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High SEE Tolerance in a Radiation Hardened CMOS Image Sensor Designed for the Meteosat Third Generation FCI-VisDA Instrument

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Introduction

- The CIS111 sensor has been designed by e2v for the Metosat Third Generation (MTG) Flexible Combined Imager instrument.
- MTG programme is a cooperation between EUMETSAT and ESA to provide meteorological data from geostationary orbit into the 2030s.
- e2v contracted by satellite prime Thales Alenia Space – France (TAS-F) to deliver a space qualified custom CMOS sensor.
- This presentation focuses on ground-based radiation testing performed to ensure suitability of the design for this application.

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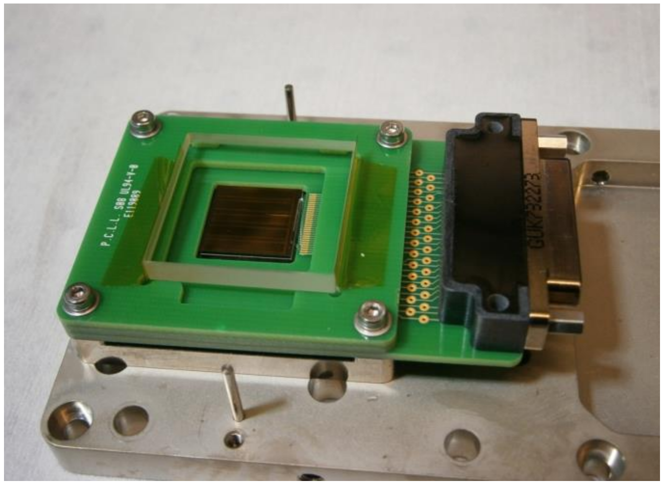
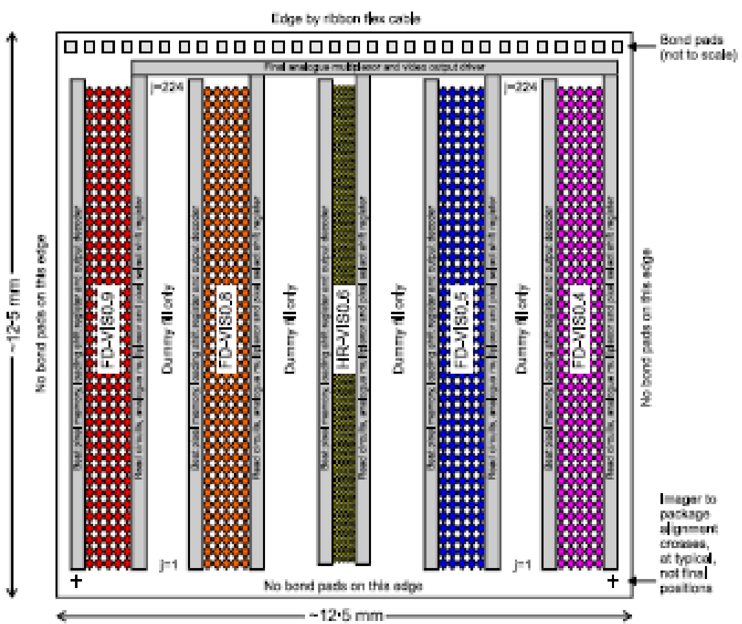
Device Description

