Active Pixel Sensor CMOS Image Array for Optical Inter-Satellite Links (OISL)

Final Presentation

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Presentation outline

• Introduction
  Project motivation, objective, scope, base line
• Activities
• Technical part
  • Image sensor outline
  • Specifications
  • Test & Measurement
  • Demo system features
• Conclusions
Introduction

Project motivation:
The growing market of satellite telecom constellations (early 2000) asked for a cost-effective beam-tracking device that could withstand the radiation load encountered in low orbit.

APS can offer benefits in terms of system-level cost-effectiveness, weight and volume.

Start from the experience gained with ASCoS design.
Introduction

Attitude Sensor Concepts for Small Satellites (ASCoSS)

Co-operation with SIRA electro-optics, Contraves and IMT (1997-1999)

Project objective:
Design a star tracker using novel technologies
   APS, MCM, Diffractive optics, …
   » FOV 20° x 20°
   » Update rate 10Hz
   » NEA 1arc minute (2σ)
   » Dim star limit: 5 m_v

Image sensor properties:
   » 512 by 512 format , 25 μm pitch CMOS Active Pixel Sensor (APS)
   » ALCATEL Micro-Electronics 0.7 Analogue CMOS process
   » Patented N-well pixel structure results in high fill factor
   » On-chip 8-bit ADC
Introduction

ASCoSS:

Corrigible items
- Design flaws in output amplifier
- Ghost image due to cross-talk
- Low MTF due to epi-layer thickness
- Pixel-to-pixel non-uniformity
- Low radiation tolerance

Conclusion of SIRA:

“The overall conclusion is that a sensor has been designed and breadboarded which could meet the target specification.”
- Positive: noise behavior
- Precludes: low MTF, non-uniformity requires on-flight calibration, poor radiation tolerance.
Introduction

Objective:

Design a next-generation CMOS Active Pixel image Sensor (APS), capable of tracking a laser beam beacon in Low Earth Orbit.

Start from ASCoSS specifications:
- Format: 512 by 512, 25 µm pixel pitch
- Equal or better noise performance

Enhancements over ASCoSS:
- Enhanced radiation tolerance
- Enhanced ADC resolution
- Improved MTF
- Improved Infra-red response
- Addressable shift registers

Envisage broader field of applications:
Low- to medium accuracy star tracking
Sun sensing
Introduction

Scope

– Design and fabrication of the image sensor
– Electro-optical and limited radiation tolerance evaluation
– Delivery of a limited number of samples
– Construction and delivery of evaluation system

Not included:
Complete qualification testing:
  environmental, life time, extended radiation testing, …
Introduction

Design base line:
- CMOS Active Pixel Sensor (APS) with 4 diodes per pixel
- Format 512 by 512 pixels
- On-chip Fixed Pattern Noise (FPN) correction
- Programmable gain output amplifier
- 10-bit ADC
- Programmable windowing
- Radiation tolerant design technique (first time !)
Activities

Study logic, project timing

| ID | Task Name                                           | Jan 9, '00 | Feb 6, '00 | Mar 5, '00 | Apr 2, '00 | Apr 30, '00 | May 28, '00 | Jun 26, '00 | Jul 21, '00 | Aug 20, '00 | Sep 17, '00 | Oct 15, '00 | Nov 12, '00 | Dec 10, '00 | Jan 7, '01 | Feb 4, '01 | Mar 4, '01 |
|----|----------------------------------------------------|------------|------------|------------|------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|------------|------------|
| 1  | OISL development                                   |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 2  | WP0. General project management (IMEC)             |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 3  | Kick-off meeting                                   |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 4  | WP1 Conceptual design (FF)                         |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 5  | WP1 final meeting                                  |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 6  | WP2 Detailed design (FF)                           |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 7  | WP2 Detailed design (FF)                           |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 8  | Detailed design                                    |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 9  | Design review meeting                              |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 10 | Rectification design review of ESA                 |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 11 | Tape out                                           |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 12 | WP3 Production                                     |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 13 | WP3.1 Lubrication (FF)                             |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 14 | Test results report                                |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 15 | WP3.2: Electro-optical evaluation (FF)             |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 16 | VPP 3.3: Radiation test (IMEC)                     |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 17 | WP 3.4: Delivery of 40 samples (FF)                |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 18 | WP3 Demonstration system (IMEC)                    |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 19 | Final documentation                                |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
| 20 | Final project meeting                              |            |            |            |            |             |             |             |             |             |             |             |             |             |            |            |
Design activities:

**Preliminary design (WP1):**
- Architectural design: first-cut specification targets and floorplan
- Simulations of pixels, shift registers, output amplifier
- Design of pixel, shift register cell, ADC basic cell
- Selection of foundry

**Detailed design (WP2):**
- Full custom IC layout with Cadence Virtuoso layout editor
- Drawing of about 100 basic unit cells
- Hierarchical design, based on parametric cells
- Start from scratch (first radiation tolerant design)
Activities

Production and testing (WP3):

Production at ALCATEL Micro-Electronics (WP 3.1)

Electro-optical evaluation (WP 3.2)
  Confirmation of design target specifications
  Spectral response, photo response, MTF, noise, dark current, ...

Radiation testing (WP 3.3)
  Only total dose test up to 230 Krad (device can probably sustain much higher levels)

Delivery of 40 samples to the agency (WP3.4)
  Functional testing of all produced devices on wafer
  Packaging and re-testing selected devices for delivery

Construction of demo system (WP 3.5)
Technical part

Outline

- Image sensor description
- Specifications
- Test & Measurement
- Packaging
- Demo system
Features

- Integrating APS in 0.5 μm CMOS technology
- 512 by 512 pixels on 25 μm pitch
- 4 diodes per pixel for improved MTF and PRNU
- Radiation tolerant design
- On-chip double sampling circuit to cancel Fixed Pattern Noise
- Electronic shutter capability
- Readout rate: up to 30 full frames per second
- Fast windowing through pre-settable start point of read-out
- On-chip 10-bit ADC
- Ceramic JLCC-84 package
Image sensor description

Image sensor outline

- Pixel Array: 512 by 512 pixels
- Y Address Decoder / Shift register
- Column amplifiers
- Prog. gain amplifier
- 10-bit ADC
- X-Start register decoder
- Y-Start register decoder
- Clk_ADC
- Aout
- D9 ... D0
- Sel
- Rst
- Col
- Ld_Y
- Ld_X
- Clk_Y
- Clk_X
- X
- C
- L
- K
- G
- G
- ac
- 1
- 0
- 1
- ef
Image sensor description

Lay-out view
Image sensor description

Pixel design

[Diagram showing pixel design with reset, integration, and read/reset phases]

- **Reset**
- **Integration**
- **Read/reset**
- **Column bus**

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**OISL Final Presentation**  16  **ESTEC, March 7, 2001**
Image sensor description

Pixel design

4 photodiodes

Charges can diffuse to neighboring pixels
Cross talk : 20%
MTF: 0.27

Almost all charges will be collected within the pixel
Cross talk : 8%
MTF: 0.4
Image sensor description
Image sensor description

Column amplifiers
Optimization (compared to ASCOSS):
- Less sensitivity to Vth variations (radiation!)
- Better fixed pattern noise
- Less power dissipation
- Simpler timing diagram

Output amplifier
Designed for 12.5 MHz & 40 pF load
Image sensor description

ADC

12.5 Msamples/s
10 bit ADC
Radiation-soft version used on ibis 4 & ...
Radiation tolerant layout
   Size has increased slightly due to radiation tolerant design
Image sensor description

Fabrication

Fabrication at ALCATEL Micro-Electronics as prototype run
- 2 wafers + 2 wafers for digital sun sensor project
- 54 devices per wafer

