Pixelated Low Gain Avalanche Detectors

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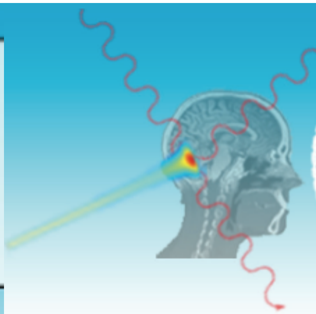
ADVANCED SEMICONDUCTOR DETECTORS FOR MEDICAL APPLICATIONS
SYMPOSIUM

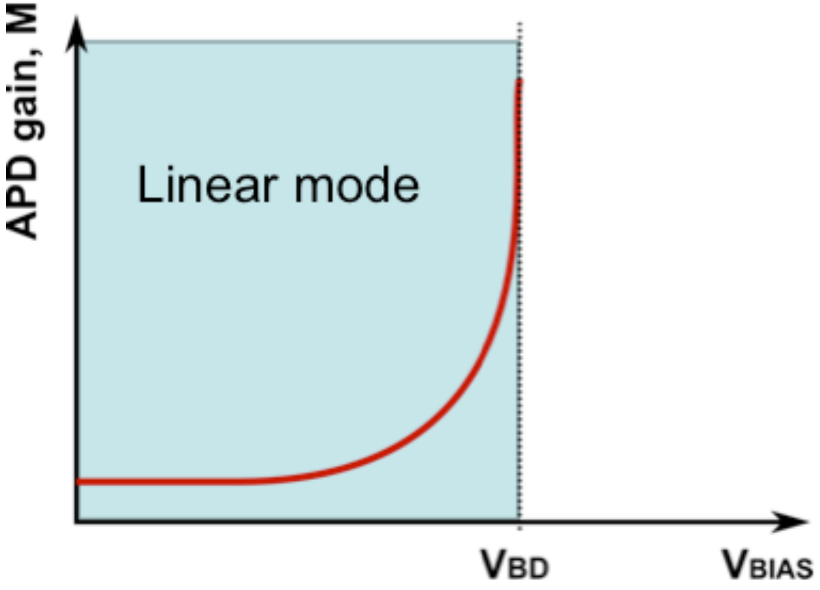


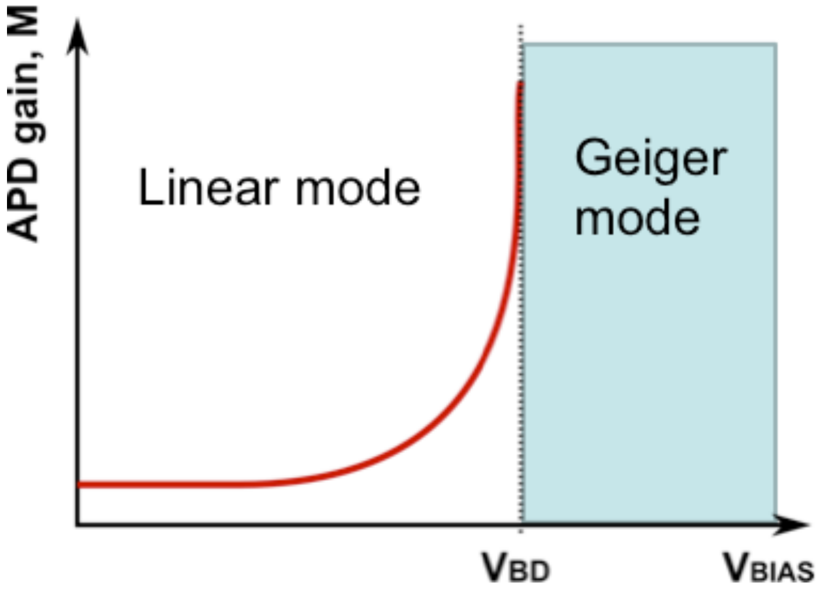
Outline

- 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 0.15μm 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

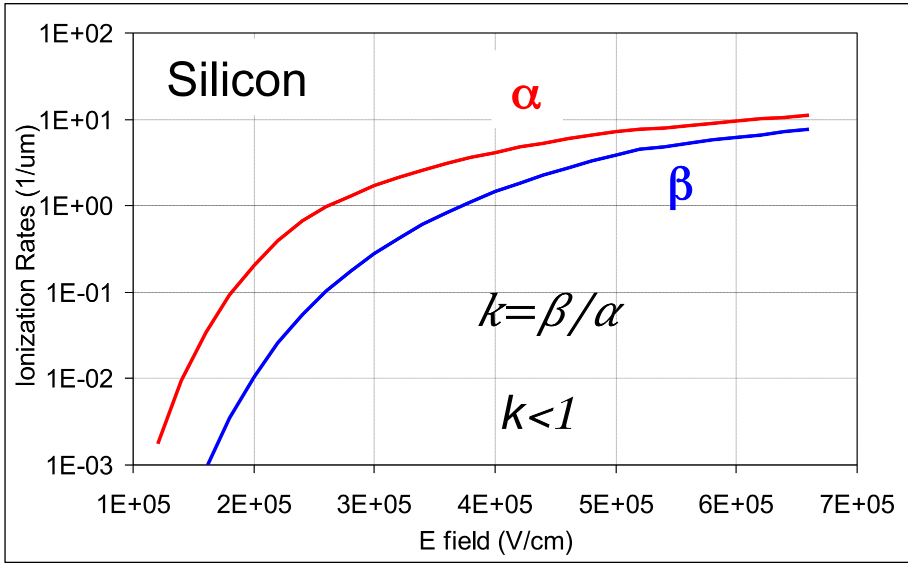
APD noise:

$$i_n^2 = 2qI_{ph} \cdot \boxed{M^2F}$$

M: multiplication gain

***F*: excess noise factor**

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



Avalanche initiated by:

α: **electron** ionization rate

β: **hole** ionization rate

electrons (low k) → **small F**

holes (high k) → **high F**

R.J. McIntyre, "Multiplication Noise in Uniform Avalanche Diodes", IEEE Trans. Electron Devices 13 (1966) 164

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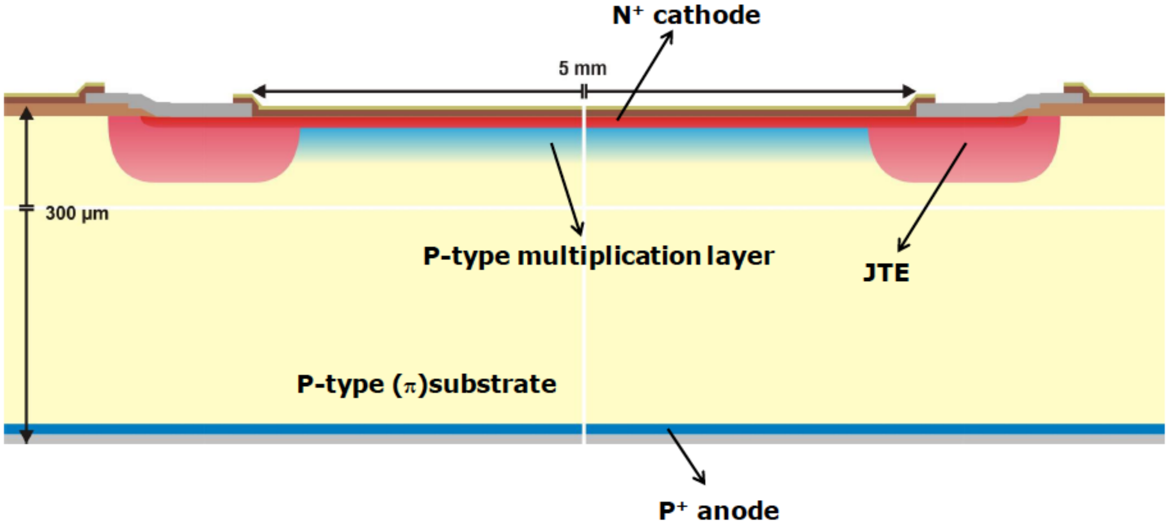
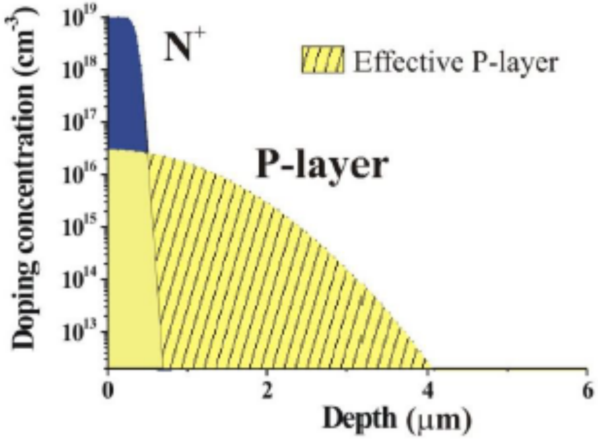
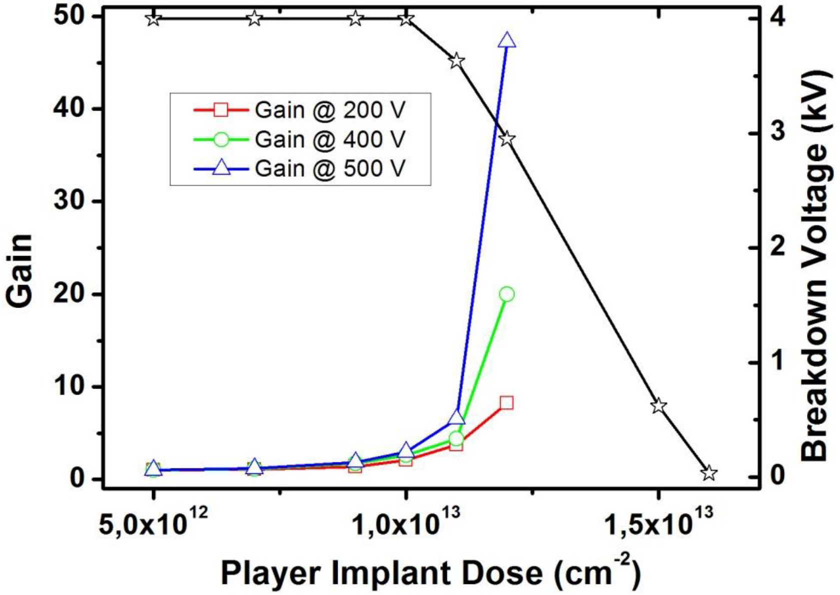
Low Gain Avalanche Detector (LGAD)