Overview

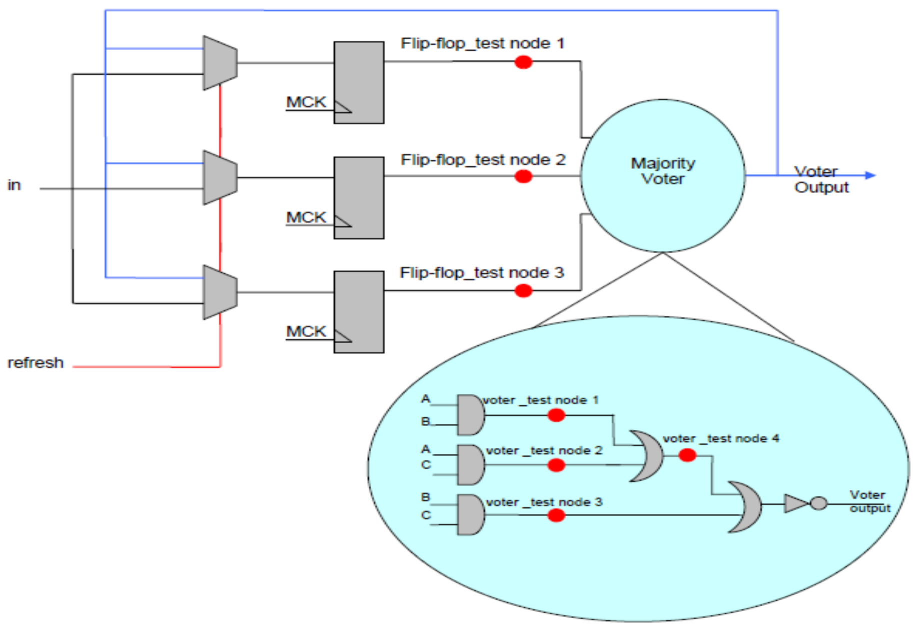




- 0.18 µm Imaging CMOS process
- 12 µm epi thickness
- 4T architecture
- 5 channel multi-spectral imager
- Integrated sequencer generates pixel timing and readout control signals
- SPI for column selection
- Analogue outputs (separate outputs for video signal and dark reference)

Device Description

Shift Registers



- Shift register architecture used on CMOS digital circuits for simplicity:
  - Integral sequencer
  - Readout Select
  - Serial Programmable Interface
- Triple mode redundancy used to increase SEU hardness.
- Two types of shift register used:
  - Rad-hard
    - Implemented for all digital control functions except for the SPI
    - TMR refreshed at 4 MHz rate
  - Low power
    - Less radiation hard
    - Implemented for the SPI
    - TMR refreshed at 2.6 kHz rate

Single Event Effects

Types of SEE

- Non-destructive
  - Single event upset (SEU) – change of logic state in memory element.
  - Single event transient (SET) – transients in circuit that lead to erroneous data being captured.
  - Single event functional interrupt (SEFI) – temporary loss of device functionality (for imager of this simplicity, this is caused by bus contention).

- Destructive
  - Single event latchup (SEL) – parasitic thyristor causes circuit lockup or catastrophic failure.

- MTG has design features to mitigate against these SEE types:
  - Triple mode redundancy (SEU)
  - Big transistors with large drive and capacitance (SET)
  - Big global clock buffers with high output capacitance (SET)
  - Layout considerations and guard rings around all wells (SEL)

Heavy Ion Testing

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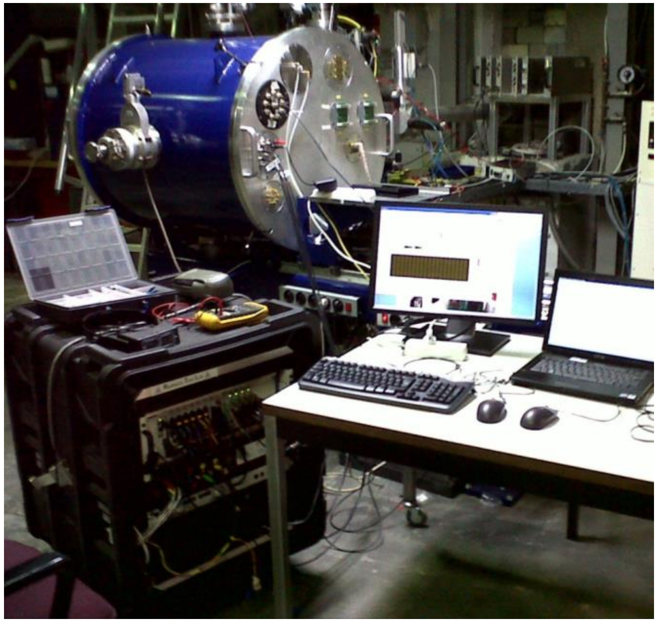
Test Facility

