Development of Depleted Monolithic Active Pixel Sensors (DMAPS) for Dosimetry in Space

H. Lambropoulos\textsuperscript{1,5}, C. Potiriadis\textsuperscript{2}, G. Theodoratos\textsuperscript{1}, I. Kazas\textsuperscript{1}, C. Papadimitropoulos\textsuperscript{2}, D. Loukas\textsuperscript{3}, I. Glikiotis\textsuperscript{1}, P. Paschalis\textsuperscript{4}, E. Dimovasili\textsuperscript{4}, M. Kokavesis\textsuperscript{1}, S. Dimopoulos\textsuperscript{1}, A. Delakoura\textsuperscript{1}, S. Pappas\textsuperscript{1}, G. Dimitropoulos\textsuperscript{1}

\textsuperscript{1} ADVEOS microelectronics PC,  
\textsuperscript{2} Greek Atomic Energy Commission,  
\textsuperscript{3} Institute of Nuclear Physics, NCSR Demokritos  
\textsuperscript{4} Department of Physics, University of Cyprus,  
\textsuperscript{5} National & Kapodistrian University of Athens

Presentation by: Haris Lambropoulos  
lambrop@uoa.gr
The MIDAS Device is developed in the context of a Technology Research Project funded by the European Space Agency under the contract 4000119598/17/NL/LF for a “Highly miniaturized ASIC radiation detector”
Quantities to be measured are radiation fluence rates, the energy distributions of different types of particles, and linear energy transfer (LET) distributions.

One may either assess the radiation field parameters near to an astronaut and then apply fluence to dose conversion coefficients for all types of particles involved for the assessment of organ doses, or one may calculate organ doses in a body using the radiation field data outside of the spacecraft and a code that combines radiation transport into the spacecraft and into the human body.

Excerpt from ICRP Publication 123, Ann. ICRP 42(4), 2013
Quantities to be determined

**Effective dose equivalent,** $H_E$

\[ H_E = \sum_T w_T \cdot H_{T,Q} \]

Sum over all tissues $T$,

$w_T$ tissue weighting factors defined in ICRP publication 103

**Dose equivalent,** $H_{T,Q}$

\[ H_{T,Q} = Q_T \cdot D_T \]

$Q_T$ : tissue quality factors defined in ICRP publication 123; parameterize the relative biological effectiveness of the high LET radiation

$D_T$ : Dose to tissue

ICRP publication 123 gives tables of dose to fluence conversion factors as a function of tissue type, particle type and energy.
ESA requirements and proposal to cope with them

Sensitivity to protons, neutrons and heavy ions:

✓ Protons: 2 to 200 MeV
✓ Neutrons: 0.1 to 200 MeV
✓ LET: $5 \cdot 10^{-4}$ to 10 MeV cm$^2$/mg

Important Top-Level requirements:

✓ Volume $<$ 50 x 50 x 10 mm$^3$
✓ Mass $<$ 50 g
✓ Device autonomous operation for 30 days
✓ Dose, Dose rate, Dose equivalent, LET spectra

Goal

a device whose size, power consumption and radiation data output will increase the level of crew autonomy as far as it concerns operational decisions related to radiation hazards

Our Proposal was

To construct a “sensitive cube” capable to register:

energy depositions by charged particles and neutrons coming from all directions

Direction of charged particle track

To infer the particle type and energy from their energy depositions

To calculate dose equivalent either by using the particles identity or their Linear Energy Transfer
The device concept
The device concept
The device concept
The device concept

- Ti cover box
- Plastic Scintillator
- Si Pin
The device concept (I)

- Ti cover box
- 2 layers of Si pixel detectors on every face
- Plastic Scintillator
- Si Pm
The device concept
The device concept
Detect protons from 2 to 200 MeV
Dynamic Range for LET spectrum measurement from $5 \cdot 10^{-4}$ MeV·cm$^2$/mg to $\geq 10$ MeV·cm$^2$/mg
Battery operation for ... 30 days

