To cite this version: Pelamatti, Alice Estimation and Modeling of Key Design Parameters of Pinned Photodiode CMOS Image Sensors for High Temporal Resolution Applications. (2015) Institute Electronics Engineers. (IEEE)
Estimation and Modeling of Key Design Parameters of Pinned Photodiode CMOS Image Sensors for High Temporal Resolution Applications

Alice PELAMATTI

Under the direction of:
Pierre MAGNAN and V. GOIFFON (ISAE-SUPAERO)
Cédric VIRMONTOIS (CNES)
Olivier SAINT-PE’ and Michel BREART DE BOISANGER (Airbus Defence&Space)

17/11/2015
Estimation and Modeling of Key Design Parameters of Pinned Photodiode CMOS Image Sensors for High Temporal Resolution Applications

Alice PELAMATTI

Under the direction of:
Pierre MAGNAN and V. GOIFFON (ISAE-SUPAERO)
Cédric VIRMONTOIS (CNES)
Olivier SAINT-PE’ and Michel BREART DE BOISANGER (Airbus Defence&Space)

17/11/2015
High temporal resolution imaging applications

- Image sensors: measure light intensity reflected/emitted by a scene

- Some applications require a very high temporal resolution
  - Burst image sensors
    - Observation of extremely fast phenomena
  - Time of flight imagers
    - Generation of 3D images
      - Consumer applications
      - Altimetry
      - Security
      - Monitoring of production lines
      - Scientific applications
CMOS Image sensors (CIS)

- **Main technology for commercial imaging applications:**
  - Development driven by massive demand for consumer electronics (smart-phones, tablet ..)
    - Multibillion $ market
    - Annual technological breakthroughs

- **Outstanding performances thanks to the introduction of the Pinned Photodiode**
  - Originally invented for interline CCD detectors [1]
  - Very high sensitivity
  - Low noise
  - Speed
  - “Smart pixels”...

- **Good candidates for high temporal resolution imaging applications**

---

Structure and operation of Pinned Photodiodes (PPD) CIS
Structure and operation of Pinned Photodiodes (PPD) CIS
Structure and operation of Pinned Photodiodes (PPD) CIS
Structure and operation of Pinned Photodiodes (PPD) CIS

Transfer Gate (TG)

p+

V_{TG} V_{FD}

V_{DD}

RST

SEL

V_{pix}

PPD

N_{PPD}

h+ e-

Floating diffusion (FD)

P-epi
Structure and operation of Pinned Photodiodes (PPD) CIS

Based on a transfer of charge

- TG off mode: CHARGE INTEGRATION PHASE
  - PPD isolated from FD \rightarrow Collection of electrons
  - Collected charge: \( Q_{PPD} \propto N_{ph} \)
- TG on mode: RESET (and READOUT) PHASE
  - PPD connected to FD \rightarrow Transfer of electrons
  - Output signal: \( \Delta V_{FD} \propto Q_{PPD} \propto N_{ph} \)
Structure and operation of Pinned Photodiodes (PPD) CIS

- Based on a transfer of charge
- Very good signal-to-noise ratio
  - Low dark current
  - High sensitivity
  - Correlated Double Sampling (CDS)
- Temporal resolution = minimum sampling time
  - Bottleneck = time to transfer charge from PPD to FD
Where does this thesis come in?

Image sensor design flow:

- **Target Imaging Application**
  - High temporal resolution detector

- **Choice of the technology**
  - Pinned Photodiode CMOS Image Sensors

- **Design phase**
  - Modeling (simulations)
  - Design of test structures
  - Experimental validation (Meas.)

- **Fabrication**
  - Final design
  - Production
  - Assessment of performances (Meas.)

- **Operation**
Where does this thesis come in?

Image sensor design flow:

**Target Imaging Application**
- High temporal resolution detector

**Choice of the technology**
- Pinned Photodiode CMOS Image Sensors

**Design phase**
- Modeling (simulations)
- Design of test structures
- Experimental validation (Meas.)

**Fabrication**
- Final design
- Production
- Assessment of performances (Meas.)

**Operation**

Goal of this work: Development of analytical, numerical and experimental tools to predict how design and operation conditions will affect temporal resolution in PPDs.
Road Map

- **Step 1: Understanding the PPD physics**
  - Development and analysis of tools to estimate PPD key charge and potential levels

[Diagram showing PPD, TG, FD, and V]
**Road Map**

- **Step 1: Understanding the PPD physics**
  - Development and analysis of tools to estimate PPD key charge and potential levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Public literature (beginning of thesis)</th>
<th>Focus of this work</th>
</tr>
</thead>
</table>
| Pinning voltage ($V_{\text{pin}}$) | ▪ Characterization tools available  
  ✓ Provide non comparable values  
  ✓ Unclear physical definition of $V_{\text{pin}}$ | ▪ Comparative study on characterization tools  
  ▪ Discussion on physical meaning of $V_{\text{pin}}$ |
Road Map

