Time-of-Flight sensors in standard CMOS technologies

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ToF sensors in standard CMOS technologies

Outline

- Context & Motivation
- Research hypotheses & Objectives
- Methodology
- Achievements & Current results
- Future Work
Objective of the thesis → fabrication of a ToF camera in standard CMOS technology
   ▶ ToF camera → recording of 3D scene
   ▶ Standard CMOS technology → Cheap technology for integrated circuits fabrication
Time-of-Flight (ToF) sensors are image sensors that capture the 3D information of a scene by measuring the time a light signal needs to travel back and forth to the target.

Range sensor applications include safety, healthcare, robotics, virtual or augmented reality, automotive,…

3D sensors technologies
- Triangulation
  - Stereo vision
  - Structured-Light
- Time-of-Flight
Stereo vision

- Disparity of the object position in two different cameras
- Advantages
  - Low cost implementation
  - Similar to human vision → well-suited for capturing images to humans
- Disadvantages
  - Correspondence problem → Computational intensive

\[ y = \frac{x}{\tan \alpha} + \frac{1}{\tan \beta} \]
Structured light

- Projection of known pattern of light
- Advantage
  - Relatively high spatial resolution
- Disadvantage
  - Need of successive projections of patterns → Low frame rate

3D sensors technologies

Time-of-Flight

- Time delay of a light signal reflected from the scene

Advantages
- Not dependent on mechanical alignment
- Mechanically compact

Disadvantages
- Specific hardware cameras needed

Figure: J. Illade-Quinteiro et al., “Four-transistor pinned photodiodes in standard technologies for time-of-flight sensors”, SST, Vol. 30, No. 4, 2015
## Context & Motivation

### 3D sensors technologies

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<th>Structured light</th>
<th>Time-of-flight</th>
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<td>HIGH</td>
<td>MEDIUM</td>
<td>LOW</td>
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<td>Material cost</td>
<td>LOW</td>
<td>HIGH</td>
<td>MEDIUM</td>
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<td>Compactness</td>
<td>LOW</td>
<td>HIGH</td>
<td>LOW</td>
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<tr>
<td>Response time</td>
<td>MEDIUM</td>
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<td>FAST</td>
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<td>Depth accuracy</td>
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<td>HIGH</td>
<td>MEDIUM</td>
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<td>Low-light performance</td>
<td>WEAK</td>
<td>GOOD</td>
<td>GOOD</td>
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<tr>
<td>Bright-light performance</td>
<td>GOOD</td>
<td>WEAK</td>
<td>GOOD</td>
</tr>
<tr>
<td>Power consumption</td>
<td>LOW</td>
<td>MEDIUM</td>
<td>SCALABLE</td>
</tr>
<tr>
<td>Range</td>
<td>LIMITED</td>
<td>SCALABLE</td>
<td>SCALABLE</td>
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Leap Motion → Triangulation
- Up to 2 feet (0.6 m)
- 2 IR cameras

https://learn.sparkfun.com/tutorials/leap-motion-teardown
Google Project Tango → Structured light
- 0.5 m – 4 m
- 4 MP 2µm RGB-IR pixel sensor

https://www.google.com/atap/projecttango/#project
Context & Motivation

Commercial examples

- Intel RealSense → Structured light
  - 0.2 m – 1.2 m
  - 1080p RGB-IR
Microsoft Kinect → Time-of-Flight
- 0.8 m – 4.2 m
- 512x424 pixels
Research hypotheses & Objectives

- ToF measurement technique
- Conventional image sensor pixels
  - Silicon photosensors
  - 3-Transistors (3T) pixel
  - 4-Transistors (4T) pixel
- 4T pixel for ToF
- 4T pixel in standard CMOS technology
Time-of-Flight sensors measure the time a light signal needs to travel back and forth to the target

\[ L = \frac{c}{2} T_{oF} \]

The light signal can be
- continuous modulated wave
- discrete pulses

We will center this presentation in the pulsed ToF

The maximum measurable distance depends on the light pulse \((T_p)\)

\[ L_{MAX} = \frac{c}{2} T_p \]
The maximum measurable distance depends on the light pulse ($T_p$)

\[
L_{\text{MAX}} = \frac{c}{2} T_p
\]

- For $T_p=50$ ns $\rightarrow L_{\text{max}}=7.5$ m
  - Larger $T_p$ reduces $L_{\text{max}}$
  - Shorter $T_p$ are difficult to sense (photosensors too slow)

Signal light power reaching the pixel is usually very low
- Because light source must satisfy eye safety regulations
- Example:
  - Light signal reflected from a distance of 1 m $\rightarrow P=9$ pW/µm² $\rightarrow \sim 2$ photons/µm² (in 50 ns)
  - Room well illuminated (1000 lux) $\rightarrow \sim 9.9$ photons/µm² (in 50 ns) $\rightarrow$ Shot noise $\sim 3.1$ photons/µm²
- Solution: accumulation of the measurement over several pulses
Three parameters are unknown in the reflected signal reaching the camera → at least three measurements per pulse needed

