Kick-Off Interdisciplinary Workshop

CMOS photodetectors

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   CMOS sensors

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**Purpose:**

Convert light into detectable electronic signal

**Principle:**

Use photoelectric effect to ‘convert’ photons ($\gamma$) to photoelectrons (pe)

\[ E_\gamma = h\nu = \frac{hc}{\lambda} \]

Absorbed $\gamma$’s impart energy to electrons (e$^-$) in the material; If $E_\gamma = h\nu > E_g$, electrons are lifted to conductance band.

→ In a Si-photodiode, these electrons can create a photocurrent.
Photodetection

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Kick-Off Meeting, Barcelona, Jan 17-18, 2017

Remember:

\[ E [\text{eV}] \approx \frac{1239}{\lambda \text{[nm]}} \]

Silicon (1100 nm)

Cut-off limits of window materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Cut-off Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaF, MgF_2, LiF, CaF_2</td>
<td>100 nm</td>
</tr>
<tr>
<td>Quartz</td>
<td>250 nm</td>
</tr>
<tr>
<td>Normal borosilicate glass</td>
<td>400 nm</td>
</tr>
<tr>
<td>Normal window glass</td>
<td>550 nm</td>
</tr>
<tr>
<td></td>
<td>700 nm</td>
</tr>
<tr>
<td>Silicon (1100 nm)</td>
<td>850 nm</td>
</tr>
</tbody>
</table>
\( \alpha = 10^3 \text{cm}^{-1} \), means an 1/e optical power absorption length of \( 1/\alpha = 10^{-3} \text{cm} = 10 \mu\text{m} \)

\[
\text{Absorption length } \ell (\mu\text{m})
\]

\[
\begin{align*}
\text{Wavelength (nm)} & \quad 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \quad 800 \quad 900 \quad 1000 \quad 1100 \\
10^4 & \quad 10^3 \quad 10^2 \quad 10^1 \quad 10^0 \quad 10^{-1} \quad 10^{-2} \quad 10^{-3}
\end{align*}
\]

\( E_g \approx 1.147 \text{ eV} \)

\( \lambda_g \approx 1081 \text{ nm} \)

Atmospheric cutoff

\( -100 \degree \text{C} = 173 \text{ K} \)

\( 77 \text{ K} \)

\( 300 \text{ K} \)

Surface effects dominate

Transparency, interference are issues

(http://pdg.ge.infn.it/~deg/ccd.html)
High sensitivity, usually expressed as quantum efficiency

$$QE(\%) = \frac{N_{pe}}{N_\gamma}$$

or radiant sensitivity or responsivity $S$ (mA/W)

$$QE(\%) \approx 124 \cdot \frac{S(\text{mA/W})}{\lambda(nm)}$$

Good linearity: Output signal $\sim$ light intensity, over a large dynamic range

Fast time response: most photodiodes have a collection time of $\mu$s

Low intrinsic noise. A noise-free detector doesn’t exist. Thermally created photoelectrons represent the lower limit for the noise rate $\sim A_o T^2 \exp(-eW_{ph}/kT)$.

+ many more (size, fill factor, radiation hardness, cost, tolerance/immunity to B-fields...)
The 1st generation of image sensors used charge coupled device (CCD) technology.

CCD inventors were granted the 2009 Nobel Prize in Physics.

CCDs dominated the market for 3 decades thanks to:
- high resolution;
- low noise.

Willard Boyle and George Smith invented CCDs in 1969.

Photo: Alcatel-Lucent/Bell Labs, 1974.
CMOS Sensors

Eric Fossum invented the CMOS APS in 1994.

Photo: Amy Etra/BusinessWeek, 2011.