- **Step 1: Understanding the PPD physics**
  - Development and analysis of tools to estimate PPD key charge and potential levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Public literature (beginning of thesis)</th>
<th>Focus of this work</th>
</tr>
</thead>
</table>
| **Pinning voltage** ($V_{pin}$) | - Characterization tools available
  - Provide non comparable values
  - Unclear physical definition of $V_{pin}$                                                           | - Comparative study on characterization tools
  - Discussion on physical meaning of $V_{pin}$                                                          |
| **Full Well Capacity** (FWC)     | - Mostly qualitative interpretations available but no real modeling                                    | - Analytical modeling of the FWC
  - Effect of experimental conditions
  - Identification of key value: the Equilibrium FWC
  - Dynamic behavior of the FWC                                                                           |
Road Map

- **Step 1: Understanding the PPD physics**
  - Development and analysis of tools to estimate PPD key charge and potential levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Public literature (beginning of thesis)</th>
<th>Focus of this work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinning voltage ($V_{pin}$)</td>
<td>▪ Characterization tools available                                                                     ▪ Comparative study on characterization tools</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Provide non comparable values                                                                        ▪ Discussion on physical meaning of $V_{pin}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Unclear physical definition of $V_{pin}$                                                             ▪ Analytical modeling of the FWC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Effect of experimental conditions</td>
<td></td>
</tr>
<tr>
<td>Full Well Capacity (FWC)</td>
<td>✓ Mostly qualitative interpretations available but no real modeling                                     ✓ Identification of key value: the Equilibrium FWC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Dynamic behavior of the FWC</td>
<td></td>
</tr>
</tbody>
</table>

- **Step 2: Estimating charge transfer time in PPDs**
  - Modeling: Montecarlo simulation (Matlab)
  - Measurement: new characterization tool based on Pulsed Storage Gate pixels
Road Map

- **Step 1: Understanding the PPD physics**
  - Development and analysis of tools to estimate PPD key charge and potential levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Public literature (beginning of thesis)</th>
<th>Focus of this work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinning voltage ($V_{pin}$)</td>
<td>- Characterization tools available&lt;br&gt;✓ Provide non comparable values&lt;br&gt;✓ Unclear physical definition of $V_{pin}$</td>
<td>- Comparative study on characterization tools&lt;br&gt;- Discussion on physical meaning of $V_{pin}$</td>
</tr>
<tr>
<td>Full Well Capacity (FWC)</td>
<td>✓ Mostly qualitative interpretations available but no real modeling</td>
<td>- Analytical modeling of the FWC&lt;br&gt;✓ Effect of experimental conditions&lt;br&gt;✓ Identification of key value: the Equilibrium FWC&lt;br&gt;✓ Dynamic behavior of the FWC</td>
</tr>
</tbody>
</table>

- **Step 2: Estimating charge transfer time in PPDs**
  - **Modeling**: Montecarlo simulation (Matlab)
  - **Measurement**: new characterization tool based on Pulsed Storage Gate pixels
Pinning voltage ($V_{\text{pin}}$)

- Pinning voltage = “PPD potential floor”
  - At $V_{\text{PPD}} = V_{\text{pin}}$ PPD is fully depleted
    - $V_{\text{pin}}$ = potential that must be applied to reach max $\Delta E_c$ from equilibrium conditions

- Key design parameter (involves several trade-offs)
  - Small $V_{\text{pin}}$:  
    - Less constraints on TG channel and FD potentials to ensure optimum transfer
  - Large $V_{\text{pin}}$:
    - Larger Full Well Capacity $\rightarrow$ larger dynamic range
Estimation of the pinning voltage

- Monitoring and estimation of the pinning voltage is important
  - During design of sensors and process development
  - For monitoring of production lines
    - $V_{\text{pin}}$ is very sensitive to variations of implantation process

- $V_{\text{pin}}$ estimation tools used in the CIS community:
  - Analytical models:
    - Offer a good understanding of the qualitative dependence of $V_{\text{pin}}$ on design parameters
    - But often too simple to predict real $V_{\text{pin}}$ values
  - TCAD simulations:
    - Valid estimation tool when exact geometry and technological details are known
  - Experimental measurements:
    - Different characterization tools based on in-pixel measurements or on test-structures
Estimation of the pinning voltage

- Monitoring and estimation of the pinning voltage is important
  - During design of sensors and process development
  - For monitoring of production lines
    - $V_{pin}$ is very sensitive to variations of implantation process

- $V_{pin}$ estimation tools used in the CIS community:
  - Analytical models:
    - Offer a good understanding of the qualitative dependence of $V_{pin}$ on design parameters
    - But often too simple to predict real $V_{pin}$ values
  - TCAD simulations:
    - Valid estimation tool when exact geometry and technological details are known
  - Experimental measurements:
    - Different characterization tools based on in-pixel measurements or on test-structures
Estimation of V_{pin}: TCAD simulations 1/3

- **TCAD simulations:**
  - Estimation of $V_{pin}$ from PPD charge vs. voltage behavior

- **$V_{pin}$ is a strong function of PPD geometry [1]**
  - 3D simulations are to be preferred for small pixels!

