Direct detection of electrons in backside illuminated CMOS imagers

Direct detection of electrons in backside illuminated CMOS imagers

Introduction of MAPS technology

Applications driving development and delineated

MIMOSA V $1 \times 10^6$ pixel device

Postprocessing for back-side illumination

HPD facility @CERN

$^3$H(T) Autoradiography with MIMOSA V ...

MIMOSA V – 1st tests in SEM & TEM e-microscope

Final prototype for Beam Monitor

Radiation hardness

Conclusions

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Introduction of MAPS technology

From digital photography

to charged particle detection

Monolithic Active Pixel Sensors (MAPS)

The detector is a standard VLSI chip. The active element is a thin moderately doped silicon layer, operated undepleted. The readout electronics is seated on top of this layer. The built-in potential, resulting from differences in doping, screens the detector from the electronics parts and confines the charge diffusing to the readout electrodes. The charge collectors are n-well/p-epi (substrate) diodes. Only NMOS transistors are used for in-pixel readout electronics, but full CMOS electronics is used on the detector periphery.

MAPS advantages:

decoupled charge sensing and signal transfer (improved radiation tolerance, random access, etc.), small pitch (high tracking precision), low amount of material, fast readout, moderate price, SoC, etc.
Applications driving MAPS development

**High Energy Physics (FLC ~ 500-1000 GeV)**

**High resolution of IP**
- Detection efficiency = ~99%
- $\delta IP < 5 \mu m \oplus 10 \mu m GeV / (p \sin^{3/2} \theta)$
  - *Multiple scattering* $< 0.1\% X_0 / \text{layer}$
  - *Thin layers* $\sim 50 \mu m$ of Si (5 layers: $R_1=1.5 \text{ cm}$; $R_5=6 \text{ cm}$)

**High granularity**
- Pixel pitch $20 \times 20 \mu m^2$

**High occupancy**
- Fast readout (25 $\mu$s – 50 $\mu$s) - background
- On-line sparsification

**Radiations**
- $\Phi_n \approx 5 \cdot 10^9 n(1 \text{ MeV})/\text{cm}^2/5 \text{ y}$
- Ionising dose = 500 kRad/5 y

Chosen technology has to combine: granularity, small thickness, high readout speed, radiation hardness

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**Material budget**
- **vertex / layer:** $< 0.1\% X_0$
- **tracker:** $0.05 X_0$
- **ecal:** $32 \times 10^6$
- **vertex:** $~800\text{ M pix.}$
- **CMS:** 39M pix.
- **tracker:** $0.30 X_0$
- **TESLA**
- **Material budget**
- **-3-**
Applications driving MAPS development

**SUCAIMA—Silicon Ultra Fast Camera for Electron and Gamma Sources in Medical Applications**

**Hadrotherapy**
- **On-line beam monitoring**
  - SLIM – SEm (secondary emission) for Low Interception Monitoring
  - Innovative Non-Destructive Beam Monitor for the Extraction Lines of a Hadrontherapy Centre

**Brachytherapy**
- **Intravascular Brachytherapy: local radiotherapy**
  - Brachytherapy reduces the restenosis rate, also in the case of a use of STENTS.
  - Dose (15-30 Gy) delivered by temporary (few minutes) implant of radioactive seeds or wires.
  - HIGH DOSE and HIGH DOSE RATE: dose evaluation is crucial

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**Diagram**
- E-beam (20 keV)
- hadron beam
- vacuum chamber
- secondary emission foil
- SEm electrons from 0.1 – 0.4 µm (Al-Al₂O₃-Al) foils

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**Intravascular Brachytherapy**
- 40mm
- (16 seeds) 2.08 GBq (56 mCi)
- ⁹⁰Sr or ¹⁴⁴Ce

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**Profile/Current Measurement**
- 5 ÷ 5000 rad/s (0.05 ÷ 50 Gy/s)
Applications delineated

Hybride Photodiode Detector (HPD) for Microscopy of the cellular dynamics

- Detection and tracking of interactions of single biological molecules in their natural environment
- Measurements of single molecules - low concentration of fluorescent markers and microscopy of intracellular ionic exchanges (flux Ca²⁺),
  Single photon detection sensitivity and high speed of acquisition (1000 fps)

1 photon / ms / pixel

100 nm!

1 ms
Applications delineated

Transmission Electron Microscope

TEM - imaging technique whereby electrons focused onto a specimen are causing an enlarged version to appear on a fluorescent screen or photographic film or can be detected by a CCD camera (directly or scintillator-coupled).