- Time-of-Flight ($T_{of}$)
- Light power of the signal (A)
- Light power of the background (B)
Research hypotheses & Objectives
ToF measurement technique

\[ x_1 = BT_p + A(T_p - T_{OF}) \]
\[ x_2 = BT_p + AT_{OF} \]
\[ x_3 = BT_p \]

\[ L = \frac{c}{2} T_p \frac{x_2 - x_3}{(x_1 - x_3) - (x_2 - x_3)} \]
Research hypotheses & Objectives
ToF measurement technique

- $T_p = 50$ ns $\rightarrow$ Pixel must have a fast response
- Received signal with low light power $\rightarrow$ Accumulation of multiple pulses
- 3 unknown parameters in the received signal $\rightarrow$ 3 measurements per pulse
Semiconductor materials have two different types of charge carriers
  ▶ Negatively charged electrons
  ▶ Positively charged holes

Pure silicon has the same density of electrons and holes in it

By doping the silicon with other elements it is possible to control the relation electron-hole
  ▶ N-doped silicon has a higher density of electrons
  ▶ P-doped silicon has a higher density of holes
Silicon for integrated circuits fabrication is usually lightly P-doped → P substrate

Photons reaching a silicon crystal can impact in an electron, liberating it from the crystal lattice → an electron-hole pair is created

Without an electric field the electron-hole pair ends up together in a recombination process
For the generation of the electric field a N-doped region (N well) is added over the P substrate → PN photodiode

- Around the PN junction an electric field is created
- The electric field separates the electron-hole pair
- The electrons are accumulated in the N well
The photogenerated electrons are accumulated in $V_{PD}$ node
At the beginning of the measurement the node is reset
The decrease in this node ($\Delta V_{PD}$) is proportional to the light intensity
Research hypotheses & Objectives

3T pixel

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Research hypotheses & Objectives
3T pixel

- Principal problems of 3T pixels
  - KTC noise → Thermal noise generated in $V_{PD}$
Research hypotheses & Objectives

3T pixel

- Principal problems of 3T pixels
  - KTC noise $\rightarrow$ Thermal noise generated in $V_{PD}$
  - Dark Current $\rightarrow$ electron-hole pairs generated in the silicon-oxide interface
Improve the 3T problems:

- KTC noise $\rightarrow$ addition of a Transmission Gate (TG) to perform CDS
- Dark Current $\rightarrow$ P$^+$ over N well
The photogenerated electrons are accumulated in $V_{PD}$ node
- At the beginning of the measurement $V_{FD}$ is reset
- At the end of the measurement charges are transferred from PD to FD
- Correlated double sampling (CDS) is performed
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Research hypotheses & Objectives

4T pixel for ToF

- $T_p = 50$ ns $\rightarrow$ Pixel must have a fast response

- Received signal with low light power $\rightarrow$ Accumulation of multiple pulses

- 3 unknown parameters in the received signal $\rightarrow$ 3 measurements per pulse
The TG control the transmission of the charges to the FD
After several accumulations the voltage in the FD is measured
Commercial PPD need a careful control of the doping concentrations
- Standard CMOS Technologies do not provide PPD 4T structures
- Design of P⁺ over Nwell with TG can be done violating layout rules
- To ensure correct behavior → Simulations with device-level simulator (ATLAS from Silvaco)
- 2-D simulations
- Parameters needed
  - Doping profiles
  - Horizontal Parameters
  - Vertical Parameters
Research hypotheses & Objectives

4T pixel in standard CMOS technology

- NWell-aligned PPD:

- P+-aligned PPD:

- NWell PD:
Achievements & Current results

- Simulation parameters estimation
- Geometrical parameters optimization
- Dark current comparison
- Reset noise analysis
- Transient response
Achievements & Current results
Geometrical parameters optimization

- Dark current (DC) effects:
  - Thermal DC
  - Surface DC
  - Band-to-band Tunneling DC
Achievements & Current results
Geometrical parameters optimization – X1 value

- Minimum value of 0.13 μm to ensure the correct biasing of the P⁺ layer
- Increasing X1 increases the area of the pixel but reduces the superficial DC generated in the NWell/Psub interface (red area)
- Selected optimum value: 0.3 μm
Achievements & Current results

Geometrical parameters optimization – X2 value

- A minimum distance of 0.12 μm necessary to provide a path between the photodiode and the TG for the photocharges transference.
- P+/NWell junction with both sides heavily doped ➔ Band-to-Band DC
- Decreasing X2 bring closer this junction and the NWell/Psub juncton ➔ increase in the curvature of the energy bands ➔ increase in the BTB-DC
- BTB-DC in this junction is the principal DC source of the NWell-aligned device
- Selected optimum value: 0.1 μm ➔ 40% of the total DC is generated by this BTB-DC
A minimum distance of 0.11 μm necessary to provide a path between the photodiode and the TG for the photocharges transference.