- **Simulation principle:**
  - Increasing $V_{inj}$ is applied to the FD with TG on
    - *Results in electrical injection of charge in the PPD until $V_{PPD}=V_{inj}$*
  - $V_{pin}$ can be estimated by monitoring $\Delta E_C$ as a function of $V_{inj}$

---

[1] Takeshita, IS&T/SPIE Electronic Imaging, 2010
Estimation of Vpin: TCAD simulations 2/3

- At $V_{PPD} = V_{inj} = 0V$ PPD is at equilibrium
Estimation of Vpin: TCAD simulations 2/3

- At $V_{PPD} = V_{inj} = 0V$ PPD is at equilibrium

Why is the PPD is at equilibrium?

EQUILIBRIUM: $I_{junc} = 0$ and $V_{PPD} = 0$

$V_{PPD}(V)$

$I_{junc}$

$\text{Equivalent circuit of simulated PPD pixel}$

$I-V$ characteristic of pn junction: Equilibrium is reached at $V_{PPD} = 0$
Estimation of $V_{pin}$: TCAD simulations 2/3

- At $V_{PPD} = V_{inj} = 0V$ PPD is at equilibrium
  - $Q_{PPD} = EFWC$ (Equilibrium FWC)

![Diagram showing electron injection and PPD]

![Graph showing $Q_{PPD} = EFWC$ vs $V_{inj}$]
Estimation of $V_{\text{pin}}$: TCAD simulations 2/3

- At $V_{\text{PPD}} = V_{\text{inj}} = 0\text{V}$ PPD is at equilibrium
  - $Q_{\text{PPD}} = \text{EFWC}$ (Equilibrium FWC)

- Initial linear decrease of $Q_{\text{PPD}}$ with $V_{\text{inj}}$
  - $C_{\text{PPD}}$ roughly constant in this region
    - $\Delta Q_{\text{PPD}} \sim C_{\text{PPD}} \times V_{\text{inj}}$
Estimation of $V_{pin}$: TCAD simulations 2/2

- At $V_{PPD}=V_{inj}=0V$ PPD is at equilibrium
  - $Q_{PPD}=EFWC$ (Equilibrium FWC)

- Initial linear decrease of $Q_{PPD}$ with $V_{inj}$
  - $C_{PPD}$ roughly constant in this region
    - $\Delta Q_{PPD} \sim C_{PPD} \times V_{inj}$

- PPD reaches its potential floor at $V_{inj}=V_{pin}$
Estimation of $V_{\text{pin}}$: TCAD simulations 3/3

- But saying that the PPD is depleted does not imply that the PPD is empty!
  - At $V_{\text{inj}} = V_{\text{pin}}$, $Q_{\text{PPD}}$ not zero yet!
    - due to thermionic emission from TG channel
Estimation of \( V_{\text{pin}} \): TCAD simulations 3/3

- But saying that the PPD is depleted does not imply that the PPD is empty!
  - At \( V_{\text{inj}} = V_{\text{pin}} \) \( Q_{\text{PPD}} \) not zero yet!
    - due to thermionic emission from TG channel
- PPD is “empty” for \( V_{\text{inj}} > V_{\text{pin}} \)
  - In public literature this point is not always clear.
Estimation of Vpin: Experimental measurements

- **In CIS community: no defined experimental standard**
  - Vpin is estimated with a multitude of custom developed tools
- **In this work:** Comparative study on main $V_{pin}$ estimation methods

- A. Pelamatti et al., IISW 2015
- A. Pelamatti et al., IEEE JEDS(under rev.)
Estimation of Vpin: Experimental measurements

- In CIS community: no defined experimental standard
  - Vpin is estimated with a multitude of custom developed tools
- In this work: Comparative study on main $V_{pin}$ estimation methods

$V_{pin}$ characterization tools

In-pixel measurements

On full PPD CIS arrays [1]

- A. Pelamatti et al., IISW 2015
- A. Pelamatti et al., IEEE JEDS(under rev.)

Estimation of Vpin: Experimental measurements

- **In CIS community: no defined experimental standard**
  - Vpin is estimated with a multitude of custom developed tools
- **In this work: Comparative study on main V\textsubscript{pin} estimation methods**

V\textsubscript{pin} characterization tools

In-pixel measurements
On full PPD CIS arrays [1]

Electrical measurements on test structures (isolated/arrays)

- A. Pelamatti et al., IISW 2015
- A. Pelamatti et al., IEEE JEDS(under rev.)

