CMOS Image Sensors in Harsh Radiation Environments

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TWEPP 2016 - Topical Workshop on Electronics for Particle Physics
26-30 September 2016
Karlsruhe Institute of Technology (KIT)
Purpose/Scope of the presentation

- Present the basic radiation effects on CMOS Image Sensors
  - Only **CIS specific** radiation effects
    - Typical technology node for the discussion: 180 nm CIS process
    - No discussion about irrelevant effects for CIS
      - e.g. SEU, MBU in highly integrated digital circuits
      - e.g. Advanced CMOS (FinFETs, FDSOI, beyond 90 nm…)
  - Mainly for harsh radiation environments
    - High TID levels (MGy – Grad)
    - High hadron flux (> $10^{18} \text{ cm}^{-2}\cdot\text{s}^{-1}$)
    - High hadron fluence (> $10^{12} \text{ cm}^{-2}$)
- Illustrate these basics degradation mechanisms by presenting results achieved in recent developments
**Outline**

- CMOS Image Sensor (CIS) technology: a brief overview
- Basic radiation induced degradation mechanisms and illustrations
  - Total Ionizing Dose (TID) effects
    - Hardening and use of CIS for ITER remote handling operations
  - Single Event Effects (SEE)
    - Use of CIS for Megajoule class Inertial Confinement Fusion (ICF) experiments
  - Displacement Damage (DD) effects
    - Prediction of DD effects for high fluence environment
CIS technology: an overview

- **CMOS Image Sensors (CIS)**
  - Most popular solid state imager technology (95% of the market)

- **CIS = CMOS Integrated Circuit**
  - Designed for optical imaging applications
  - Manufactured with a CMOS process optimized for imaging
CIS manufacturing process: CMOS vs CIS

Compared to standard CMOS, CIS processes have:

- Optimized dielectric stack (reduced number of metal levels, planarization, anti-reflection coating, color filters, microlenses...)
- Optimized epitaxial layer and doping profiles (for photo-detection)
  - Dedicated photodiode doping profiles
  - Optimized threshold voltages…
CIS technology: pixel architecture

- Two basic pixel designs used in most of CIS

**3T-Pixel**

- **Schematic**
- **Conventional Photodiode**
- **3T-Pixel X-X’ cut**

**4T-PPD-Pixel**

- **Schematic**
- **Buried Photodiode (PPD)**
- **4T-PPD-Pixel X-X’ cut**

- **Conventional photodiode**
- **Pinned (buried) PhotoDiode (PPD)**
**CIS, APS & MAPS?**

<table>
<thead>
<tr>
<th>Feature</th>
<th>CIS</th>
<th>MAPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Pixel Sensor*</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>CMOS Integrated Circuit</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Monolithic</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Dedicated CMOS process</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Optimized/dedicated photodiode doping profiles</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Optimized/dedicated optical interfaces (AR coating / color filters /</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>microlenses / light-guide…)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Usual purpose</td>
<td>Optical imaging</td>
<td>Particle detection</td>
</tr>
</tbody>
</table>

CMOS Image Sensor = CMOS APS + optical imager design + dedicated CIS process

Total Ionizing Dose (TID) effects
Basic radiation effects: TID

Ionizing radiation

Polysilicon gate

Silicon

$\text{SiO}_2$

Trapped Charge

Hole trap

Silicon
Basic radiation effects: TID

- Polysilicon gate
- Silicon
- Ionizing radiation
- Trapped Charge
- Interface States
Basic radiation effects: TID

- Ionizing radiation (X, γ, charged particles…)
  - Generate electron-hole pairs in dielectrics
  - Leading to the buildup of permanent defects:
    - Oxide Trapped (OT) charge (positive in most cases)
    - Interface states (IT) at Si/Oxide interface
TID effects in CIS MOSFETs: gate oxide

- **Gate oxide trapped charge (+):**
  - Negative threshold voltage shift ($\Delta V_{th}<0$)

- **Gate oxide interface states (x):**
  - Subthreshold slope decrease
TID effects in CIS MOSFETs: STI

- **Shallow Trench Isolation (STI) trapped charge (+):**
  - Sidewall (drain to source) leakage
  - Further negative threshold voltage shift ($\Delta V_{th}<0$) called Radiation Induced Narrow Channel Effect (RINCE*)
  - (Inter-device leakage)

*F. Faccio et al., IEEE TNS, Dec. 2005
Enclosed Geometry: example of the ELT

- **Enclosed Layout Transistor (ELT)**
  - Circular gate design
  - No more channel edges
  - no more STI related effects
    - No more RINCE
    - No more sidewall leakage

- Other enclosed geometry designs exist
  (see for exemple W. Snoeys et al, IEEE TNS, Aug. 2002.)