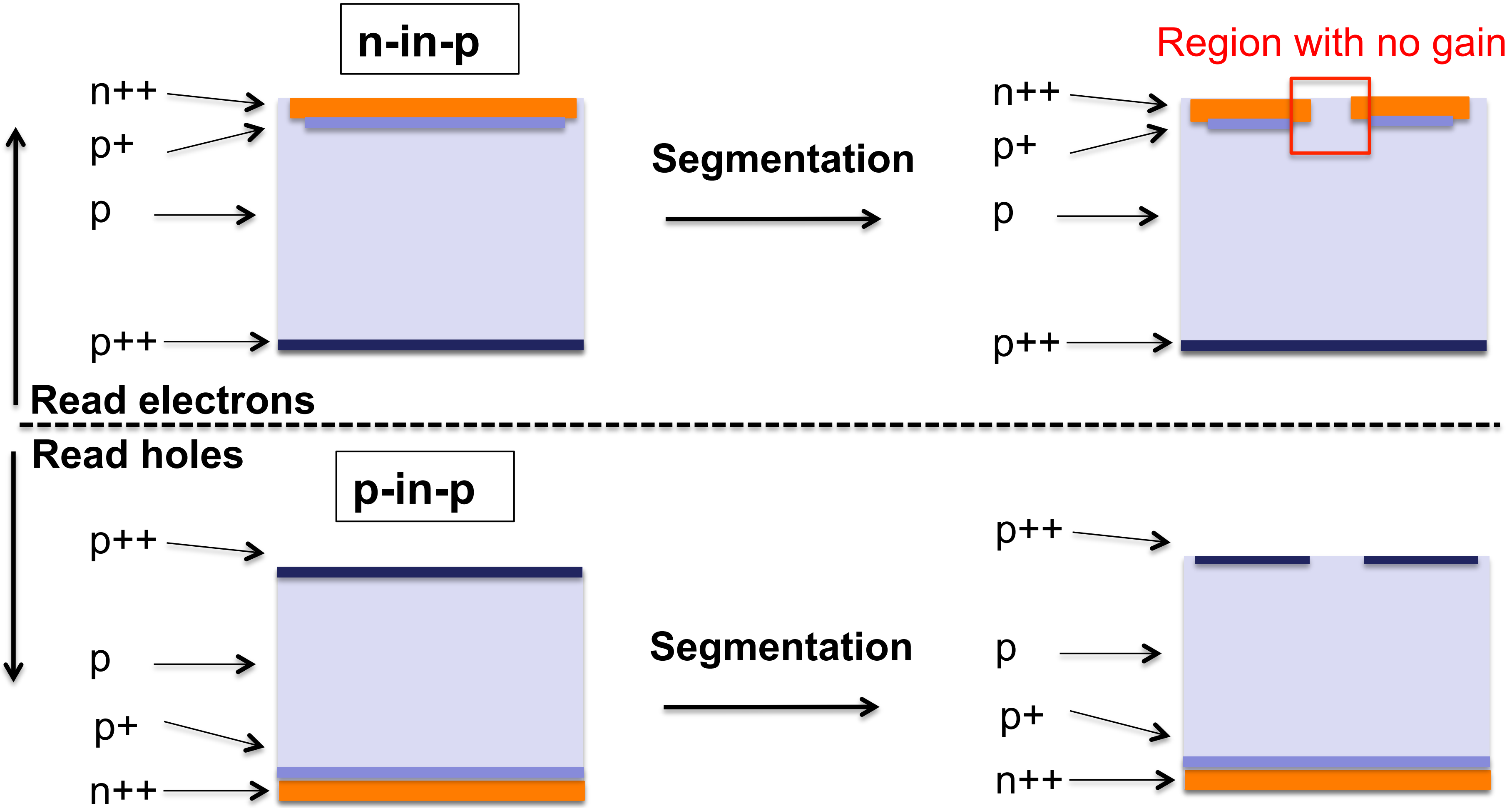
G. Pellegrini, et al., HSTD9 (2013)