Estimation of $V_{\text{pin}}$: Experimental measurements

- **In CIS community: no defined experimental standard**
  - $V_{\text{pin}}$ is estimated with a multitude of custom developed tools
- **In this work:** Comparative study on main $V_{\text{pin}}$ estimation methods

- **In-pin measurements**
  - On full PPD CIS arrays [1]

- **V$_{\text{pin}}$ characterization tools**

- **Electrical measurements on test structures (isolated/arrays)**
  - I-V measurements on **JFET structures** implemented with PPD implants [2-3]
  - C-V measurements on PPD (or partially PPD) arrays [4]


- A. Pelamatti et al., IISW 2015
- A. Pelamatti et al., IEEE JEDS(under rev.)
Comparison of $V_{pin}$ characterization tools

<table>
<thead>
<tr>
<th>Pro&amp; Cons:</th>
<th>Principle</th>
<th>Real pixel env.</th>
<th>Cost (surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-pixel method [1]</td>
<td><img src="#" alt="Graph" /></td>
<td><img src="#" alt="Smiley" /></td>
<td><img src="#" alt="Emoticon" /></td>
</tr>
</tbody>
</table>

## Comparison of $V_{\text{pin}}$ characterization tools

<table>
<thead>
<tr>
<th>Pro &amp; Cons:</th>
<th>Principle</th>
<th>Real pixel env.</th>
<th>Cost (surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-pixel method [1]</strong></td>
<td><img src="image" alt="Pinning Voltage characteristic" /></td>
<td><img src="image" alt="Green smiley" /></td>
<td><img src="image" alt="Red sad" /></td>
</tr>
<tr>
<td>C-V method</td>
<td><img src="image" alt="C-V method diagram" /></td>
<td><img src="image" alt="Green smiley" /></td>
<td><img src="image" alt="Red sad" /></td>
</tr>
</tbody>
</table>


(*) Courtesy of A. Lahav (TowerJazz)
## Comparison of \( V_{\text{pin}} \) characterization tools

<table>
<thead>
<tr>
<th>Pro&amp; Cons:</th>
<th>Principle</th>
<th>Real pixel env.</th>
<th>Cost (surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-pixel method [1]</strong></td>
<td><img src="image" alt="Pinning Voltage characteristic" /></td>
<td><img src="image" alt="Emoticon" /></td>
<td><img src="image" alt="Emoticon" /></td>
</tr>
<tr>
<td><strong>C-V method</strong></td>
<td><img src="image" alt="C_(meas(F))" /></td>
<td><img src="image" alt="Emoticon" /></td>
<td><img src="image" alt="Emoticon" /></td>
</tr>
<tr>
<td><strong>JFET methods</strong></td>
<td><img src="image" alt="IDS vs VDS" /></td>
<td><img src="image" alt="Emoticon" /></td>
<td><img src="image" alt="Emoticon" /></td>
</tr>
</tbody>
</table>


(*) Courtesy of A. Lahav (TowerJazz)
Comparison of $V_{\text{pin}}$ characterization tools

<table>
<thead>
<tr>
<th>Pro&amp; Cons:</th>
<th>Principle</th>
<th>Real pixel env.</th>
<th>Cost (surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-pixel method [1]</strong></td>
<td><img src="image1" alt="Pinning Voltage characteristic" /></td>
<td><img src="#" alt="Green" /></td>
<td><img src="#" alt="Red" /></td>
</tr>
<tr>
<td><img src="image2" alt="In-pixel method" /></td>
<td>$Q_{\text{inj}}$ (ke$^-$)</td>
<td>$V_{\text{inj}}$ (V)</td>
<td>$V_{\text{pin}}$</td>
</tr>
<tr>
<td><strong>C-V method</strong></td>
<td><img src="image3" alt="C-V Characteristic" /></td>
<td><img src="#" alt="Green" /></td>
<td><img src="#" alt="Red" /></td>
</tr>
<tr>
<td><img src="image4" alt="C-V method" /></td>
<td>$C_{\text{meas}}$ (F)</td>
<td>$V_{\text{meas}}$ (V)</td>
<td>$V_{\text{pin}}$ (*)</td>
</tr>
<tr>
<td><strong>JFET methods</strong></td>
<td><img src="image5" alt="JFET Characteristic" /></td>
<td><img src="#" alt="Green" /></td>
<td><img src="#" alt="Red" /></td>
</tr>
<tr>
<td><img src="image6" alt="JFET methods" /></td>
<td>$I_{\text{DS}}$ (A)</td>
<td>$V_{\text{SG}}$ (V)</td>
<td>$V_{\text{pin}}$</td>
</tr>
</tbody>
</table>

- **It is suggested to combine:**
  - In pixel measurements [1]
  - Standard JFET pinch-off voltage measurements such as the square root method [2]
    - Only JFET-method which provides absolute and comparable $V_{\text{pin}}$ values

---


(*) Courtesy of A. Lahav (TowerJazz)
Road Map

- **Step 1:** Understanding the PPD physics
  - Development and analysis of tools to estimate PPD key charge and potential levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Public literature (beginning of thesis)</th>
<th>Focus of this work</th>
</tr>
</thead>
</table>
| Pinning voltage \((V_{\text{pin}})\) | - Characterization tools available  
  ✓ Provide non comparable values  
  ✓ Unclear physical definition of \(V_{\text{pin}}\) | - Comparative study on characterization tools  
  - Discussion on physical meaning of \(V_{\text{pin}}\) |
| Full Well Capacity (FWC) | ✓ Mostly qualitative interpretations available but no real modeling | - Analytical modeling of the FWC  
  ✓ Effect of experimental conditions  
  ✓ Identification of key value: the Equilibrium FWC  
  ✓ Dynamic behavior of the FWC |