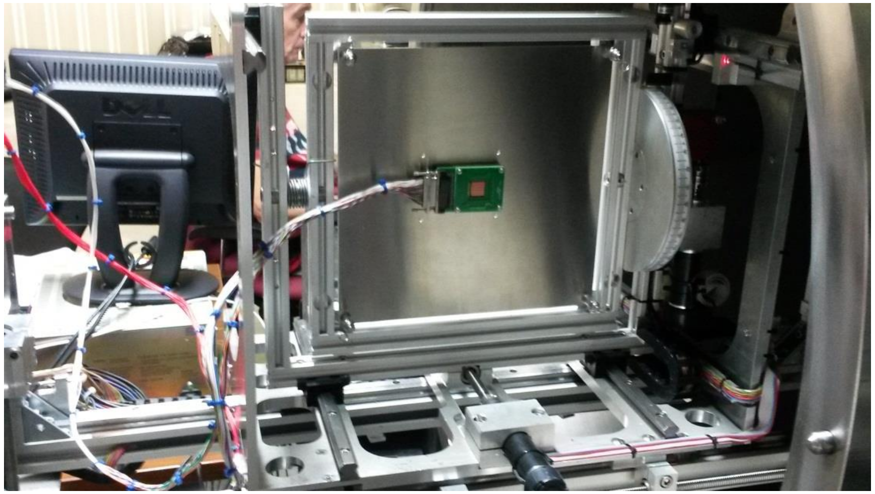


- Test facility at Universite Catholique Louvain (UCL), Belgium.

- Cyclotron has two heavy ion cocktails:
  - Low energy – LET range 3 to 67 MeV cm^2 mg^{-1}
  - High energy – LET range 1 to 31 MeV cm^2 mg^{-1}

- Heritage
  - Sentinel 2 A/B
  - CIS108 Radiation Testchip (e2v Private Venture)
  - MTG FCI VisDA

- Future
  - Sentinel 2 C/D
  - CIS115 (BI CMOS based on CIS107 OCI)
  - CIS113 (used for TAOS II) ???
  - Radiation Testchip 2 (e2v Private Venture)



Heavy Ion Testing

Methodology

- Test modes during irradiation should be representative of how the device will be run by the end user.

- NORMAL imaging mode
  - Test for latchup in any CMOS circuit (power consumption monitoring)
  - Memory upsets in SPI (SEU)
    - In this mode, the TMR is refreshed every 2.6 kHz.
  - Circuit lockups (SEFI)

- SCAN mode
  - Pass data pattern through readout selection shift registers and compare input to the output (SEU).
  - Clock speed is 4 MHz to replicate operation of sequencer or readout selection in NORMAL operation.

Test Results

Single Event Latchup

- No SEL observed at a LET of up to 67.7 MeV cm^2 mg^{-1}.

- Low energy cocktail – tested up to 67.7 MeV cm^2 mg^{-1} (Xenon ion).
  - Tilt angle 0° due to low range of xenon ion in silicon.
  - Total Fluence of 2.56×10^7 cm^{-2}.

- High energy cocktail – tested up to an effective LET of 65.2 MeV cm^2 mg^{-1} (Krypton ion at 60° tilt angle, LET at normal incidence 32.6 MeV cm^2 mg^{-1}).
  - Total fluence of 1.51×10^7 cm^{-2}.

- No high current states observed due to SEFI.

Test Results

Single Event Upset

Rad-hard Shift Register – Used for Integral Sequencer and Timing and Readout Functions

