Improved radiation tolerance of MAPS using a depleted epitaxial layer

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Monolithic Active Pixel Sensors

Under development since 1999 at IPHC (Strasbourg):

1. MAPS implemented in standard CMOS substrate with readout electronics
2. use p-epitaxial layer as sensing volume (~10-20 μm)
3. Nwell Diodes collect e-h pair liberated by the particle

• low cost
• high granularity
• low material budget
• in-pixel signal amplification
• low noise
• integrated readout and signal processing
MAPS implemented in standard CMOS technology

standard CMOS technology p-epitaxial layer has low resistivity $\sim 10 \ \Omega \ cm$
MAPS: charge collection

Particle traverses the sensing volume

Blue: electrons
Red: holes
MAPS: tolerance to non-ionising radiation

1. charge collection is large (>100 ns) because of not depleted P-epi
2. non-ionising radiation create traps

optimization of the pitch size, Nwell diode size

But: signal-to-noise ratio drops down to ~15 after fluence of the order $10^{13}$ $\text{n}_{\text{eq}}/\text{cm}^2$

optimise doping of the p-epitaxial layer...
MAPS: improving tolerance to non-ionising radiation

The technology optimisation is very expensive... but if there are some common problems has to be solved for commercial applications, one can try to use it.

the need of industry for improvement of the photo-sensing elements embedded in to CMOS chip led to replacing low resistivity (~10 Ω cm) epitaxial layer by relatively high resistivity thin epitaxial layer (~1000 Ω cm), and this was commercially available as an options for standard 0.6 μm process

this layer should be possible to deplete at standard CMOS voltages (<5V)
TCAD Simulations: MAPS in a high resistivity epitaxial layer

For comparison: standard CMOS technology, low resistivity P-epi

high resistivity P-epi: size of depletion zone size is comparable to the P-epi thickness!
Mimosa25 sensor prototype in a high resistivity epitaxial layer

20\,\mu m pitch size, 3 matrixes of 16 columns and 32 rows

32.5\,\mu m^2

16 or 32.5\,\mu m^2
Mimosa25: calibration with $^{55}$Fe

Seed pixel signal from $^{55}$Fe (5.9keV and 6.5keV)

- RS 16 $\mu$m²
- SB 32.5 $\mu$m²
- RS 32.5 $\mu$m²
- RS 16 $\mu$m² irradiated at $3\times10^{13} \text{ n}_\text{eq}/\text{cm}^2$
- SB 32.5 $\mu$m² irradiated at $3\times10^{13} \text{ n}_\text{eq}/\text{cm}^2$
- RS 32.5 $\mu$m² irradiated at $3\times10^{13} \text{ n}_\text{eq}/\text{cm}^2$

5.9 keV converted to charge carriers near Nwell Diode: used to calibrate readout gain

6.5 keV

temperature 20 $^\circ$C
Mimosa25: measurements with $^{106}$Ru

Seed pixel signal from $^{106}$Ru (~m.i.p.)
- RS 16 $\mu$m$^2$
- SB 32.5 $\mu$m$^2$
- RS 32.5 $\mu$m$^2$
- RS 16 $\mu$m$^2$ irradiated at $3 \times 10^{13}$ n$_{eq}$/cm$^2$
- SB 32.5 $\mu$m$^2$ irradiated at $3 \times 10^{13}$ n$_{eq}$/cm$^2$
- RS 32.5 $\mu$m$^2$ irradiated at $3 \times 10^{13}$ n$_{eq}$/cm$^2$

Landau distribution m.p.v., used to evaluate the sensors for to m.i.p.

Temperature 20 $^\circ$C
Charge collection and charge sharing comparison for non-irradiated sensors

saturation \(\rightarrow >90\%\) of charge is collected is 3 pixels \(\rightarrow\) very low charge spread for depleted substrate

signal in seed is doubled

Collected charge from m.i.p. (most probable value)
- **Mimosa1, 14 µm epi, RS 9.61 µm², 20x20 µm² pitch**
- **Mimosa25, 15 µm epi, SB 32.5 µm², 20x20 µm² pitch**
- **Mimosa18, 14 µm epi, SB 14.62 µm², 10x10 µm² pitch**
Comparison of charge collection for irradiated sensors

- For depleted epitaxial layer, the excellent charge collection is maintained up to the maximum tested value of $3 \times 10^{13}$ n$_{eq}$/cm$^2$.

- Results from test beam at CERN with pions of 120 GeV/c show similar values (<10% of difference).
Conclusions

- MAPS can profit from using resent commercially available CMOS process developed for embedded in chip photodiodes: high resistivity depleted epitaxial layer

- Mimosa25 sensor MAPS prototype was implemented first time in a high resistivity epitaxial layer

- The sensor was calibrated and tested with m.i.p.s

- The signal-to-noise ratio for m.p.v. of landau distribution is about 35 for the Mimosa25 "SB 32.5 μm\(^2\)" exposed to a fluence of \(3 \times 10^{13} \text{ n}_{\text{eq/cm}^2}\), compared to 14.7 for \(0.2 \times 10^{13} \text{ n}_{\text{eq/cm}^2}\) for the low-resistivity epitaxial layer

- The sensors implemented in a depleted epitaxial layer have double signal-to-noise ratio for the fluence of 15 times larger

\[\Rightarrow\] The limit of radiation tolerance of MAPS can be extended by the order of magnitude up to \(~10^{14} \text{ n}_{\text{eq/cm}^2}\)
Perspectives

• At the moment only 0.6 μm technology is commercially available, which may be not sufficient for complex circuitry integrated in MAPS. -> 3D integration techniques combining different technologies provide a very attractive solution.

• Development of technologies (at least two by now) with a smaller feature size in a similar high resistivity epitaxial layer has been started.