Pixelated Low Gain Avalanche Detectors

Gian-Franco Dalla Betta

Department of Industrial Engineering, University of Trento and INFN Trento Institute for Fundamental Physics and Applications
Via Sommarive 9, 38123 Povo di Trento (TN), Italy

gianfranco.dallabetta@unitn.it
Outline

• Introduction:
  – Avalanche PhotoDiodes (APDs)

• Low Gain Avalanche Detector (LGAD)
  – From pads to pixels
  – Proposed double-sided sensor
  – Simulated performance

• CMOS Avalanche PhotoDiodes
  – Experimental results for standard 0.15\(\mu\)m CMOS
  – Gain and noise modeling

• Conclusions
Avalanche PhotoDiodes (APDs)

P-N junctions diodes specially made to exploit impact ionization effects

Linear mode: $V < V_{BD}$:
- Photo-current amplified by a factor $M$
- Output current proportional to the optical power

Geiger mode: $V > V_{BD}$:
- Digital photon counter
- Output signal stream with $N$ pulses/s
- Core of SiPMs
Linear-Mode APDs applications

Linear-mode APDs are suitable for applications requiring **high bandwidth** and **high sensitivity**:

- Telecommunication receivers
- High speed laser scanners
- Time-resolved imaging (ToF ranging, FLIM)
- X – γ rays, ionizing particles for biomedical and physics applications (w and w/o scintillators)
Linear-mode APDs Figures of Merit

- Quantum Efficiency
- Excess noise factor
- Gain-Bandwidth product
- Dark current
- Breakdown voltage
- Temperature sensitivity
- Breakdown voltage uniformity
- Avalanche gain uniformity

Pixel Arrays
Excess noise factor

APD noise:

\[ i_n^2 = 2qI_{ph} \cdot M^2 F \]

- \( M \): multiplication gain
- \( F \): excess noise factor

\[ F = M \cdot k + \left( 2 - \frac{1}{M} \right) \cdot (1 - k) \]

Avalanche initiated by:

- \( \alpha \): electron ionization rate
- \( \beta \): hole ionization rate

Electrons (low k) \( \Rightarrow \) small F
Holes (high k) \( \Rightarrow \) high F

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• Conclusions
• APDs revisited for ionizing particles
• Aiming at low gain both before and after irradiation
• Gain vs breakdown voltage trade-off
• High sensitivity to the implant dose of the multiplication layer
• JTE to prevent from edge breakdown
From pads to pixels

Possible segmentation options in electron multiplying structures

- **n-in-p**
  - Read electrons
  - Segmentation
  - Region with no gain

- **p-in-p**
  - Read holes
  - Segmentation
Not a completely new problem …

- APD arrays for fast X-ray hybrid pixel detectors
- Special technology developed by Excelitas Canada Inc.
- Thickness 120 µm and 200 µm, gain ~ 100 @ Vbias = 500V
- Large gain non uniformity ±15%

C. Thil et al., 2012 IEEE NSS, N1-231
A double-sided pixelated LGAD

- Pixel side is simple, gain side quite complex (4 doping steps)
- Plan: start from thick 6” wafers (275 µm) before going thinner (100 µm)
- TCAD simulations to predict the performance
TCAD (1): Electrical parameters

- Simulation results scaled to 50x50 µm² pixels
- Strong impact of the B dose on the breakdown voltage
- Comparison at similar breakdown voltage
- Two-phase depletion behavior observed in both C-V and I-V
TCAD (2): Gain and noise

- Simulated with mip (Heavy Ion Model) in cylindrical coordinates
- Gain defined as ratio of integral charge with/without avalanche
- Similar gain at high voltage (~15) but with quite different trend

Excess noise factor can be fit with:

\[ F = M \cdot k + \left( 2 - \frac{1}{M} \right) \cdot (1 - k) \]

\[ k = \frac{\alpha_p}{\alpha_n} \text{ – ionization ratio} \]

R.J. McIntyre, IEEE TED 13 (1966) 164
TCAD (3): Signals

- Current pulses in response to a mip (cylindrical coordinates) at different voltages
- Pulse duration dominated by drift of multiplied holes, thus proportional to the substrate thickness
- Impact of segmentation (weighting field): significant delay for 275 µm, much smaller for 100 µm
• Fast timing circuits might be difficult to embed in small pixels
• But different functions could be divided between the two sides:
  - Position measurement from the small pixel side
  - Time measurement from the gain side → capacitance is an issue
• Segmentation of the gain side (macro – pixels, ~1mm², ~1pF)
Segmentation of the gain side

- Same technology, different layout
- Acceptable efficiency reduction from macro-pixel edges (~5%)
- It can work safely up to >1200V before breakdown
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APD integration in CMOS

• Significant results in the past ten years
• Mainly driven by telecom receivers, but increasing interest also for imaging
• Advantages:
  – Integrated electronics: low parasitics, low costs
  – Array fabrication possible
• Challenges:
  – Guard ring fabrication
  – Doping profiles not optimized for low noise and high quantum efficiency
p+/nwell APD in 0.15µm CMOS

- Shallow junction ~ 0.2µm
- p-sub low-doped guard ring
- Active region: p+/nwell junction


APD active region can be approximated with an abrupt junction
pwell/n-iso APD in 0.15µm CMOS

L. Pancheri et al., IEEE EDL 35 (2014) 566

APD active region can be approximated with a linearly graded junction

- Deep junction > 1µm
- p-sub low-doped guard ring
- Active region: pwell/n-iso junction
Gain vs Voltage

$p+/nwell$

$V_B = 16.1\, V, \sigma = 90\, mV$

$V_B = 23.1\, V, \sigma = 260\, mV$

Multiplication gain, $M$

Reverse voltage [V]

Multiplication gain, $M$

Reverse voltage [V]
Quantum Efficiency

Better in the UV and blue

Better in the NIR

In both cases interference fringes due to non optimized optical stack (no ARC)
Excess Noise Factor

- UV light: electron-initiated avalanche
- NIR light: mixed – majority of hole injection

- UV light: electron-initiated avalanche
- NIR light: mixed – majority of electron injection
Ionization Rate Models

1) Local model:
\( \alpha \) depends only on the electric field \( E \)

Local model: McIntyre, IEEE TED, 1966
Ion. rates: Okuto and Crowell, SSE, 1975

2) Non-local model:
- The electron needs to acquire energy from \( E \) before being able to cause impact ionization
- \( \alpha \) depends on electric field \( E \) and position \( x \)

3) Simplified non-local model:
- Dead-space \( d_e \) defines a sharp transition
- \( d_e \) proportional to ionization threshold energy

Non-local (dead-space) model: Hayat et al., IEEE JQE, 1992
F vs M: model comparison

- Local model not suitable due to high electric field and narrow space-charge regions
- Very good agreement with non-local models for electron-initiated avalanche
F vs M: non-local model

- Also non-local model with hole-initiated avalanche overestimates F
- Good agreement with NIR approximation (mixed injection) with $X_j$ as a fitting parameter
Conclusions

1) Design options for pixelated LGADs were reported
   - TCAD simulations have been used to predict the sensor performance with encouraging results

2) Low-noise APDs can be integrated in CMOS processes
   - Good uniformity → Arrays are feasible
   - Non-local ionization models can yield an accurate excess noise predictions

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