

• The MUPIX4 has already the required analog performance

• Currently, the performance of MUPIX6 is being tested at PSI
Backup slides
Mechanical prototype and sandwich Design

HV-MAP
Thinned to 50 μm
sensor size 1 x 2 cm² or 2x2 cm²

Kapton™ flex print
25 μm Kapton™
12.5 μm Al traces

Kapton™ Frame Modules
25 μm foil
self support

<0.1% X₀ per layer
Thinned sensor

PSI test beam
Result: No significant difference in pulse shape
Temperature stability

• Latency measurement

• LED pulse to a pixel discriminator output

Result: Temperature dependence within the resolution setup
Result after 380MRad radiation and $\sim 8 \times 10^{15} n_{eq} \text{ cm}^{-2}$

- Perform: Irradiation at PS (CERN) for 180 nm HV CMOS

Result: The chip works, particles are measured when the chip is in the beam

Courtesy: RESMDD 2012, Ivan Peric