Process:
- Alcatel Microelectronics 0.5 μm analogue-signal CMOS, 5 μm epi-layer
- Analogue cores: full-custom, manual layout
- I/O pads and power pads: manual layout
# Electro-optical specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>400 – 1000 nm</td>
</tr>
<tr>
<td>Quantum Efficiency x Fill Factor</td>
<td>Max. 35%</td>
</tr>
<tr>
<td>Full Well capacity</td>
<td>311K electrons</td>
</tr>
<tr>
<td>Linear range within ± 1%</td>
<td>128K electrons</td>
</tr>
<tr>
<td>Output signal swing</td>
<td>1.68 V</td>
</tr>
<tr>
<td>Conversion gain</td>
<td>5.7 μV/e-</td>
</tr>
<tr>
<td>kTC noise</td>
<td>76 e-</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>74 dB (5000:1)</td>
</tr>
<tr>
<td>Fixed Pattern Noise</td>
<td>$1\sigma &lt; 0.1%$ of full well</td>
</tr>
<tr>
<td>Photo Response Non-uniformity at Qsat/2</td>
<td>Local: $1\sigma &lt; 0.39%$ of signal</td>
</tr>
<tr>
<td></td>
<td>Global: $1\sigma &lt; 1.3%$ of signal</td>
</tr>
<tr>
<td>Average dark current signal</td>
<td>4750 e- / s</td>
</tr>
<tr>
<td>MTF</td>
<td>Horizontal: 0.36</td>
</tr>
<tr>
<td></td>
<td>Vertical: 0.39</td>
</tr>
<tr>
<td>Anti-blooming capacity</td>
<td>x 1000 to x 100 000</td>
</tr>
<tr>
<td>ADC</td>
<td>10 bit</td>
</tr>
<tr>
<td>ADC linearity</td>
<td>± 3.5 counts</td>
</tr>
<tr>
<td>Missing codes</td>
<td>none</td>
</tr>
<tr>
<td>ADC setup time</td>
<td>310 ns to error &lt;1% (large signal)</td>
</tr>
<tr>
<td>ADC delay time</td>
<td>125 ns</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>&lt; 350 mW</td>
</tr>
</tbody>
</table>
Test & Measurement

Outline

- Packaging, operation and bias conditions
- Electro-optical evaluation
- Radiation testing
- Functional testing of delivery samples
Packaging, Operation and Bias conditions

- Package devices from one wafer in 84 pin J-lead with glass cover
- Operate one device in test system
- Establish bias conditions: voltage and timing, resulting in datasheet
- Verify bias conditions on 5 devices
Electro-optical evaluation: overview

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Test sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral response</td>
<td>On test structure on 3 samples</td>
</tr>
<tr>
<td>Photo-voltaic response</td>
<td>On 3 pixel on 3 devices each at different gain settings</td>
</tr>
<tr>
<td>Pixel profile</td>
<td>On 3 pixel on 3 devices in both horizontal and vertical direction</td>
</tr>
<tr>
<td>Dark current</td>
<td>On 5 pixels on 5 devices</td>
</tr>
<tr>
<td>FPN</td>
<td>On 50% of the pixels of 5 devices</td>
</tr>
<tr>
<td>PRNU</td>
<td>On 50% of the pixels of 5 devices</td>
</tr>
<tr>
<td>Noise</td>
<td>On 5 pixels on 5 devices</td>
</tr>
<tr>
<td>Power</td>
<td>On 5 devices</td>
</tr>
<tr>
<td>Output amplifier DC response</td>
<td>On 3 devices</td>
</tr>
<tr>
<td>Output amplifier gain/phase diagram</td>
<td>On 3 devices</td>
</tr>
<tr>
<td>ADC minimum set-up time</td>
<td>On 3 devices</td>
</tr>
<tr>
<td>ADC missing codes</td>
<td>On 3 devices</td>
</tr>
<tr>
<td>ADC linearity</td>
<td>On 3 devices</td>
</tr>
</tbody>
</table>
Spectral response and quantum efficiency
Photo-voltaic response

Allows to calculate saturation charge, linear region and conversion factor.
Test & Measurement