- **Step 2:** Estimating charge transfer time in PPDs
  - Modeling: Montecarlo simulation (Matlab)  
  - Measurement: new characterization tool based on Pulsed Storage Gate pixels
Full Well Capacity (FWC)

- Full Well Capacity (FWC) = max # of electrons that can be stored on $C_{PPD}$
  - If the output range is not limited by readout electronics (or ADC),
    - the saturation of output signal corresponds to the FWC
- Except for a few publications [1-2], the FWC is usually considered as a fixed PPD parameter

![Graph showing Full Well Capacity over normalized integration time.](image)
**Full Well Capacity (FWC)**

- As shown in this work the FWC depends on experimental conditions:
  - Photon flux $\Phi_{ph}$
  - Temperature $T$
  - TG biasing during integration (VLOTG)

![Graph showing FWC](image)

- $V_{LOTG} = -0.4V$
- $V_{LOTG} = +0.3V$
- Higher photon flux
- Lower temperature
- Dark, $V_{LOTG} = +0.3V$
- Dark


Modeling of the FWC

- **Main PPD current contributions:**
  1. Current of pn junction:
     \[ I_{\text{junc}} = I_{\text{sat}} \left( 1 - e^{-\frac{V_{\text{PPD}}}{nV_{\text{th}}}} \right) \]
  2. Photo-current:
     \[ I_{\text{ph}} = \eta \Phi_{\text{ph}} \]
  3. TG sub-threshold current
     \[ I_{\text{sub}} = f(V_{\text{LOTG}}) \]

- **FWC is reached when no more current can charge** \( C_{\text{PPD}} \)
  - Open circuit condition \((I_{\text{tot}} = 0 \text{ and } V_{\text{PPD}} = V_{\text{FW}})\)

- **It can be modeled as:**

\[
\text{FWC} = \frac{1}{q} \int_{V_{\text{FW}}}^{V_{\text{pin}}} C_{\text{PPD}}(V_{\text{PPD}}) dV_{\text{PPD}} \sim \frac{1}{q} C_{\text{PPD}} (V_{\text{pin}} - V_{\text{OC}})
\]

Max \( V_{\text{PPD}} \) reached after reset

Min \( V_{\text{PPD}} \) reached at full well
Equilibrium FWC (EFWC)

- In the dark, with $V_{LOTG} < 0$
  \[ I_{tot} = I_{junc} \Rightarrow \text{PPD discharged only by dark current} \]
Equilibrium FWC (EFWC)

- In the dark, with $V_{LOTG} < 0$

  $I_{tot} = I_{junc} \rightarrow$ PPD discharged only by dark current
Equilibrium FWC (EFWC)

- In the dark, with $V_{LOTG} < 0$
  - $I_{tot} = I_{junc} \rightarrow$ PPD discharged only by dark current
  - Like in standard p-n junction, equilibrium is reached at $V_{FW} = 0$

$$\text{EFWC} = \frac{1}{q} \int_0^{V_{pin}} C_{PPD}(V_{PPD}) \, dV_{PPD} \sim \frac{1}{q} C_{PPD} V_{pin}$$

- Important reference value:
  - Sole FWC value which only depends on PPD parameters

Pelamatti *IEEE EDL, 2013*
FWC behavior under illumination 1/2

- Under illumination, $V_{\text{LOTG}} < 0$
  $$I_{\text{tot}} = I_{\text{junc}} - I_{\text{ph}}$$
  - The photo-current results in a vertical shift of the $I_{\text{tot}}$-$V_{\text{PPD}}$ curve

\[\text{Diagram showing the components and equations related to FWC behavior under illumination.}\]
FWC behavior under illumination 1/2

- Under illumination, \( V_{\text{LOTG}} < 0 \)
  \[
  I_{\text{tot}} = I_{\text{junc}} - I_{\text{ph}}
  \]
  - The photo-current results in a vertical shift of the \( I_{\text{tot}} - V_{\text{PPD}} \) curve
FWC behavior under illumination 1/2

- Under illumination, $V_{\text{LOTG}} < 0$
  
  $$I_{\text{tot}} = I_{\text{junc}} - I_{\text{ph}}$$

  - The photo-current results in a vertical shift of the $I_{\text{tot}}$-$V_{\text{PPD}}$ curve

- Open circuit condition ($I_{\text{tot}} = 0$) is reached for $V_{\text{FW}} < 0$
  
  - Under illumination $\text{FWC} > \text{EFWC}$ (if TG leakage is negligible)
  - PPD becomes forward biased to reach open circuit condition!