*G. Anelli et al., IEEE TNS, 1999.*
MGy/Grad irradiation effects on N-MOSFETs (180 nm CIS)

Standard N-MOSFET seriously degraded @ 100 Mrad / 1 MGy
ELT mandatory to avoid RINCE and sidewall leakage

Courtesy of Marc Gaillardin (CEA DAM)
MGy/Grad irradiation effects on P-MOSFETs (180 nm CIS)

- **STD**
  - 30 Mrad / 300 kGy

- **ELT**
  - 300 Mrad
  - 3 MGy

**TID**

*Courtesy of Marc Gaillardin (CEA DAM)*

- **Standard P-MOSFET unusable after** $\approx 10$ Mrad / 100 kGy
- **ELT mandatory to avoid RINCE**
MGy/Grad irradiation effects: 
Pinned PhotoDiode (PPD) (4T pixel)

Before Irradiation
- Depleted region well protected from the interfaces
- Ultra low dark current
- High Charge Transfer Efficiency (CTE)

After Irradiation (high TID)
- Intense dark current
- Very poor CTE

PMD Oxide Trapped charge (OT)
è Pinning layer depletion

No Radiation-Hardening-By-Design Solution (thus far)
MGy/Grad irradiation effects: Conventional Photodiode (3T pixel)

Before Irradiation
- Depletion region in contact with Si/SiO₂ interface
- Higher dark current than PPD
- No CTE issue (no transfer)

After Irradiation (high TID)
- Short-circuit between diodes
- Intense dark current
- No CTE issue (no transfer)

Can be mitigated by design!
Basic TID radiation effects on CIS: a summary

- For MGy range CIS design **Enclosed Geometries are mandatory for both N and P MOSFETs**
  - But gate oxide can still induce a threshold voltage shift
    - *Due to OT or IT*
    - *In both N and P channel MOSFETs*

- Both photodiodes (pinned and conventional) are **seriously degraded** by high levels of TID
  - Large dark current increase
  - Loss of functionality

- Radiation-Hardened-By-Design photodiodes are required:
  - Solutions *only exist for conventional photodiodes*

Conventional photodiode recommended for high TID!
TID effects/hardening illustration: ITER remote handling imaging system

-ITER remote handling operations require imaging systems
  - Compact, lightweight and low power/voltage
  - Radiation hard (failure TID $\gg 1\text{MGy(SiO}_2$))
    - *Gamma radiation only* (plasma OFF)
  - Color and high definition ($\geq 1\text{Mpix}$)
- Tube camera, **not suitable** because of
  - Size, cabling, voltage, resolution and reliability
- Existing solid-state image sensor based camera
  - **Limited** by their radiation *hardness: $\leq 100\text{kGy}$*

*Dedicated development required*
Camera Radiation Hardening Strategy

Integrate all the required electronics on a **single** Rad Hard (RH) CMOS IC

- RH Camera-on-a-Chip
  - No need for additional MGy RH electronics
  - Very compact
  - Complete control of the radiation hardness

Associated RH developments
- Rad-Hard **optical system** (led by Univ. Saint-Etienne)
- Rad-Hard LED based **illumination system** (led by CEA)
First technology evaluation demonstrator*

128x128 10µm pitch pixels

Most sensitive part: 3.3V analog circuits

- Pure 1.8V digital and I/O pads: imec DARE 180 nm platform
- 3.3V Analog/Mixed signal circuits and pixels \(\leftarrow\) Rad-Hard by ISAE

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*V. Goiffon et al., IEEE TNS, Dec. 2015
CMOS Image Sensor (CIS) Design: photodiode radiation hardening

**Issue with standard diode:**
peripheral oxide (STI here):

**Selected RHBD technique:**
use of a polysilicon gate to shield the junction from the trapped positive charge:

- Principle of the gate diode

+ voluntary gate-to-N overlap to shield the junction

*V. Goiffon et al., IEEE TNS, Dec. 2015*
Post Irradiation Results: Raw Images (no image correction)

Before Irradiation  
@4 MGy (400 Mrad)  
@10 MGy (1 Grad)

Gate-on-N-Overlap Rad-Hard pixel

Acceptable image degradation even after 1 Grad (10 MGy)!
Second technology evaluation
demonstrator: 1.8V RHBD pixel array

- Full 1.8V instead of 1.8/3.3V
- 9 pixel design variations
- Half of the sensor covered by a Color Filter Array (CFA)

Raw images captured by the manufactured CMOS image sensor:

- No functionality loss!