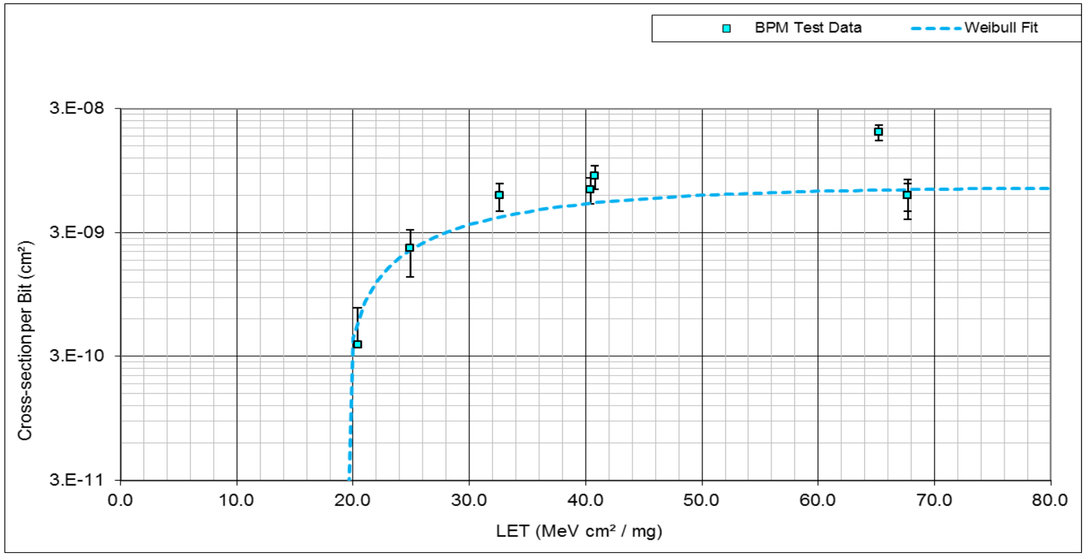
Ion Species	Tilt Angle [°]	Effective LET [MeV cm^2 mg^{-1}]	Effective Flux [cm^{-2} s^{-1}]	Effective Fluence [cm^{-2}]	Number of Errors
$^{132}Xe^{26+}$	0	67.7	5e3	2.1e6	0
$^{84}Kr^{17+}$	0	40.4	5e3	2.6e6	0
$^{84}Kr^{25+}$	60	65.2	7e3	1e7	1
$^{84}Kr^{25+}$	60	65.2	7e3	2.1e6	0

- Threshold LET ~ 65 MeV cm^2 mg^{-1} (although exact position is not clear).
- Saturation cross-section = ???
- To accurately determine Cross-section vs. LET characteristic would require ion species with LET > 67 MeV cm^2 mg^{-1}.

Test Results

Single Event Upset

Low-Power Shift Register – Used for Serial Programmable Interface



- Fitted Parameters
  - LET_{th} = 19 MeV cm^2 mg^{-1}
  - σ_{sat} = 7.9 x 10-9 cm^2 bit^{-1}
  - S = 1.2
  - W = 12.6

- LET_{th} > 15 MeV cm^2 mg^{-1} means that proton SEE tests are not necessary.

Data Analysis

Calculating Mission SEE Rate

- Cross-section vs. LET characteristic is used to estimate mission SEE rate.
- Most common algorithm used is the rectangular parallelepiped (RPP) model.
- But the RPP model could not be used in this instance:
  - For very rad-hard circuits (threshold LET > 67 MeV cm^2 mg^{-1}) it is impossible to determine the saturation cross-section.
  - For shift register with triple mode redundancy, the cross-section is a function of radiation flux.
    - Radiation flux during testing >> radiation flux in space
    - Therefore the measured cross-section < mission SEE cross-section, giving very inaccurate results
- Instead e2v performed a worst case analysis to estimate in-flight SEE rate.
- To accurately calculate the mission SEE rate of triple mode redundant features, requires a specialised test method and test structures.
  - Requires measurement of Cross-section vs. LET characteristic on single shift register without TMR.

Data Analysis

Worst Case Analysis

- A worst case analysis was used to estimate the in-orbit SEE rates for latchup and upsets.
- As there is not enough information for a full cross-section vs. LET curve, instead a step function is used with the step at LET_{th}
- Predicted SEE Rate:
  - Single Event Latchup
    - Mission Rate < 2×10^{-6} day^{-1}
    - Reliability over 8.5 year mission lifetime > 99.2 %
  - Single Event Upset in rad-hard shift register (sequencer, timing and readout control)
    - Mission Rate < 4×10^{-12} day^{-1}
    - Availability over 8.5 year mission lifetime > 99.9999 %
  - Single Event Upset in low-power shift register (serial programmable interface)
    - Mission Rate < 1×10^{-8} day^{-1}
    - Availability over 8.5 year mission lifetime > 99.996 %

Conclusions

- Sensor for Meteosat Third Generation FCI-VisDA shows high immunity to SEE.
- Sensor is invulnerable to proton induced SEE.
- Calculating an in-orbit SEE rate is complicated by the triple mode redundancy of shift registers.
- Only a worst case in-orbit SEE rate can be obtained.
- Despite the worst case analysis, the results are still extremely positive.

Acknowledgements

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