Advantages of MAPS and how one can gain w.r.t. existing Techniques (fluorescent screens, negatives or CCDs):

- High efficiency - thanks to direct detection,
- On-line image – some processing possibly integrated on a detector chip,
- High sensitivity (single electron sensitivity),
- No blurring due to charge transfer,
- High speed by use of multiple readout channels,
- Radiation hardness – conversion to voltage in place where collection.

Idea of P. Rehak, J. Wall ... and goal of my 1-mont stay @ BNL
MIMOSA V 1×10^6 PIXEL DEVICE

Chip-Detector design

- 0.6 µm CMOS process with 14 µm epitaxial layer,
- 4 matrices of 512 × 512 pixels read-out in parallel;
- pixel: 17 × 17 µm², diodes: P1 - 9.6 pm², P2 - 24.0 pm²,
- control logic and all pads aligned along one side,

RESULTS:

- Noise mean ENC: 20.74 e⁻
- Detection efficiency MIPs (ε): 99.3%
- Spatial resolution MIPs (σ): 1.7 µm
- Pixel-pixel gain nonuniformity: ~3%

MIMOSA = Minimum Ionising Particle MOS APS
Matrix of sequentially addressed pixels, multiplexed on single output buffer.
Architecture of the prototype

In summing operation of signals from 3 consecutive pixels, 2 groups of signals are activated alternatively i.e.
the first group: VSW1, VSW2, VSW3
the second group: VSW4, VSW5, VSW6

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MIMOSA V 1×10^6 PIXEL DEVICE

Default Readout Method

RESET

FRAME_n

FRAME_{n+1}

NEXT RESET

A

B

leakage current

signal + leakage current
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Directly detected low energy electron $e^-$

Wire bonding interconnection
Back-side illuminated MIMOSA V device

Back-side illuminated thinned M5 device – as a test vehicle for demonstration of 20keV E⁻ detection capability for Beam Monitoring system and other affined applications

- Back-side passivation « A » + entrance window 160nm
- Back-side passivation « A » + entrance window 110nm
- Back-side passivation « B » + entrance window 75nm, 110nm and 160nm

- Bonding with 17 µm Al wire
- Device thinned down to epitaxial layer to ~10 µm in collaboration with industrial partner
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HPD facility @CERN

Simplified view of vacuum pot with proximity focusing optics HPD using CsI photocathode

With invaluable help of J.Seguinot, A.Braems and C.Joram from CERN
1st STEP (electrons from photocathode: bombarded by residual ions, or from photons from micro-discharges (2x10^{-5} mbar) (?))

2nd STEP (electrons emitted from CsI photocathode excited by photons (220nm edge) from arc lamp)
Hit distrib. (500 e-) on MIMOSA V for point source

$RMS_x = 360 \, \mu m, \ RMS_z = 280 \, \mu m$
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2.5 keV

3.0 keV

-89.2 nm -44.6 nm 0.0 nm 44.6 nm 89.2 nm

SiO2 160.00 nm

62.1 nm

124.2 nm

-150.4 nm -75.2 nm 0.0 nm 75.2 nm 150.4 nm

SiO2 160.00 nm

0.0 nm

104.7 nm

209.4 nm

5.0% 10.0% 25.0% 50.0% 75.0% 90.0%

5.0% 10.0% 25.0% 50.0% 75.0% 90.0%

HIntensity Position: 0.00nm Energy: 2.50KeV BackScattering Coefficient: 0.1395%

HIntensity Position: 0.00nm Energy: 3.00KeV BackScattering Coefficient: 0.1270%

[Graphs showing energy distribution and range max for 2.5 keV and 3 keV electrons]

# Hits Normalized

Range Max [nm]

0.0000 0.0005 0.0010 0.0015 0.0020 0.0025 0.0030 0.0035

0 20 40 60 80 100 120 140 160 180 200 220 240

[Histograms for 2.5 keV and 3 keV electrons]

Hits (Normalized)

for 2.5 keV e-

20000 events

Hits (Normalized)

for 3 keV e-

20000 events
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HPD facility @CERN - Simulation

160nm entrance window stops completely e- < 2.5keV

Backscattering will <pollute> recorded spectras

19.6keV transmitted @20keV (95%)
9.35keV @ 10keV (90%), 5keV @6keV (80%)

for 160nm entr. window

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20kV NO COOLING

1 Pixel – Cluster Signal Distribution

4 Pixel – Cluster Signal Distribution

9 Pixel – Cluster Signal Distribution

25 Pixel – Cluster Signal Distribution

Histograms for reconstructed signal clusters 44623 hits
**15kV**

**Data for 1st step - no cooling**

1 Pixel – Cluster Signal Distribution

4 Pixel – Cluster Signal Distribution

9 Pixel – Cluster Signal Distribution

25 Pixel – Cluster Signal Distribution

Histograms for reconstructed signal clusters: 16254 hits
Close to linear dependence « signal magnitude v.s. accelerating voltage » for 7.5 – 20 keV; x-axis intercept at 2.48kV, dependence broken for 4 keV no detectable signal observed
17.5kV ARC LAMP ON