Unirradiated
6 MGy(SiO$_2$) / 600 Mrad
Color Filter Array: Radiation Hardness Evaluation

No significant color filter degradation

*V. Goiffon et al., IEEE NSREC 2016
Main Radiation Effects: Dark Current Increase

- Standard PD: $10^7 \times$ dark current rise @10kGy (1Mrad)
  - no longer functional at higher radiation dose
- Rad-Hard diodes functional @ 6 MGy/600 Mrad
- Factor of 5 improvement between the first and second demonstrator (5X dark current reduction)

*V. Goiffon et al., IEEE NSREC 2016
Multi MGy Rad-Hard Color Digital Camera-on-a-chip appears feasible

First results are promising but development shall continue:
  - Integrate all the functions in a single Rad-Hard HD sensor
Single Event Effects (SEE)
Single Event Effects in CIS: Basics

**Single Event Effect (SEE) =** perturbation/degradation caused by a single energetic particle

**Main mechanism:**

- Generation of a high density of $e^-/h^+$ pairs along the particle track
- Leading to:
  - *Transient perturbation (Single Event Transient (SET))*
  - *Permanent change of a digital value (Single Event Upset (SEU))*
  - *Triggering of a parasitic thyristor (Single Event Latchup)*
  - *...and many other possible parasitic effects!*

**Outline**

- CIS overview
- Rad. Effects
- TID
- SEE
- DD

**Si substrate**

*Courtesy of Marc Gaillardin (CEA DAM)*
What kind of SEE CIS are sensitive to?

- **In theory: all kind**, as any CMOS Mixed-Signal Integrated Circuit

For this presentation, focus only on SEEs that are specific to CIS, i.e. SEEs in:

- *Pixel arrays*
- *Analog readout chain*
- *Decoders*

Other optional integrated functions are not discussed here.
Single Event Effects in CIS: pixel array

For basic pixel architecture (3T/4T):
- No SEL (no in-pixel PMOSFET)
- No SEU (no in-pixel memory)
- Only Single Event Transient (SET)

SET: the ion induced charge is collected by the photodiodes leading to a parasitic signal:
- Spreading over several pixels
- Lasting a single frame

420 MeV Xe ions

120 pixels 1.2 mm

600 MeV Kr ion

256 pixels 1.8 mm
Single Event Effects in CIS: SET in decoders

- If an ion strike the decoders during readout, a transient artefact can appear on the readout image.

Usually not an issue:
- Low occurrence probability (compared to pixel SET)
- Transient effect that disappears on the next frame
Latchup can also occur in decoders leading to permanent artefact
- CIS are often immune to such SEL thanks to thin epitaxial layer
- Generally disappears after powering OFF and ON the sensor (no permanent damage)
In CIS required integrated functions:

- The main SEE are Single Event Transients (SET) in pixel array.

- Other effects are generally not an issue:
  - SET in decoders or readout chain are infrequent and only corrupt one pixel or one row of a single frame.
  - CIS are generally immune to SEL and if not:
    - Can be powered OFF to recover (if non-destructive).
    - Can be hardened-by-design.

- SEE in additional integrated functions (e.g. SEU in on-chip sequencers) can be an issue:
  - Requires a specific analysis of each additional CMOS function.
  - Not a problem for basic CIS without such functions.
Plasma diagnostics in MJ class ICF facilities radiation environment during each laser shot:
- 14 MeV neutrons
- Expected fluence: $10^{12} \text{n.cm}^{-2}$
- Estimated flux > $10^{18} \text{n.cm}^{-2}.\text{s}^{-1}$

Existing Plasma Diagnostics cannot withstand these conditions

A X-ray Plasma Diagnostic demonstrator has been developed (with CEA DAM and UJM) to demonstrate the potential of CIS for this application
ICF X-ray Plasma Diagnostic principle

- At LLE OMEGA facility: 60 laser beams (40kJ) focus on a 1 mm target during 1 ps leading to a fusion reaction.
- The X-ray signal emitted by the fusion plasma is imaged through:
  - A Multi-pinholes array thanks to an X-ray-to-light converter deposited on top of the CIS.
- An intense neutron pulse is also generated leading to SEE perturbations.