![Diagram of FWC behavior under illumination](image)
FWC behavior under illumination 2/2

- The FWC can be expressed as:
  \[
  FWC(\Phi_{ph}) = EFWC + \frac{1}{q} C_{PPD} n v_{th} \ln \left[ 1 + \frac{I_{ph}(\Phi_{ph})}{I_{sat}} \right]
  \]

- The FWC is a logarithmic function of \( \Phi_{ph} \)
  - It depends on the signal intensity!
FWC behavior under illumination 2/2

- The FWC can be expressed as:
  \[
  FWC(\Phi_{ph}) = EFWC + \frac{1}{q} C_{PPD} n_{th} \ln \left[ 1 + \frac{I_{ph}(\Phi_{ph})}{I_{sat}} \right]
  \]

- The FWC is a logarithmic function of \( \Phi_{ph} \)
  - It depends on the signal intensity!

- Consequence:
  - If the transfer function is measured at a constant integration time and increasing \( \Phi_{ph} \) the curve never saturates
FWC behavior under illumination 2/2

- The FWC can be expressed as:

\[ FWC(\Phi_{ph}) = EFWC + \frac{1}{q} C_{PPD} n_{th} \ln \left[ 1 + \frac{I_{ph}(\Phi_{ph})}{I_{sat}} \right] \]

- The FWC is a logarithmic function of \( \Phi_{ph} \)
  - It depends on the signal intensity!

**Consequence:**

- If the transfer function is measured at a constant integration time and increasing \( \Phi_{ph} \) the curve never saturates

The faster we pour … the larger the glass!
What happens if the PPD is at full well and we turn-off the light?

Equivalent PPD circuit
FWC in non-stationary illumination conditions

- What happens if the PPD is at full well and we turn-off the light?

![Equivalent PPD circuit diagram]

\[ V_{PPD} < 0 \]

\[ I_{TOT} \]

Reverse bias

EFWC

Forward bias

FWC

\[ V_{pin} \]

\[ V_{PPD(V)} \]

\[ I_{junc} \]

\[ I_{junc} + I_{ph}(\Phi_{ph}) \]

\[ v_{FW} < 0 \]
FWC in non-stationary illumination conditions

- What happens if the PPD is at full well and we turn-off the light?
FWC in non-stationary illumination conditions

- What happens if the PPD is at full well and we turn-off the light?

![Equivalent PPD circuit](image)

**Equivalent PPD circuit**

- **Reverse bias**
- **Forward bias**

**Graph**

- **V**<sub>PPD(V)</sub>
- **V**<sub>pin</sub>
- **I**<sub>junc</sub>
- **I**<sub>TOT</sub>
- **QPPD(e⁻)**
- **V**<sub>FW=0</sub>

EQUILIBRIUM
FWC in non-stationary illumination conditions

- What happens if the PPD is at full well and we turn-off the light?
  - The PPD tends to a new equilibrium condition ... how fast?
FWC in non-stationary illumination conditions

- What happens if the PPD is at full well and we turn-off the light?
  - The PPD tends to a new equilibrium condition … how fast?


FWC transient: QPPD is sampled at an increasing delay from the light step
**FWC in non-stationary illumination conditions**

- **What happens if the PPD is at full well and we turn-off the light?**
  - The PPD tends to a new equilibrium condition ... how fast?

- **Consequences:**
  - If a target application involves non-stationary illumination:
    - the PPD must be sized to ensure that \( Q_{PPD} < EFWC \)
    - Otherwise the measured signal will depend on the sampling instant!

---


**FWC transient:** QPPD is sampled at an increasing delay from the light step
Effect of temperature on the FWC
Effect of temperature on the FWC

- It can be shown that $V_{\text{pin}}$ increases with temperature [1]
- Since $\text{EFWC}(T) \sim \frac{1}{q} C_{PPD} V_{\text{pin}}(T)$ it also increases with temperature

Effect of temperature on the FWC

- It can be shown that $V_{\text{pin}}$ increases with temperature [1]
- Since $\text{EFWC}(T) \sim \frac{1}{q} C_{\text{PPD}} V_{\text{pin}}(T)$ it also increases with temperature
- Under illumination the FWC can increase or decrease with temperature:

$$\text{FWC}(\Phi_{\text{ph}}, T) = \text{EFWC}(T) + \frac{1}{q} C_{\text{PPD}} n_{\text{th}} \ln \left[ 1 + \frac{I_{\text{ph}}(\Phi_{\text{ph}})}{I_{\text{sat}}(T)} \right]$$

It can be shown that \( V_{pin} \) increases with temperature [1].

Since \( \text{EFWC}(T) \sim \frac{1}{q} C_{PPD} V_{pin}(T) \) it also increases with temperature.