- 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

Region with no gain

n++
p+
p
p++

Segmentation

n++
p+
p
p++

Read electrons

Read holes

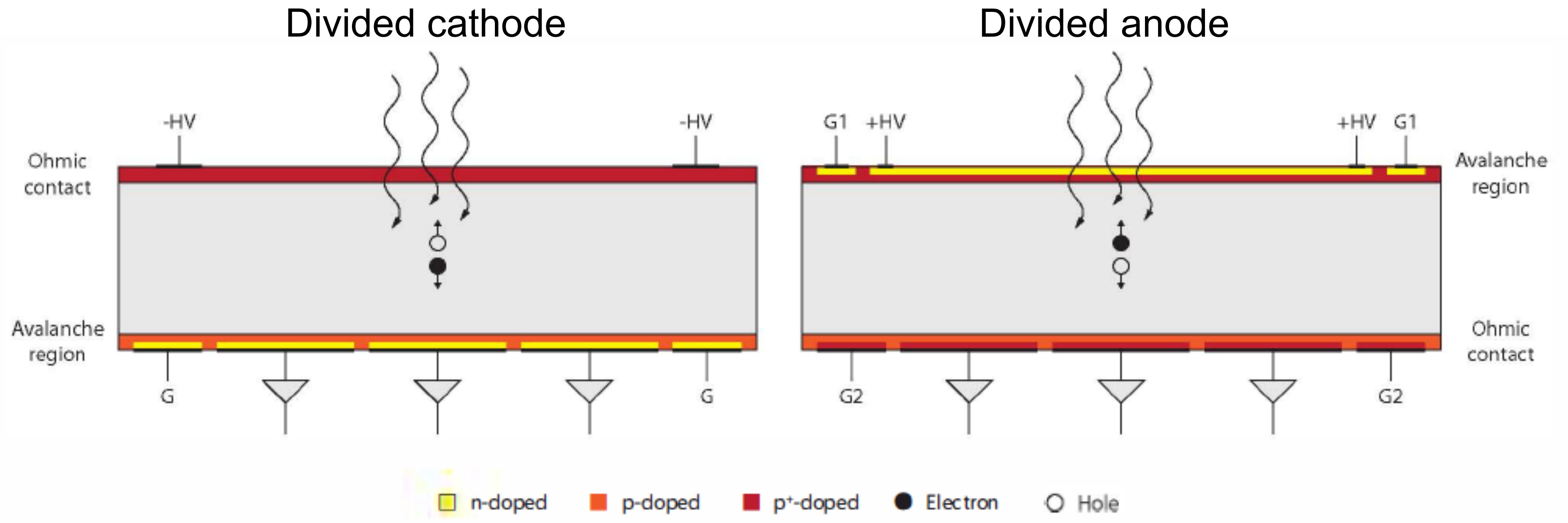
p-in-p

p++
p
p+
n++

Segmentation

p++
p
p+
n++

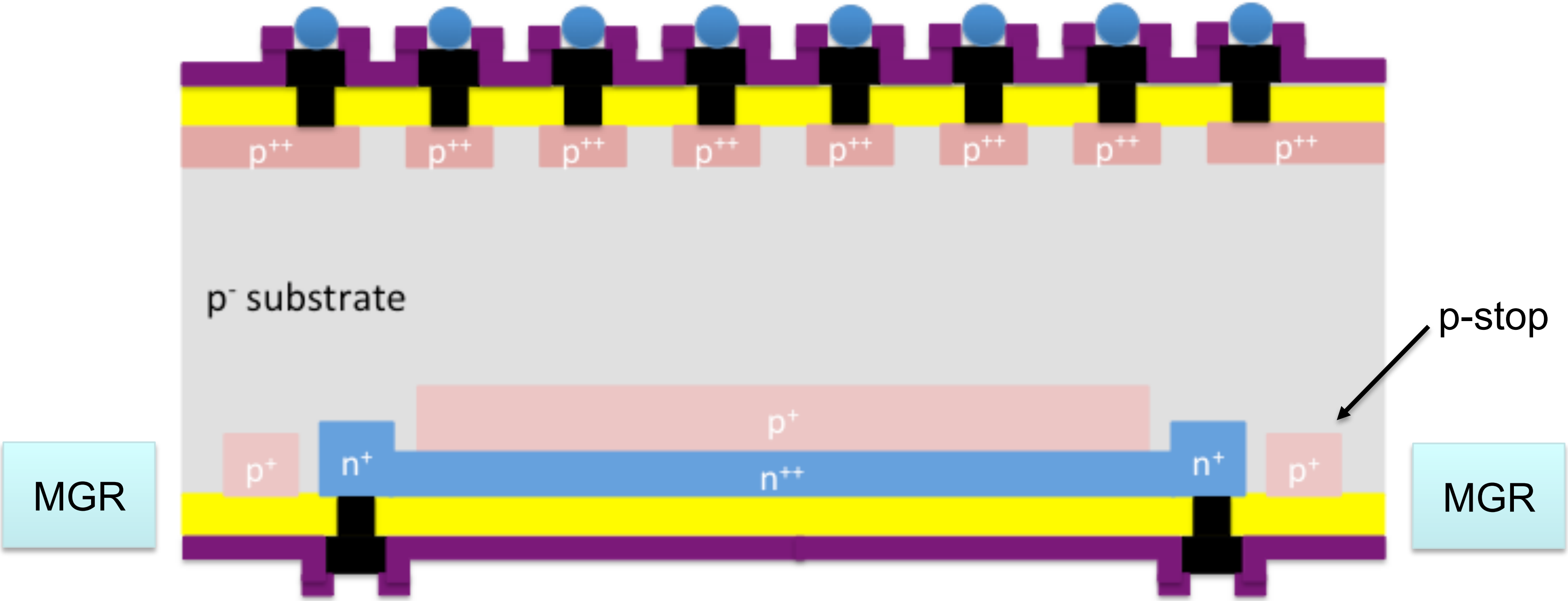
Not a completely new problem …



- 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

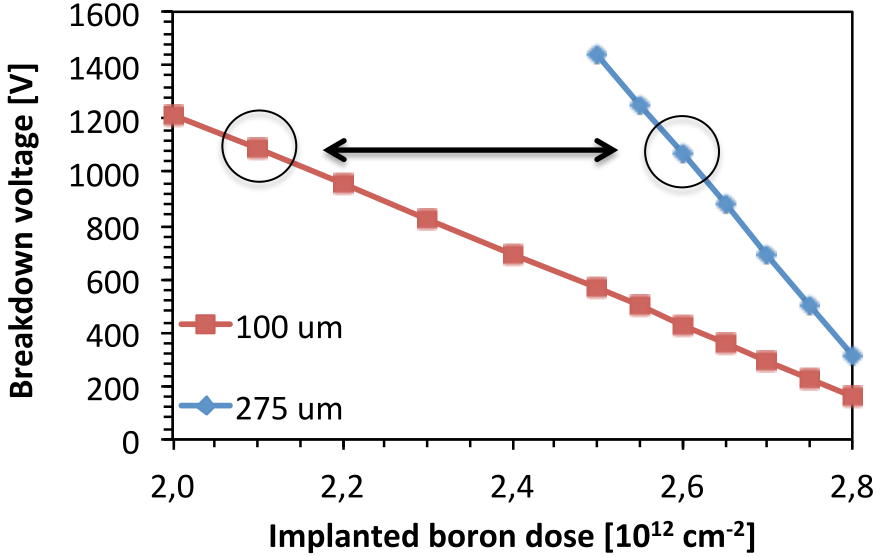
A double-sided pixelated LGAD

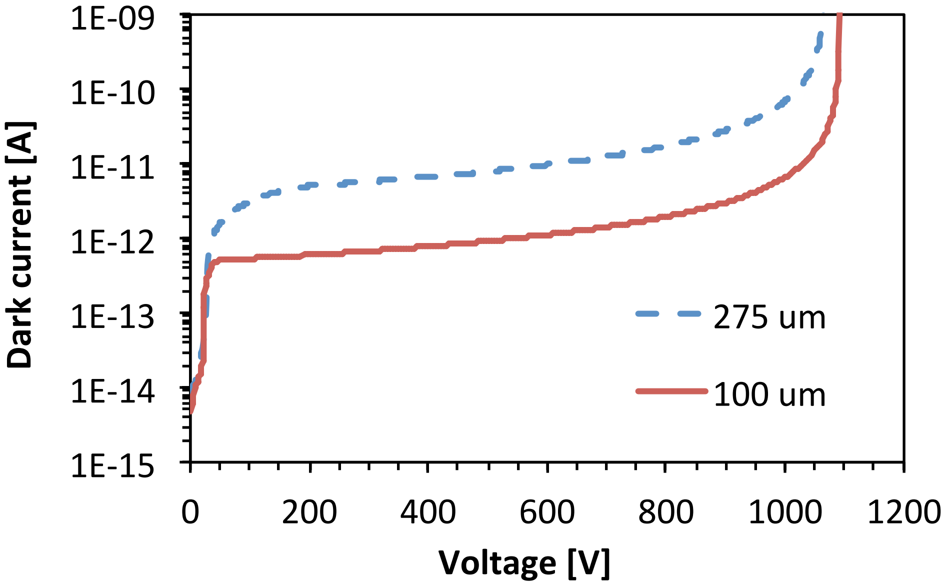


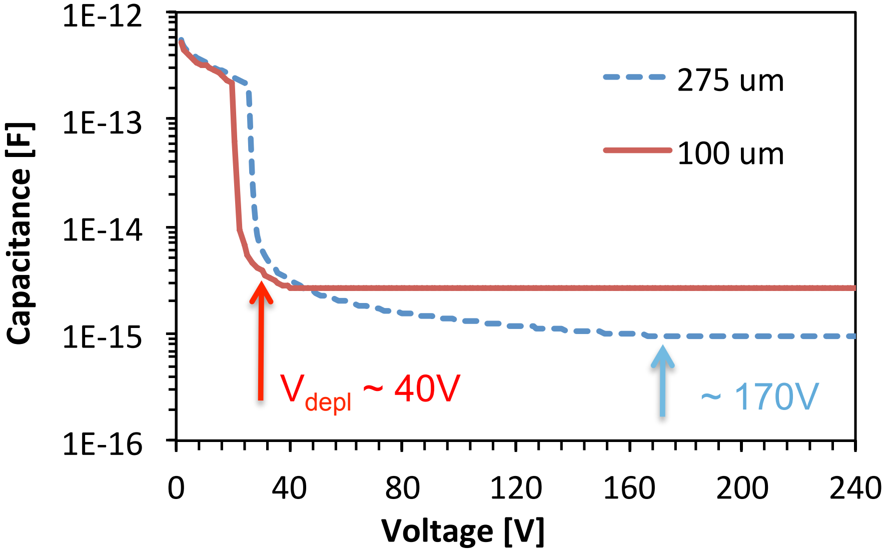