Translation:
The minimum detectable charge should come from the deposited energy in Si by minimum ionizing protons:

Power consumption: Even a target of 10mW/cm$^2$ is a big challenge

Count rate: $10000$ cm$^{-2}$·s$^{-1}$ means 1 count /s for an area of 100 x 100 $\mu$m$^2$
Technology proposed:

Principle of operation illustrated in the manufacturer technology chosen:
# The MIDAS chip

## Summary of Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip dimensions</td>
<td>4290 x 3550 um</td>
</tr>
<tr>
<td>Pixel array size</td>
<td>32 x 32</td>
</tr>
<tr>
<td>Pixel pitch in x</td>
<td>100.5um and 110.5um alternatively</td>
</tr>
<tr>
<td>Pixel pitch in y</td>
<td>105.91um</td>
</tr>
<tr>
<td>Charge dynamic range</td>
<td>0.5fCb to 6pCb</td>
</tr>
<tr>
<td>High gain - range</td>
<td>0.884 mV/fCb - 0.5fCb to 1.2pCb</td>
</tr>
<tr>
<td>Low gain - range</td>
<td>0.179 mV/fCb - 0.5fCb to 6pCb</td>
</tr>
<tr>
<td>Power supply</td>
<td>1.8V</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;10mW</td>
</tr>
<tr>
<td>Readout mode</td>
<td>Normal: only hit pixels are read</td>
</tr>
<tr>
<td></td>
<td>Full array: all pixels are read</td>
</tr>
<tr>
<td></td>
<td>Single pixel: a chosen pixel is read</td>
</tr>
<tr>
<td>Digitization</td>
<td>11 bits on chip SAR ADC</td>
</tr>
<tr>
<td>Readout interface</td>
<td>SPI</td>
</tr>
<tr>
<td>Readout time per pixel</td>
<td>600 ns with 12 MHz clock</td>
</tr>
</tbody>
</table>

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**Die photo**

![Die photo of the MIDAS chip](image)
Architecture

Architecture-block diagram

Signal readout chain

Digital Controller, Register File & SPI Slave Interface

11-bit ADC

SPI Master Interface

Pixel

Pixel

Row Buffer

Single to Differential

SAR ADC

Analog

Test

Bus

Test

PAD

ATB

PAD
Pixel operation explained

**PIXEL WAITING FOR A HIT**

- **Parasitic Cap 1 = 0.5pF**
- **Lateral overflow switch**
- **Cap 2 = 4.5pF**
- **Vreset**
- **Vdd**
- **DICE Flip Flop**
- **“Error amplifier” Comparator**
- **“monostable”**
- **Hit_flag=0**
- **Pixel_out**
- **Leakage current**

- **Vreset** connected to -28 V
Pixel operation explained

Pixel HIT

- 28 V

Parasitic Cap 1 = 0.5 pF

Lateral overflow Cap 2 = 4.5 pF

“Error amplifier” Comparator

DICE Flip Flop

“monostable”

Vreset

Hit_flag = 1

Signal + leakage current

Pixel_out

“Comparator”

“monostable”

Lateral overflow switch
Pixel operation explained

**PIXEL 1st READ**

- **Parasitic Cap = 0.5pF**
- **Lateral overflow Cap = 4.5pF**
- **“Error amplifier” Comparator**
- **DICE Flip Flop**
- **“monostable”**
- **Hit_flag = 1**
- **Pixel_out**
- **V@ Cap 1**

Leakage current

-28 V

Vreset

Vdd

Vreset

Vreset

Lateral overflow switch

“monostable”
Pixel operation explained

**PIXEL 2\textsuperscript{nd} READ**

- Leakage current
- Parasitic Cap = 0.5pF
- "Error amplifier" Comparator
- DICE Flip Flop
- "monostable"
- Hit_flag=1
- Pixel\(_{out}\) $V@ (\text{Cap 1 + Cap 2})$