Under illumination the FWC can increase or decrease with temperature:

\[
\text{FWC}(\Phi_{ph}, T) = \text{EFWC}(T) + \frac{1}{q} C_{PPD} n v_{th} \ln \left[ 1 + \frac{I_{ph}(\Phi_{ph})}{I_{sat}(T)} \right]
\]

**Consequences:**
- The temperature behavior of the FWC depends on the illumination level!
- In particular it is determined by the ratio 
  \[
  \frac{I_{ph}(\Phi_{ph})}{I_{sat}(T)}
  \]

Effect of $V_{LOTG}$ on the FWC

- $V_{LOTG}$ during operation depends on the target application
  - Accumulation mode ($V_{LOTG}<0$): reduction of dark current [1]
  - Depletion mode ($V_{LOTG}>0$): implementation of anti-blooming function
- As addressed in the literature, the FWC variation with $V_{LOTG}$ have been reported in the literature [1-3]

Effect of $V_{\text{LOTG}}$ on the FWC

- $V_{\text{LOTG}}$ during operation depends on the target application
  - Accumulation mode ($V_{\text{LOTG}}<0$): reduction of dark current [1]
  - Depletion mode ($V_{\text{LOTG}}>0$): implementation of anti-blooming function
- As addressed in the literature, the FWC variation with $V_{\text{LOTG}}$ have been reported in the literature [1-3]
- The model developed in this work allows prediction of FWC variations with $V_{\text{LOTG}}$ both in the dark and under illumination

\[ \text{FWC} = \text{EFWC} \]

\[ -\Delta \text{FWC} \propto V_{\text{LOTG}} \]

Example of model validation in dark conditions

Road Map

- **Step 1: Understanding the PPD physics**
  - Development and analysis of tools to estimate PPD key charge and potential levels

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Public literature (beginning of thesis)</th>
<th>Focus of this work</th>
</tr>
</thead>
</table>
| Pinning voltage ($V_{\text{pin}}$) | - Characterization tools available  
  - Provide non comparable values  
  - Unclear physical definition of $V_{\text{pin}}$                                           | - Comparative study on characterization tools  
  - Discussion on physical meaning of $V_{\text{pin}}$                                         |
| Full Well Capacity (FWC) | - Mostly qualitative interpretations available but no real modeling                                   | - Analytical modeling of the FWC  
  - Effect of experimental conditions  
  - Identification of key value: the Equilibrium FWC  
  - Dynamic behavior of the FWC                                                                |

- **Step 2: Estimating charge transfer time in PPDs**
  - **Modeling:** Montecarlo simulation (Matlab)  
  - **Measurement:** new characterization tool based on Pulsed Storage Gate pixels
Goal: modeling charge transfer to predict temporal resolution

In large PPD pixels potential is mainly flat

- Main charge transport mechanism = thermal diffusion

Charge transfer can be modeled:

A. With numerical solution of diffusion equations
B. Random walk (RW) of single carriers in the PPD

In small PPD pixels other effects such as charge drift due to fringing fields and electrostatic repulsion should also be taken into account

- TCAD simulations are often to be preferred
In this work: development of a Montecarlo model of the RW of single carriers in the PPD

- Electrons are initially located at the end of the PPD
- The model estimates the time to transfer each electron to the FD
Charge Transfer Inefficiency and transfer time

- Transfer time can vary of several orders of magnitude!
  - But if charge transfer is not a deterministic process…
    - *What do we refer to by “transfer time”?*
Charge Transfer Inefficiency and transfer time

- Transfer time can vary of several orders of magnitude!
  - But if charge transfer is not a deterministic process…
    - *What do we refer to by “transfer time”?*

- First solution: estimate Charge Transfer Inefficiency (CTI) instead
  - Measures the ability (on average) of transferring $Q_{PPD}$

\[
CTI = 1 - \frac{Q_{out}}{Q_{PPD}}
\]
Charge Transfer Inefficiency and transfer time

- Transfer time can vary of several orders of magnitude!
  - But if charge transfer is not a deterministic process…
    - What do we refer to by “transfer time”?

- First solution: estimate Charge Transfer Inefficiency (CTI) instead
  - Measures the ability (on average) of transferring $Q_{PPD}$

$$CTI = 1 - \frac{Q_{out}}{Q_{PPD}}$$

- But if we really need to estimate the “transfer time” to size a device?
  - Transfer time could be defined as the minimum TG “ON time” to reach a given CTI
Montecarlo simulation: Effect of PPD length on CTI

- Simulation of charge transfer, **main observations:**
  - Increasing the PPD length results in a shift of the CTI curve
  - The transfer time increases as the square of the PPD length

![Graph showing the effect of PPD length on CTI](image-url)

CTI simulated for ≠ PPD lengths ($L_{PPD}$)

Random walk of single e-

Reflecting wall

Absorbing well

Transfer time vs. PPD length (μm)

Quadratic fit $y = x^2$
Experimental measurements: How to fairly compare CTI?