- Pixel side is simple, gain side quite complex (4 doping steps)
- Plan: start from thick 6” wafers (275 μm) before going thinner (100 μm)
- TCAD simulations to predict the performance

G.F. Dalla Betta, RESMDD 2014

TCAD (1): Electrical parameters

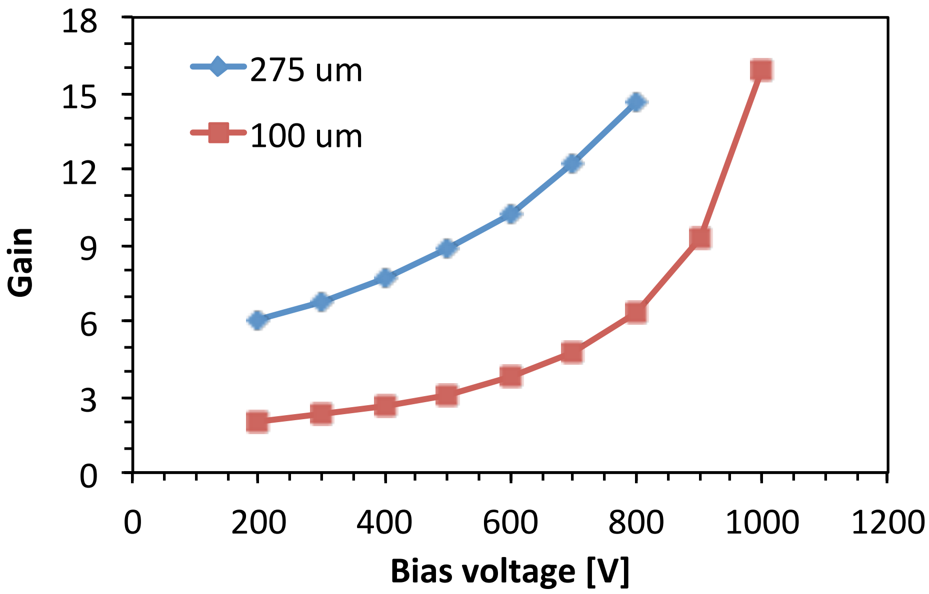


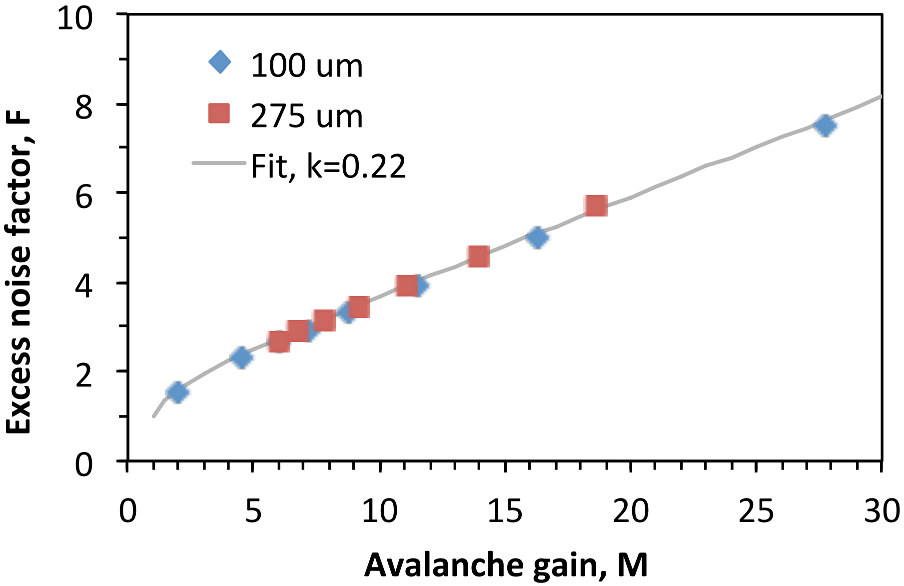




- Simulation results scaled to 50x50 μm^2 pixels
- Strong impact of the B dose on the breakdown voltage
- Comparison at similar breakdown voltage
- Two-phase depletion behavior observed in both C-V and I-V