~200k HITS

Full 1x10^6 IMAGE
f$^{55}$Fe

Count
Seed pixel histogram

5.9 / 6.5 keV calibration peak

let's look closer

Histogram for seed pixel S/N=3.5 cut

32716 hits
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Histogram for seed pixel S=210 cut

Model: Gauss
Equation: $y = y_0 + \frac{A}{(w \sqrt{\pi}/2))} \cdot e^{-2((x-x_c)/w)^2}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
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<tbody>
<tr>
<td>$y_0$</td>
<td>48.72</td>
<td>±35.85</td>
</tr>
<tr>
<td>$x_c$</td>
<td>241.45</td>
<td>±0.18</td>
</tr>
<tr>
<td>$w$</td>
<td>15.45</td>
<td>±0.45</td>
</tr>
<tr>
<td>$A$</td>
<td>53869</td>
<td>±1631</td>
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<tr>
<td>$x_c$</td>
<td>266.93</td>
<td>±0.43</td>
</tr>
<tr>
<td>$w$</td>
<td>11.09</td>
<td>±0.97</td>
</tr>
<tr>
<td>$A$</td>
<td>13780</td>
<td>±1299</td>
</tr>
</tbody>
</table>

Signal [ADC]

46552 (29000) Hits
55Fe

Histogram for 5×5 pixel

Peak for summed signal partially approaches to the calibration peak

32716 (0) hits
Number of entries in calibration peak after subtraction of the left side tail: 29000 frames.

Extrapolated number of hits for seed pixel:

\[ N_{\text{tot}} = 1.6 \times 10^6; \]
\[ N_{\text{tot}}, N_{\text{ent}} 100\% = 1.8\%. \]

Volume of full charge collection:

\[ V_f = 3.3^2 \times 2.5 + (1.3 + 1.8) = 8 \times 10^{-3} \text{m}^3 = 74 \text{mm}^3 \]

Volume of pixel:

\[ V_p = 17^2 \times 10.4 = 3005 \text{mm}^3 \]

Mean depth of diode from backside:

\[ S_d = 8.24 \mu\text{m} \]

Percentage of full conversion in seed pixel:

\[ \frac{N_{\text{ent}}}{N_{\text{tot}}} \times 100\% = \frac{29000}{1.6 \times 10^6} \times 100\% = 1.8\% \]

Verifying CCE for 5.9 \text{keV} photons and b' s:

For photons:

\[ \text{CCE} = \frac{160 \text{ADC}}{241 \text{ADC}} \times 100\% = 66\% \] and \[ 241 \text{ADC} \times 1640 \text{e}^- \text{h}^+ \]

Thus for b' s: \[ 0 \text{keV} \rightarrow \text{ADC} \times 3232 \text{e}^- \text{h}^+ \]

But: \[ 20 \text{keV} \times 3.6 \text{eV} = 5555 \text{e}^- \text{h}^+ \]

and \[ 0.5 \text{keV} \text{loss on entrance} = 138 \text{e}^- \text{h}^+ \]

Thus: \[ \text{CCE}_{b'} = 3232 \text{e}^- \text{h}^+ - 5555 \text{e}^- \text{h}^+ + 138 \text{e}^- \text{h}^+ \times 100\% = 59\% \]

Simply “edgy” model of n-well/p-epi diode (1.8µm @ 3V)
Common requirement in biology: to map radioactive labels - $^3$H, $^{14}$C, $^{32}$P, $^{35}$S, $^{125}$I... in thin tissue sections, electrophoresis gels (of DNA or proteins), etc. X-ray film (the default imaging medium) and exposure times (~days to months) - $^3$H. $^3$H betas (endpoint 18.6 keV) weakly penetrating in any detection medium.

Polymer source
281 kBq (20/05/1999)
$1 \times 1 \times 0.1 \text{ cm}^3$

$^3$H-polybutyl methacrylate source
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$^3$H(T) Autoradiography with MIMOSA V ...