- Difficult to compare CTI in pixels with different size and geometries
  - Different initial charge level and initial charge distribution

- In this work: measurements of CTI on pulsed Storage-Gate (SG) pixels
  1. Allows reproduction of a worst case transfer condition
  2. CTI measured for same initial $Q_{PPD}$
  3. Transfer time is swept by changing delay between TG and SG edges
     - Does not require very short TG pulses
Experimental results: effect of PPD length

- **Device under test:**
  - Small arrays of rectangular SG pixels
  - With different PPD lengths (same PPD width=5µm)
  - 0.18µm PPD CIS commercial technology
Experimental results: effect of PPD length

- **Device under test:**
  - Small arrays of rectangular SG pixels
  - With different PPD lengths (same PPD width=5µm)
  - 0.18µm PPD CIS commercial technology

- **Experimental Results:**
  - Same CTI length dependence as in simulations (increases with $L_{PPD}^2$)
Experimental results: effect of PPD length

- **Device under test:**
  - Small arrays of rectangular SG pixels
  - With different PPD lengths (same PPD width=5µm)
  - 0.18µm PPD CIS commercial technology

- **Experimental Results:**
  - Same CTI length dependence as in simulations (increases with $L_{PPD}^2$)
  - Transfer time is almost 2 orders of magnitude larger than predicted by diffusion equations!
Proposed explanation: potential obstacles

- As suggested in the literature [1-4] poor CTI can be explained by ‘potential obstacles’
  - Located along the charge transfer path (potential barrier/pocket)
  - Electrons can therefore:
    - “cross” the barrier by **thermionic emission**
    - or “bounce” on the barrier
  - The probability of crossing is a function of the barrier height ($\propto e^{-\Phi_b}$)

- **Montecarlo Simulations:**
  - Increasing $\Phi_b$ can result in transfer time worsening of several orders of magnitude

Potential obstacles: Effect of $V_{\text{HITG}}$

- **TCAD simulations:**
  - Potential barrier is reduced by increasing $V_{\text{HITG}}$

- **Experimental Results:**
  - Improvement of CTI with increasing $V_{\text{HITG}}$
    - even at typical TG biasing levels!
  - Confirms the hypothesis that in the tested structure charge transfer is limited by potential obstacles
What can we do?

- Due to potential obstacles, thermal diffusion is too slow to target high temporal resolution on large pixels
  - Charge transfer must be enhanced!

- In the literature, charge transfer is accelerated with two different approaches:
  1. Generation of a drift field
     - By geometrical modulation [1]
     - By doping modulation [2]
     - By lateral gates [3]
  2. Introduction of a collection well close to the TG [4]
     - Results in a smaller transfer length
     - Suitable when a large collection area (but a small dynamic range) are needed

---

Conclusion

- Focus of this thesis: Development of a toolbox for the modeling and estimation of PPD key parameters for high temporal resolution applications

1. Estimation of the pinning voltage:
   - Example of extraction of $V_{\text{pin}}$ from TCAD simulations
     - PPD is not empty at $V_{\text{PPD}} = V_{\text{pin}}$
   - Experimental measurement of $V_{\text{pin}}$
     - In this work it is suggested to couple In-pixel methods and standard JFET pinch-off voltage estimation methods

2. Analytical model of the FWC:
   - The EFWC is the sole FWC values which only depends on $V_{\text{pin}}$
     - The EFWC can be a useful reference value to study the PPD physics [1-5]
     - FWC values are meaningless unless experimental conditions are specified!

3. Modeling and measurement of charge transfer time:
   - Montecarlo simulation of the random walk of single carriers
     - Takes also into account the effect of potential obstacles
   - Measurement of CTI baes on a Storage Gate method
     - Allows estimation of CTI with same initial charge level, whichever the PPD geometry

Outlook

What next?

- The results of this work emphasized the need to define standard estimation tools for the estimation PPD parameters
  - to provide comparable $V_{pin}$ and FWC values
- Modeling of charge transfer:
  - Improvement of the Montecarlo model to take into account $V_{PPD}$ variations during transfer
    - iterative re-calculation of $V_{PPD}$ such as in [1]
- CTI measurements:
  - The pulsed SG method should be validated
    - on larger pixel arrays
    - to compare more exotic PPD geometries
- Estimation of the CVF is also a critical point
  - Existing tools have been developed for CCDs and 3T APS
  - They are not always suitable to estimate the CVF in PPD CIS

[1] Han, TED, 2015
Acknowledgments

I would like to thank...

- **ISAE, CNES** and **Airbus Defence&Space** for supporting this thesis.

- **Pierre MAGNAN** and **Vincent GOIFFON** for giving me the opportunity to start this Ph.D. thesis and for teaching along this journey.

- **Cédric VIRMONTOIS** (CNES), **Olivier SAINT-PE** (AD&S) and **Michel BREART DE BOISANGER** (AD&S), for following my Ph.D. work during these 3 years.

- **Aziouz CHABANE**, **Paola CERVANTES** and **Barbara AVON**, for helping me during the development of the experimental set-up.

- My **Ph.D. fellows**, for the charming company and for the infinite discussions on the philosophy of the p-n junction.

- All my colleagues from **CIMI** for helping along the way.

- **Eleanor HUDSON** and **my mother**, for their invaluable help in the correction and translation of the manuscript.
Thank you for your attention!