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

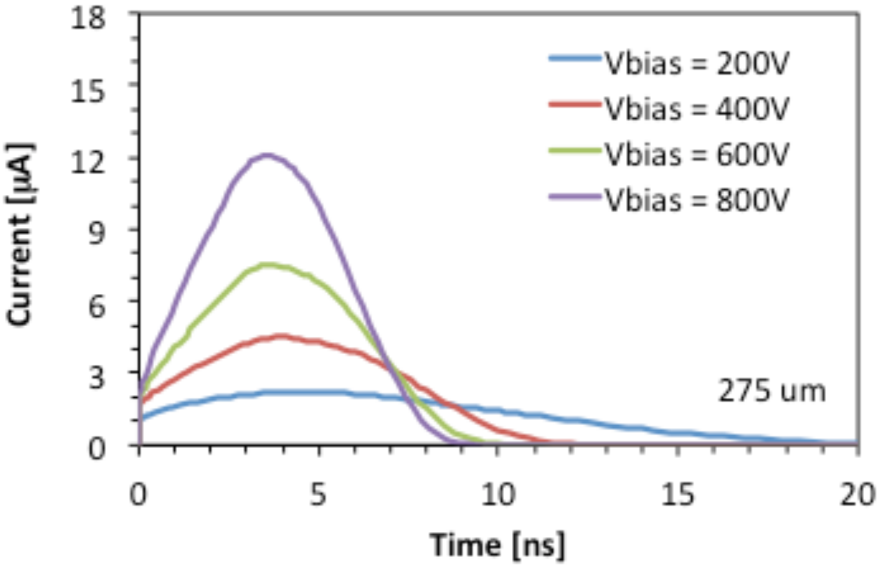
Excess noise factor can be fit with:

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

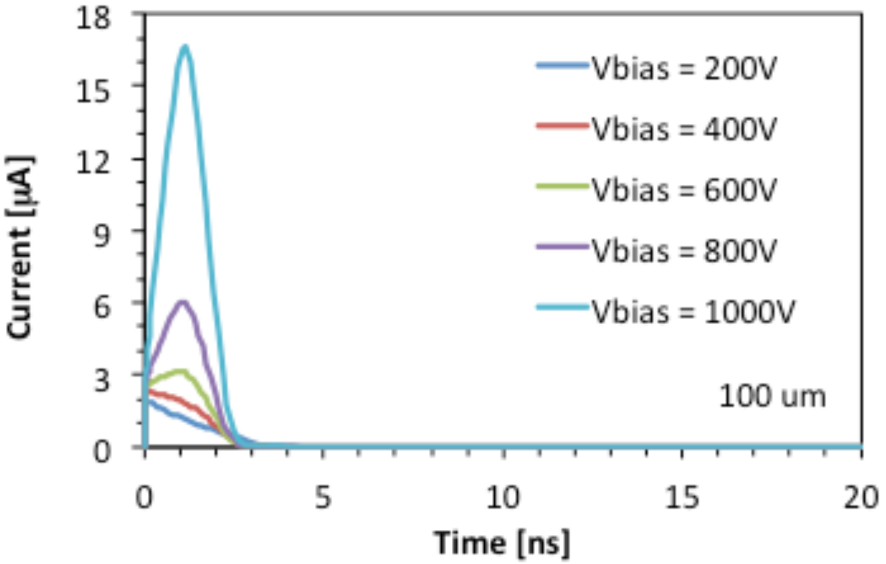
k= α_p/α_n – ionization ratio

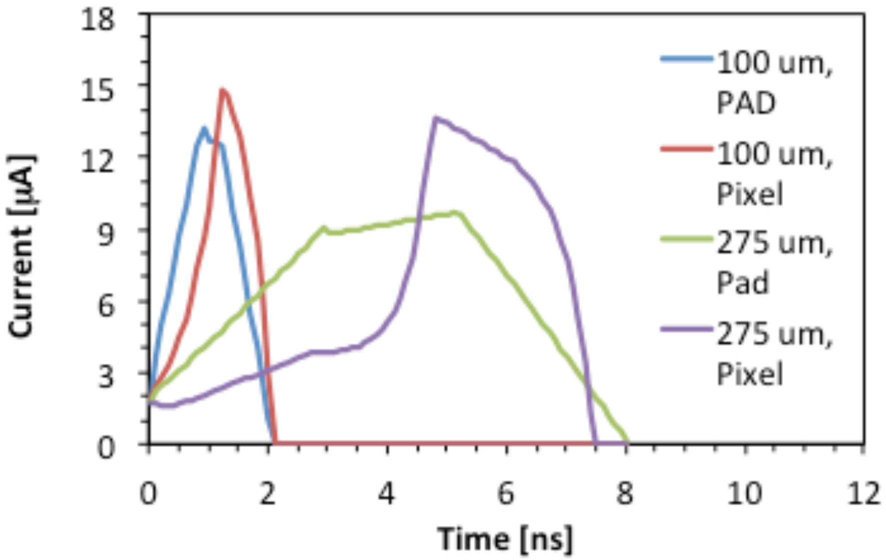
R.J. McIntyre, IEEE TED 13 (1966) 164

TCAD (3): Signals



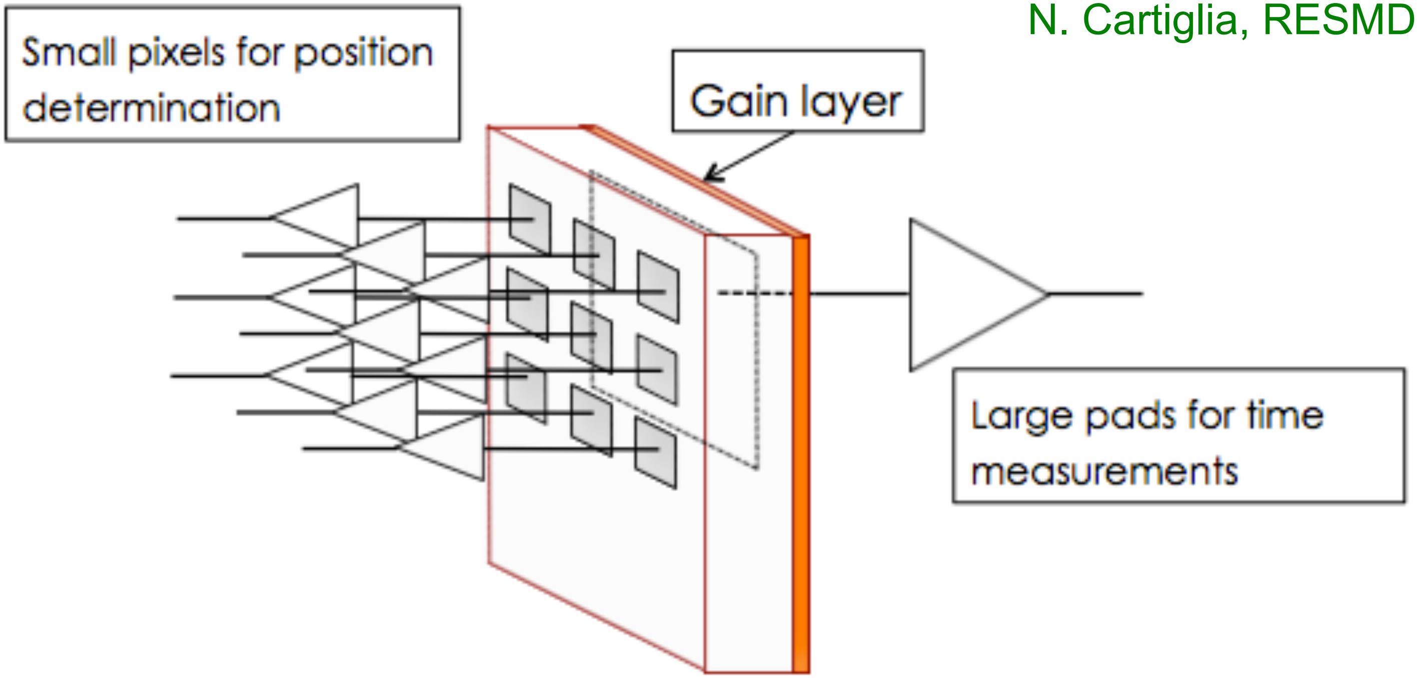
- Current pulses in response to a mip (cylindrical coordinates) at different voltages
- Pulse duration dominated by drift of multiplied holes, thus proportional to the substrate thickness
- Impact of segmentation (weighting field): significant delay for 275 μm, much smaller for 100 μm