MV + $^3$H inside cooling box

DAQ card

PC for ON-LINE analysis

Equiv. 20 min exposition
After some initial worries, clean and well correlated with HPD data $^3$H(T) spectra were obtained!
Scanning of single pixel with e- beam (25keV SEM hit multiplicity ~5-10 e-)

Beam Scanning

approximated PSF

mean signal ADC

normalised amplitude [

resolution [lines/um]
Scanning of whole array surface with e-beam
(40keV TEM hit multiplicity in single image~1e-)

- Image of a crystal specimen obtained with high dose exposure (average of 200 frames)
- Image of a metal needle obtained with low dose exposure (average of 300 frames)
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**MIMOSA V – 1st tests in SEM and TEM e-microscope**

**120 keV**

**Estimation of resolution from basic images**

- Pixel sub-divided in 51 units, projection and sum for 512 lines, slope minimising width after derivation.
40 keV

$Y$ - projection

Gaussian fits

$1\sigma = 17.8 \mu m$

400 keV

$Y$ - projection

Gaussian fits

$1\sigma = 12.3 \mu m$
Electron spectrum for 40 keV

5×5 pixel cluster

Model: Gauss
\[ y = y_0 + \left( A/(\sqrt{2\pi})\right) \exp\left(\frac{-2*((x-xc)/w)^2}{R^2}\right) \]

- 40 keV e-
- 5x5 pixel cluster
- 578065 entries
- Gaussian fits

<table>
<thead>
<tr>
<th>Entries [#]</th>
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<tbody>
<tr>
<td>Signal Amplitude [ADC]</td>
</tr>
</tbody>
</table>
Final prototype for Beam Monitor

Electron Imager

- sensitivity to 20keV $e^-$
- image $\varnothing$ after demag. $\approx$16 mm,
- signal range: $10^4 \div 10^8$ e/\( \text{mm}^2/\text{s} \) @ 20 keV energy $\Rightarrow$ p beam: 3 (0.3 @ 2$\sigma$) - 9$\times$10$^3$ of 20 keV electrons @ 200$\times$200 $\mu$m$^2$ pixels / 100 $\mu$s,
- time resolution = 100 $\mu$s (signal integration and 10 kHz readout),
- spatial res.: 5000 cells or more...,
- no dead time (missing beam fluctuations is not an option).

- Four sub-arrays of 28$\times$112 pixels read out in parallel $\Rightarrow$ $\text{read/integr} < 100 \mu$s, no dead time – alternate integration and readout in halves of pixels,
- Total array of 112$\times$112 153$\times$153$\mu$m$^2$ square pixels, each pixel – interdigitated array of small n-well/p-epi diodes.

- delivered $\sim$15th of July, tests!

AMS CUA 0.6 $\mu$m
17.136$\times$17136 mm$^2$
MimoTera:

- Two 9×9 interdigitated arrays of n-well/p-epi diodes (5×5 µm²) with two independent FE electronics – avoiding dead area,
- No dead time in pixel operation – alternate reset and integration in both arrays,
- In-pixel storage capacitors – choice ~0.5pF or ~5pF to cope with signal range (poly1 over tox capacitors),
- Readout without CDS – kTC noise,
- Signal swing ~2 V (pixel and chip output) @ 40Mpixel/s,
- Design risks: tox over whole pixel – no DIFF type defined,

> CVF=250nV/e- @ 500fF; noise ~1000 e-  280 e- kTC (ENC) @ 500fF
Final prototype for Beam Monitor

Pixel schematic diagram

Half B

Switch to vdda to cut consumption when line precharging

Half A

M1 - reset transistor
M2 - hold switch
M3 - source follower
M4 - access switch
M5 - capa choice
Radiation Hardness

Neutron Irradiations

tests up to $10^{13} \text{n}_{1\text{MeVeq/cm}^2}$ fluences up to $10^{12} \text{n}_{1\text{MeVeq/cm}^2}$ are still acceptable (2 orders of magnitude above FLC requirements$=10^9 \text{n}_{1\text{MeVeq/cm}^2/\text{year}}$)

\[
\frac{1}{\tau_R} = \frac{1}{\tau_0} + \kappa \tau \Phi
\]
carrier lifetime altered

Ionising Irradiations
doses up to this level acceptable above FLC requirements 50 krad/year, exact sources of performance losses under investigation (diode size and placements of transistors are important parameters)
Conclusions, plans...

Ability of back-side illuminated thinned MAPS detectors for low/medium energy e⁻ imaging – shown!

1) Low-intercepting Beam Monitoring: principle shown, final device, tests !,

2) HPD for biology: principle shown, work on position resolution + speed + duty cycle, tests !,

3) Autoradiography (³H etc.): principle shown, spatial resolution fine, work on duty cycle!,

4) E⁻ microscope: first results quite promising, work on data, propose device adapted to this application,

Still good understanding of the detector needed; How many blind pixels? Uniformity of signal from different pixels?, etc...

Finish with analysing of disponible data a.s.a.p.,

Prepare new PCBs + test chips with different entrance windows and back-side implantations @ HPD – 1 week in sept./Oct. (?), new tests with microscope (?)