- Vreset
- Vdd
- V\(_{reset}\)
- "Lateral overflow switch"
- Lateral overflow Cap = 4.5pF

- "Comparator"
- "Error amplifier"
- "monostable"
- DICE
- "Lateral overflow switch"
- "Pixel\(_{out}\)"
- "Hit_flag=1"
- "V\(_{reset}\)"
- "V\(_{dd}\)"
- "Leakage current"
- "Parasitic Cap = 0.5pF"
- "DICE Flip Flop"
- "Error amplifier"
- "V\(_{reset}\)"
- "V\(_{dd}\)"
**Pixel operation explained**

### Pixel Reset

- **Parasitic Cap 1 = 0.5pF**
- **Cap 2 = 4.5pF**
- **Lateral overflow switch**
- **DICE Flip Flop**
- **Hit_flag=0**
- **Pixel_out**
- **Leakage current**
- **-28 V**
- **“Error amplifier” + Comparator**

**“monostable”**
First measurements

The x-y axes are the pixels and the colour scale is the difference of ADC values of the pixel output with illumination from the ADC value without illumination. Non illuminated pixels give a 0 difference. The bottom right figure shows a vertical zone pattern which appears right after HV is applied.
Test of the in-pixel error amplifier-comparator with a laser source

Calculated deposited charge

% difference sim - exp

Single to differential converter positive out

Observation point

Sensor cathode

$V_{in} = 1.6 \text{ V}$

$V_{DD} = 1.8 \text{ V}$

Row buffer

$V_{bas} = -28 \text{ V}$

In-pixel circuit

$2.08 \text{ mV}$

$51 \text{ mV}$

$8 \text{ ms}$

$180 \text{ mV}$
Conclusions-Perspectives

• The first prototype of high dynamic range depleted monolithic active pixel sensors for measuring energy deposition from Galactic Cosmic Rays and Solar Energetic particles has been manufactured.

• Measurements with laser pulses have proven that the in-pixel error amplifier – comparator works as designed

• Measurements with test beams are pending

• A new version with incremental improvements is designed

• Depleted monolithic active pixel sensors can be used for compact dosimeters or radiation monitors in space. Simulation results show that particle discrimination and energy determination can be achieved. We have proposed also the development of a radiation monitor for Galileo satellites:
Protons with energy higher than 600 MeV give almost identical energy deposition distributions onto the Silicon Pixels. The MIDAS detector can only count the protons with energies higher than 600 MeV.

Even if the MIDAS dosimeter cannot distinguish energies higher than 600 MeV, the resulting uncertainty in the estimation of the effective dose equivalent is lower than 10% in the case of the Cosmic ray energy spectrums and negligible in the case of Solar Particle Events.
Spectra for GCR and SEP

Normalized energy deposition spectrums:

i) SPE+CR
ii) CR
Discrimination and cross over between the most abundant ions in cosmic rays

<table>
<thead>
<tr>
<th></th>
<th>“Normalized energy deposition” bins in keV (min – max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>0</td>
</tr>
<tr>
<td>max</td>
<td>50</td>
</tr>
<tr>
<td>proton</td>
<td>0.95</td>
</tr>
<tr>
<td>alpha</td>
<td>0.14</td>
</tr>
<tr>
<td>^12C</td>
<td>0.002</td>
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<tr>
<td>^14N</td>
<td>0</td>
</tr>
<tr>
<td>^16O</td>
<td>0</td>
</tr>
<tr>
<td>^20Ne</td>
<td>0</td>
</tr>
<tr>
<td>^28Si</td>
<td>0</td>
</tr>
<tr>
<td>^40Ca</td>
<td>0</td>
</tr>
<tr>
<td>^44Ti</td>
<td>0</td>
</tr>
<tr>
<td>^56Fe</td>
<td>0</td>
</tr>
</tbody>
</table>