Pixel profile

Horizontally

Vertically
ADC set up time
Radiation testing

Pre- and post- irradiation tests:
- Functional test
- Power consumption: functional and under DC bias
- Dark current on 5 pixels
- Fixed Pattern Noise (FPN) on 50% central area
- Photo Response Non Uniformity (PRNU) on 50% central area

Total dose irradiation (CO 60) of 10 samples with varying dose

<table>
<thead>
<tr>
<th>Approximate insertion time</th>
<th>Sample ID</th>
<th>Total dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>S1, S2</td>
<td>230 Krad</td>
</tr>
<tr>
<td>T0 + 24 hr.</td>
<td>S3, S4</td>
<td>110 Krad</td>
</tr>
<tr>
<td>T0 + 38 hr.</td>
<td>S5, S6</td>
<td>40 Krad</td>
</tr>
<tr>
<td>T0 + 42 hr.</td>
<td>S7, S8</td>
<td>20 Krad</td>
</tr>
<tr>
<td>T0 + 44 hr.</td>
<td>S9, S10</td>
<td>10 Krad</td>
</tr>
<tr>
<td>T0 + 46 hr.</td>
<td>End of irradiation</td>
<td></td>
</tr>
</tbody>
</table>
Functional testing on wafer

High yield: 50% of the devices have less than 10 isolated defect pixels.

Functional test on wafer:
   At 50% uniform illumination
   Power consumption
   Average gray value and standard deviation
   Number of bad pixels (bright/dark)
   Number of bad pixels with bad neighbor (bright/dark)
   Number of bad columns/rows based upon average column/row value and standard deviation

Select 40 best devices
Packaging in 84 J-lead package with glass window
Visual inspection of images from packaged devices at 50% uniform illumination
Packaging

84-J-leaded package
Ceramic package (black alumina), gold leads
Custom designed for Fillfactory to contain large-area image sensors

Position of die in package within known tolerances

Drawing not to scale
Demo system

Main demo system features:

- Apply power, logic signals and DC bias to OISL image sensor for proper read-out at nominal or at reduced speed

- Control sensor properties:
  - Integration time (setting by line or by frame)
  - Windowing
  - Gain setting

- Capture one frame in memory buffer at nominal read-out speed

- Transfer image to PC via printer port and display on PC screen

- Store image in different file formats:
  - nip (16 bit), PGM, BMP, tab-separated text
Continuation

Other projects, based upon OISL were started:

**Application in ISLFE breadboard**
- Breadboard for optical link
- SIRA Electro-optics and Contraves

**Low cost digital sun sensor**
- Funded by ESA
- 2 consortia:
  - TNO-TPD, Sodern, Fillfactory: use OISL sensor as is
  - Officine Galileo: 1024 x 1024 format, 1 diode pixel (15 µm)

**Atmospheric Chemistry Experiment (ACE)**
- Canadian Space Agency, ABB Bomem (Quebec)
- Sensor development funded by the Belgian government through Prodex
- 256 x 256, 4-diode pixel (25 µm), with black reference pixels
- Flight qualification, launch: July 2002

**Interest from industry**
- Large pixel format
- Large area
- High uniformity
Conclusions

OISL is the first complete image sensor that was designed with the novel radiation-tolerant design technique.

The design was successful: the device is operational and meets all predicted specifications except ADC speed.

<table>
<thead>
<tr>
<th>Design target</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>512 by 512, 25 µm pixel pitch</td>
<td>By design</td>
</tr>
<tr>
<td>Equal or better noise performance</td>
<td>Better noise performance through better amplifier design</td>
</tr>
<tr>
<td>Enhanced radiation tolerance</td>
<td>Novel design technique successfully applied</td>
</tr>
<tr>
<td>Enhanced ADC resolution</td>
<td>10 bit, radiation tolerant</td>
</tr>
<tr>
<td>Improved MTF</td>
<td>4-diode pixel has very high MTF</td>
</tr>
<tr>
<td>Improved Infra-red response</td>
<td>Not improved over ASCoSS, but uncommitted</td>
</tr>
<tr>
<td>Windowing</td>
<td>Successful implementation of addressable shift registers</td>
</tr>
</tbody>
</table>
Demo