- 2nd generation image sensors used CMOS active pixel sensor (APS) technology.
- It was developed at NASA’s Jet Propulsion Laboratory.
- Dominated low-power imaging thanks to:
  - On-chip integration with CMOS devices;
  - Simple supply system.
<table>
<thead>
<tr>
<th>Market</th>
<th>2014</th>
<th>2015</th>
<th>CAGR 2015-2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile</td>
<td>$5,908</td>
<td>$6,665</td>
<td>12%</td>
</tr>
<tr>
<td>Consumer</td>
<td>$1,611</td>
<td>$1,401</td>
<td>1%</td>
</tr>
<tr>
<td>Computing</td>
<td>$1,187</td>
<td>$1,052</td>
<td>-3%</td>
</tr>
<tr>
<td>Automotive</td>
<td>$279</td>
<td>$537</td>
<td>23%</td>
</tr>
<tr>
<td>Medical</td>
<td>$29</td>
<td>$34</td>
<td>15%</td>
</tr>
<tr>
<td>Security</td>
<td>$140</td>
<td>$388</td>
<td>11%</td>
</tr>
<tr>
<td>Industrial/Space/Defence</td>
<td>$146</td>
<td>$271</td>
<td>10%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$9,300</td>
<td>$10,348</td>
<td>10.4%</td>
</tr>
</tbody>
</table>

2015 CIS Revenue breakdown by market:

- **2014 $9,300M**
- **2015 $10,348M**

Humans on earth: 7.500M
Photodetection basics
Photodetection basics

- PN junction in reverse bias

- Generated carriers are removed by built-in field in depletion region.
- Very small current (reverse current)

- Photo-generated carriers drift into P (holes) and N (electrons) regions creating currents.
- One photon creates one electron and hole
PIN photodiode

Avalanche photodiode

High-efficiency detectors
Avalanche photodiodes

- Drifting electrons generated within the near intrinsic region drift diffuse into the p-region.
- The large E fields provide enough kinetic energy to impact-ionize some of the Si covalent bonds and release more EHPs.
- Secondary e-h are accelerated by the same high fields, ionize and generate even more EHPs
- This effect leads to an avalanche of impact ionization processes and the photodiode can be said to possess and internal gain mechanism
Avalanche photodiodes

A. Arbat, PhD, Towards a forward tracker detector based on Geiger mode avalanche photodiodes for future linear colliders, 2010.
Haitz’s planar diode (early 60’s)

Implementation of avalanche photodiodes

Niclass et al., Sel. Topics in Quantum Electronics, 2007
Main figure of merit. PDE

- PDE depends of overvoltage
  \( \text{OV} \uparrow, \text{PDE} \uparrow \)

- PDE depends on the technological process
  Deeper junction, more infrared
  Shallower junction, more ultraviolet

\[ \text{PDE} = \text{QE} \times \eta \]
- \( \text{QE} = \) quantum efficiency
- \( \eta = \) avalanche triggering probability
Main figure of merit. PDE
Main figures of merit. Noise

Sources of noise counts in GAPDs:

1. Dark counts (uncorrelated noise)
   (a) Thermal generation (SRH)
   (b) Trap assisted thermal/SRH generation
   (c) Band-to-band tunneling
   (d) Trap assisted tunneling
   - Measured as dark counts/s (Dark Count Rate)
   - Dependent on - fabrication process (traps)
   - reverse bias overvoltage (V_OV)
   - working T
   - Reduced by - area ↓, V_OV ↓, T ↓

2. Afterpulses (correlated noise)
   (e) e– (left) and h+ (hole) afterpulses
   - Dependent on - trapping centers
   - number of charge carriers
   - Reduced by - C_p (parasitic capacitance) ↓
   - active quenching
   - dead time ↑

3. Crosstalk (correlated noise)
   (f) Electrical crosstalk
   - Dependent on - pixel separation
   - Suppressed by - using different wells
   (g) Optical crosstalk
   - Dependent on - pixel separation
   - Reduced by - limiting Geiger current
   - using trenches

(f) Primary carrier triggers avalanche (due to absorbed radiation or other phenomena → noise)

(g) Photons emitted due to electroluminescence

new avalanche

n-well

primary avalanche

recombination
drift
diffusion

(h) New avalanche

y-axis: Density (cm^-3)

h^+ Density (cm^-3)

8.0E+19
6.6E+15
5.4E+11
4.4E+07
3.6E+03
2.9E-01
Main figures of merit. Noise

- DC are due to thermally generated carriers
- Moderate DCR without STI
  \[1 \text{ Hz/\mu m}^2 < \text{DCR} < 10^2 \text{ Hz/\mu m}^2\]
- High DCR with STI
  \[\text{DCR} \approx 1 \text{ MHz}\]
- Depends on process and overvoltage and area