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Outline

CIS overview
Basics
Rad. Effects
TID
SEE
DD

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At LLE OMEGA facility: 60 laser beams (40kJ) focus on a 1 mm target during 1 ps leading to a fusion reaction. The X-ray signal emitted by the fusion plasma is imaged through:

- A Multi-pinholes array thanks to an X-ray-to-light converter deposited on top of the CIS.

An intense neutron pulse is also generated leading to SEE perturbations.
Several experiments performed since 2010 at the Laboratory for Laser Energetics of Univ. Rochester, NY.

To approach MegaJoule class ICF experiment conditions, the diagnostic demonstrator is inserted directly inside the target chamber:

- As close as possible to the target (35 cm)
- Maximum neutron flux reached at CIS level
  \[ \approx \text{a few } 10^{18} \text{ cm}^{-2}\cdot\text{s}^{-1} \]
ICF X-ray Plasma Diagnostic Demonstrator: Hardening Approach

**Hardening at the sensor level:**
- Selection of a **simple and robust CIS architecture** with only the required on-chip functions to reduce SEE sensitivity
- No real use of RHBD technique for this application

**System level hardening:**
- Delay the acquisition of the X-ray plasma image to avoid the neutron pulse perturbation
- Use of a slow Radiation-to-Light Convertor
- **Dump all the parasitic charge** with a global reset feature
- Only perform **critical operations** (ADC, data transmission) after the neutron pulse

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![Diagram](Image)

**Lasers on Target**

- **Neutron pulse**
  - $T_0 + 100\text{ps}$

- **Slow decay X-ray scintillator**
  - GLOBAL RST
  - $+1\mu\text{s}$

- Image acquisition and read-out
ICF X-ray Plasma Diagnostic Demonstrator: Results

Expected result (simulation)  Without “global reset” mode  With “global reset” mode

- No SEE, no functionality loss:
  - full camera design robust to several $10^{18}$ cm$^{-2}$s$^{-1}$
- GR mode efficiently removes the neutron induced parasitic signal
- Ability of CIS based camera to capture an image at such a high neutron flux demonstrated
Displacement Damage (DD) effects
Displacement Damage (DD) Effects on CIS

- **DD** = result of non-ionizing interactions leading to displacement of silicon atoms
- Contrary to TID, DD effects exhibit an almost universal behavior in silicon based detectors and sensors
  - DD effects can be anticipated accurately in most CIS
  - DD effects can be “modulated” by design optimization…
  - …but not really mitigated by design

Courtesy of Antoine JAY (ISAE-SUPAERO)
A. Jay, IEEE NSREC 2016
DD effects lead to the creation of SRH centers
- Can act as generation/recombination centers or as charge trap

Main effects originating from the photodiodes:
- Dark current increase (defect x in depletion region)
- Possible quantum efficiency reduction due to recombination centers x (usually not observed)

Not considered:
- Charge trapping: no proven effect in CIS
- Type inversion*: not likely in CIS for typical fluences (<10^{14} n/cm²)

*M. Moll PhD. Thesis, 1999
Displacement Damage Induced Dark Current Increase

- **Dark frame** no irradiation
- **Neutron irradiation** (DD effects only)
- **$^{60}$Co $\gamma$-ray irradiation** (TID effects only)

**Graph:**
- **X-axis:** Dark current (fA)
- **Y-axis:** Frequency (arbitrary unit)
- **Labels:** Before irradiation, After 22 MeV neutron irradiation

**Observations:**
- Uniform gray level increase
- Non-uniform degradation (hot pixels)
Displacement Damage Effects on CIS: Universal Damage Factor

- Srour et al. 2000* Universal Damage Factor applied to CIS

\[ \Delta I_{obs} = q \cdot K \cdot V_{dep} \cdot D_{dd} \]

- No fitting parameter
- At 23°C: \( K = 1.4 \pm 0.5 \text{ cm}^{-3} \cdot \text{s}^{-1} \cdot (\text{MeV/g})^{-1} \)
- Verified on CIS from many foundries up to \( 10^{13} \text{ n/cm}^2 \)