NWell under the TG with positive voltage → NWell operates in accumulation → behaves as being more doped → more BTB-DC

The BTB-DC is 6 orders of magnitude larger than in the other case

Commercial PPD 4T pixels probably use this structure but with a P layer under the TG to alleviate the BTB-DC:

I. Inoue et al., “Low-Leakage-Current and Low-Operating-Voltage Buried Photodiode for a CMOS Imager,”
The reset operation effects degrades the performance of the pixel

Only depends on the capacitance of the FD node → Equal for the 3 studied structure

Reset noise effects
  - Thermal noise (random)
  - Clock feedthrough (systematic)
  - Reset dependence with the illumination (systematic)
  - Leakage currents (systematic)

\[ \Delta V_{FDMAX} = 150 \text{ mV} \]

\[ V_{SWING,MAX} = \Delta V_{FDMAX} - \Delta V_{SYST,TOTAL} \]

Best case scenario

\[ \Delta L = \frac{L_{MAX}}{2\sqrt{2}} \frac{\Delta V_{THERMAL}}{V_{SWING,MAX}} \]
Thermal noise:

- Random movement of the electrons through the reset transistor

\[
\Delta V_{\text{thermal}} = \sqrt{\frac{kT}{C_{FD}}}
\]

\[
\Delta V_{\text{thermal}} \approx 7 \text{ mV} \quad \rightarrow \quad \Delta L \approx 7.07 \text{ cm}
\]
Achievements & Current results
Reset noise analysis

Clock feedthrough:
- Coupling of the $V_{\text{RESET}}$ signal and the $V_{FD}$ node through the $C_{gs}$ capacitance

$$\Delta V_{syst,clk} = \Delta V_g \frac{C_{gs}}{C_{gs} + C_{FD}}$$

<table>
<thead>
<tr>
<th>$W$ (µm)</th>
<th>$X_{FD}$ (µm)</th>
<th>$\Delta V_{syst,clk}$ (mV)</th>
<th>$\Delta L$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>133.1</td>
<td>62.76</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>121.5</td>
<td>37.22</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>103.4</td>
<td>22.76</td>
</tr>
<tr>
<td>0.5</td>
<td>2</td>
<td>69.6</td>
<td>13.19</td>
</tr>
<tr>
<td>0.25</td>
<td>2</td>
<td>36.15</td>
<td>9.32</td>
</tr>
</tbody>
</table>
Achievements & Current results
Reset noise analysis

- Dependence of the reset voltage with the illumination:
  - Initial reset voltage depends on the photogenerated current

<table>
<thead>
<tr>
<th>$I_{ph}$ (pA)</th>
<th>$\Delta V_{syst,light}$ (mV)</th>
<th>$\Delta L$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.5</td>
<td>7.09</td>
</tr>
<tr>
<td>500</td>
<td>1.4</td>
<td>7.14</td>
</tr>
<tr>
<td>2000</td>
<td>5.1</td>
<td>7.32</td>
</tr>
<tr>
<td>5000</td>
<td>11.2</td>
<td>7.64</td>
</tr>
</tbody>
</table>
Achievements & Current results
Reset noise analysis

- Leakage current:
  - Through the reset transistor flows some current even being cut off

\[ \Delta V_{syst,leakage} \leq 10 \, mV \rightarrow \Delta L \leq 7.57 \, \text{cm} \]
Achievements & Current results

Transient analysis

- Square light pulses are assumed for the ToF calculation
- The transmission of the electrons from the PD to the FD needs a finite amount of time
- This generates a deviation from square pulses
Achievements & Current results

Transient analysis

- **NWell-aligned PPD:**

- **NWell PD:**
Achievements & Current results

Transient analysis

- Deviation from the square signal

\[
I_{\text{signal}} = \begin{cases} 
I_m \left[ 1 - e^{-\frac{t}{\tau}} \right] & \text{if } 0 < t < T_p \\
I_m e^{-\frac{t}{\tau}} & \text{if } 0 < t < T_p \\
0 & \text{if } t < 0
\end{cases}
\]

\[
L_{\text{meas}} = \frac{L + L_{\text{max}} f(T_{OF})}{g(T_{OF})} \\
f(T_{OF}) = 1 + e^{-n} \left[ 1 - 2e^{\frac{n T_{OF}}{T_p}} \right] \\
g(T_{OF}) = 1 + e^{-n} \left[ 1 - e^{\frac{-n T_{OF}}{T_p}} \right]
\]

\[
n = \frac{T_p}{\tau}
\]
Achievements & Current results

Transient analysis

- Deviation from the square signal
Achievements & Current results

Publications

- Conferences:
Achievements & Current results

Publications

- Accepted publications:

- 7 months of internship in Fondazione Bruno Kessler (FBK), Trento, Italy

- This work has been partially funded by Spanish government projects TEC2009-12686 MICINN, TEC2012-38921-C02 MINECO (FEDER), Xunta de Galicia with EM2013/038, EM2014/012, AE CITIUS (CN2012/151, (FEDER)), GPC2013/040 (FEDER).

Future work

- Design of an appropriate pixel for ToF in CMOS standard technology
- Fabrication of the chip in 0.18 µm technology
- Test of the chip
- Defense of the thesis in the first trimester of 2016
Gracias por su atención

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