Eva Vilella, Feasibility of Geiger-mode avalanche photodiodes in CMOS standard technologies for tracker detectors, PhD 2013.
Gating of avalanche photodiodes

Valid for those applications where the signal time arrival can be known in advance (time-gated FLIM)

- The sensor is periodically activated and deactivated under the command of a trigger signal

Noise, Advantages of time-gated operation (2)

- Afterpulses are caused by carriers trapped during the avalanche discharging and then released triggering a new avalanche.
- Afterpulses depend on the process.
- Can be eliminated with non-active periods ($t_{OFF}$).

The image is for a 0.35um process.

$t_{OFF} = 80$ns

$t_{OFF} = 300$ns

E. Vilella et al., DTIP 2013
### Passive quenching and recharge

- **Quenching** → lower $V_{\text{bias}} = V_{\text{BD}}$ after an avalanche
  - Resistive element in series with the sensor
  - Resistor with $10^2$ kΩ (area ↑) or MOS transistor with proper (W/L) and bias
  - $\tau_Q = (C_D + C_P) \cdot R_D$

- **Recharge** → increase $V_{\text{bias}} > V_{\text{BD}}$ after quenching
  - Quenching element is used for recharge too
  - $\tau_R = (C_D + C_P) \cdot R_Q$
  - Poor control over quenching and recharge times
  - $R_Q \uparrow$, $\tau_Q \downarrow$, $\tau_R \uparrow$ (and vice versa)

**Readout circuit:**
- CMOS inverter
- Voltage comparator
- Source follower

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**Readout circuit:**

- $V_{\text{bias}} = V_{\text{BD}} + V_{\text{OV}}$
- $V_{\text{out}}$

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Random access, full camera readout

C. Niclass et al. 2005 “A single photon detector array with 64x64 resolution and millimetric depth accuracy for 3D imaging”

Event driven readout, few pixels read

C. Niclass et al. 2007 “A CMOS 64x48 single photon avalanche diode array with event-driven readout”

Parallel readout, full camera readout

C. Niclass et al. 2008 “A 128x128 single-photon imager with on-chip column-level 10b time-to-digital converter array capable of 97ps resolution”

In-pixel storing, full camera readout

F. Guerrieri et al. 2008 “Fast single-photon imager acquires 1024 pixels at 100 kframe/s”

Pipelined readout

M. Sergio et al. 2007 “A 128x2 CMOS single photon streak camera with timing-preserving latchless pipeline readout”

M. Gersbach et al. 2009 “A parallel 32x32 time-to-digital converter array fabricated in a 130nm imaging CMOS technology”
Application. Fluorescence lifetime.

- Non-radiative transition
- Absorption
- Fluorescence
- Ground State
- Direct
- Indirect

Channel edge

Optical Waveform

Detector Signal:
- Period 1
- Period 2
- Period 3
- Period 4
- Period 5
- Period 6
- Period 7
- Period 8
- Period 9
- Period 10
- Period N

Result after collecting many Photons

memory location

UA

Time (ns)

1 μM
1/2 μM
1/4 μM
1/8 μM
1/16 μM

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CMOS photodetectors in ChipScope

Lateral resolution:

$$\left( \delta x_{\text{min}}, \delta y_{\text{min}} \right) = \Delta_{\text{min}} = \frac{\lambda}{2n \sin \alpha},$$

Axial resolution:

$$\delta z_{\text{min}} \approx \frac{\lambda}{2n (\sin \alpha)^2}$$
ChipScope concept

- LEDs of nanometric size are turn on and off
- Photodetector measures light
  - Single photon detection
  - Sub-ns time response
- Pulses of light are counted for each LED
- Images are formed by considering all LEDs

The technology is based on a disruptive approach that consist in obtaining the high resolution using spatially resolved illuminator. It is a long term vision to create an inexpensive technology.

Expertise from different scientific areas: physics, material science, computer science, biology.
Thank you for your attention!