Displacement Damage Effects on CIS: Empirical Prediction Model*

- **Exponential dark current Probability Density Function (PDF)** for low doses and small volumes (one dark current source per pixel):
  \[ f_{\nu_{\text{dark}}}(x) = \frac{1}{\nu_{\text{dark}}} \exp \left( -\frac{x}{\nu_{\text{dark}}} \right) \]

- **Convolution** of the PDF at higher doses and larger volumes (superimposition of several dark current sources per pixel):
  \[ f_{\Delta I_{\text{obs}}}(x) = Poisson(k = 1, \mu) \times f_{\nu_{\text{dark}}}(x) + Poisson(k = 2, \mu) \times f_{\nu_{\text{dark}}}(x) \times f_{\nu_{\text{dark}}}(x) + \cdots \]
  \[ \mu = \gamma_{\text{dark}} \times V_{\text{dep}} \times DDD \]
  is the convolution parameter and represents the **mean number of sources per pixel**

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\*Virmontois et al., IEEE TNS, Aug. 2012
*Belloir et al., Optics Express, Feb. 2016
Displacement Damage Effects on CIS: Empirical Prediction Model

In the same way as the Universal Damage Factor, the two parameters of this empirical model $v_{\text{dark}}$ and $\gamma_{\text{dark}}$:  
- Appear to be constant for neutron/protons/ions of a few MeV to 500 MeV

In practice, this empirical model can be used to anticipate the absolute DD induced dark current distribution  
- Without any parameter adjustment

Parameter values

Average dark current per source

$u_{\text{dark}} \approx 5000 \text{ e}-/s \ @ \ 23^\circ\text{C}$

$\gamma_{\text{dark}} \approx \frac{1}{50,000} \mu\text{m}^{-3}\ (\text{TeV/g})^{-1}$

1 source per pixel for a dose of 500 TeV/g in a 100 $\mu\text{m}^3$ depleted volume

*Belloir et al., Optics Express, Feb. 2016*
Displacement Damage Effects on CIS: Empirical Prediction Model

Typical results of the prediction model:
- 4 CIS with 4 different pixel pitches (4.5 / 7 / 9 and 14 µm)
- At low ($3 \times 10^{10}$) and high ($4 \times 10^{12}$) fluence

*Belloir et al., Optics Express, Feb. 2016*
Displacement Damage (DD) Effects on CIS: A summary

- Main DD effects in CIS up to $10^{13}$-$10^{14}$ n/cm²:
  - Dark Current Increase

- DD induced Dark Current increase can be anticipated by using:
  - Srour Universal Damage Factor for the mean value
  - The presented empirical model for the full distribution

- These models can be used to optimize the design to modulate the effects (no real mitigation possible by design):
  - Small depletion volume $\rightarrow$ lower mean dark current, larger non-uniformities
  - Large depletion volume $\rightarrow$ higher mean dark current but less non-uniformity

System level mitigation: cooling!
Talk Summary

- **MGy-Grad Total Ionizing Dose effects on CIS**
  - Large dark current increase and MOSFET voltage shifts
  - All these effects can be partially mitigated by design
    - Use of ELT and conventional photodiode recommended

- **Radiation hardened CIS can provide useful images** after several MGy

- **High flux Single Event Effects (SEE) in CIS**:
  - Main issue: transient deposited parasitic charge (SET)
  - Other SEEs can be avoided by sensor or system design

- **CIS based camera can stand neutron flux up to** $10^{18}$ n.cm$^{-2}$.s$^{-1}$

- **High fluence displacement damage effects in CIS**
  - Main effect: dark current increase
  - Can be predicted up to $10^{14}$ n/cm$^2$ and mitigated at system level (e.g. cooling)
MGy-Grad Total Ionizing Dose effects on CIS
- Large dark current increase and MOSFET voltage shifts
- All these effects can be partially mitigated by design
  Use of ELTs

Radiation hardening after several MGY

High flux Single Event Effects (SEE) in CIS:
- Main issue: transient deposited parasitic charge (SET)
- Other SEEs can be avoided by sensor or system design
- CIS based camera can stand neutron flux up to $10^{18}$ n.cm$^{-2}$.s$^{-1}$

High fluence displacement damage effects in CIS
- Main effect: dark current increase
- Can be predicted up to $10^{14}$ n/cm$^2$ and mitigated at system level (e.g. cooling)

In a nutshell:
- The main issues (TID/SEE/DD) come from the photodiode
- CIS are a good choice for harsh radiation environments!
Thank you!

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