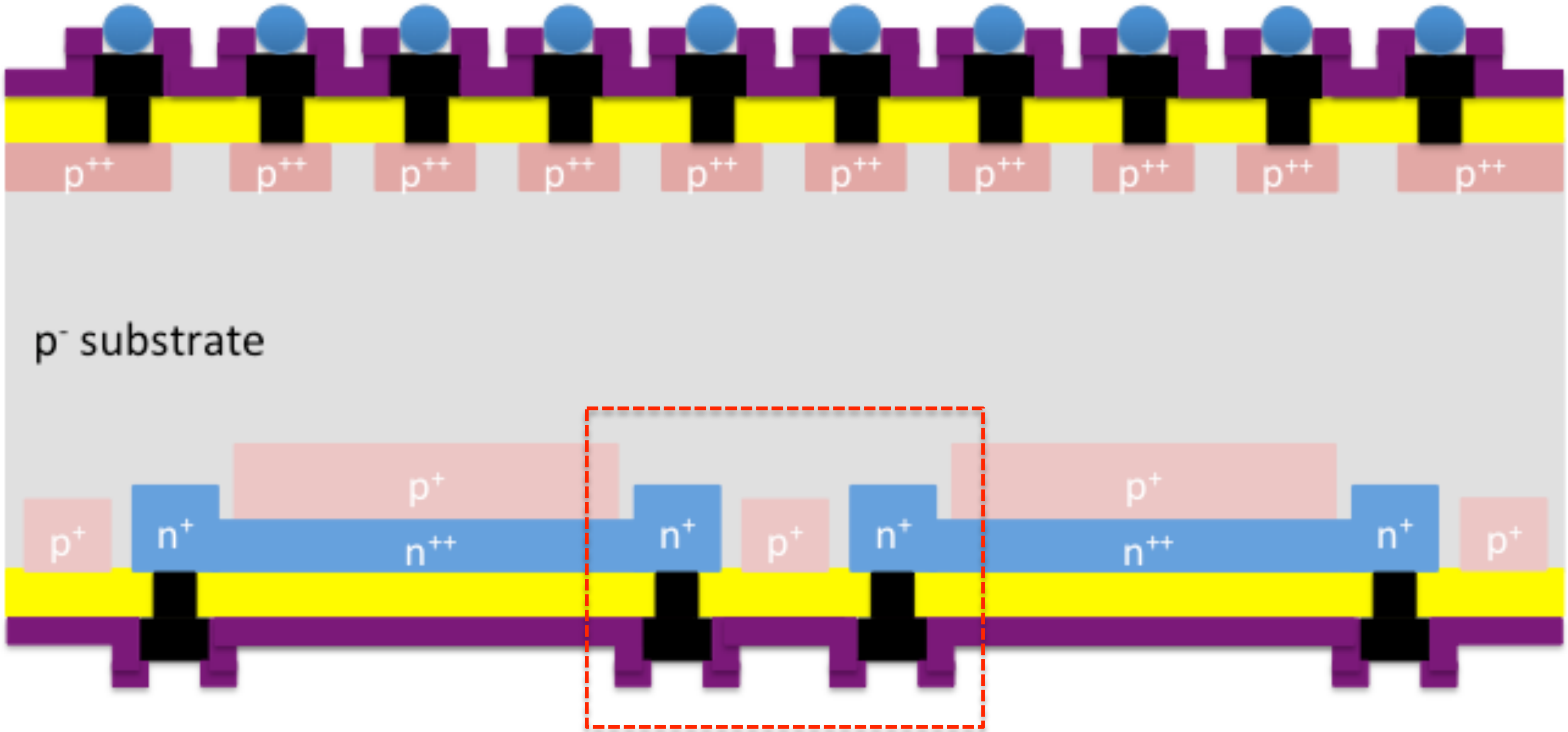
Going one step further

N. Cartiglia, RESMDD 2014



- 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, ~1mm^2, ~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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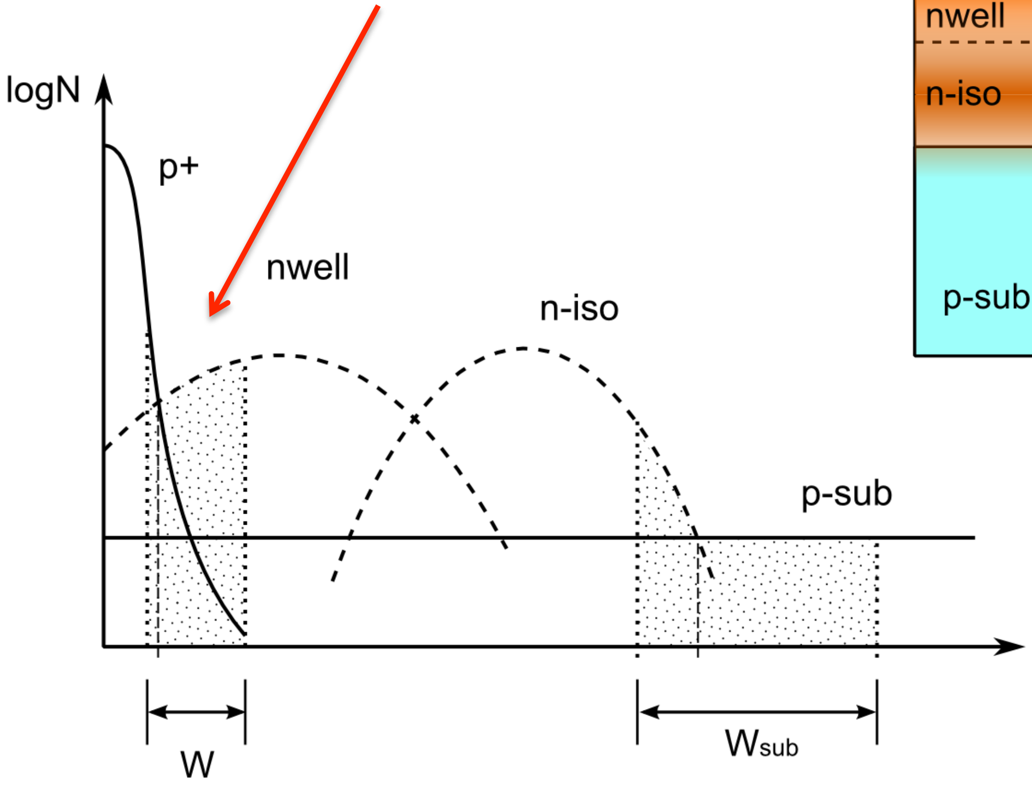
APD integration in CMOS

- 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

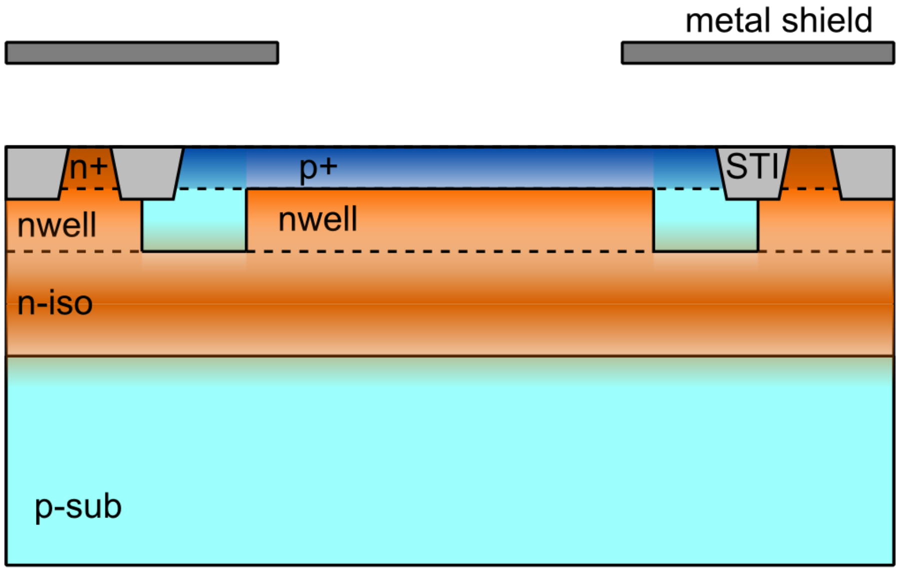
p+/nwell APD in 0.15μm CMOS

L. Pancheri et al., Proc. SPIE 8982 (2014)

APD active region can be approximated with an **abrupt junction**



p+/nwell

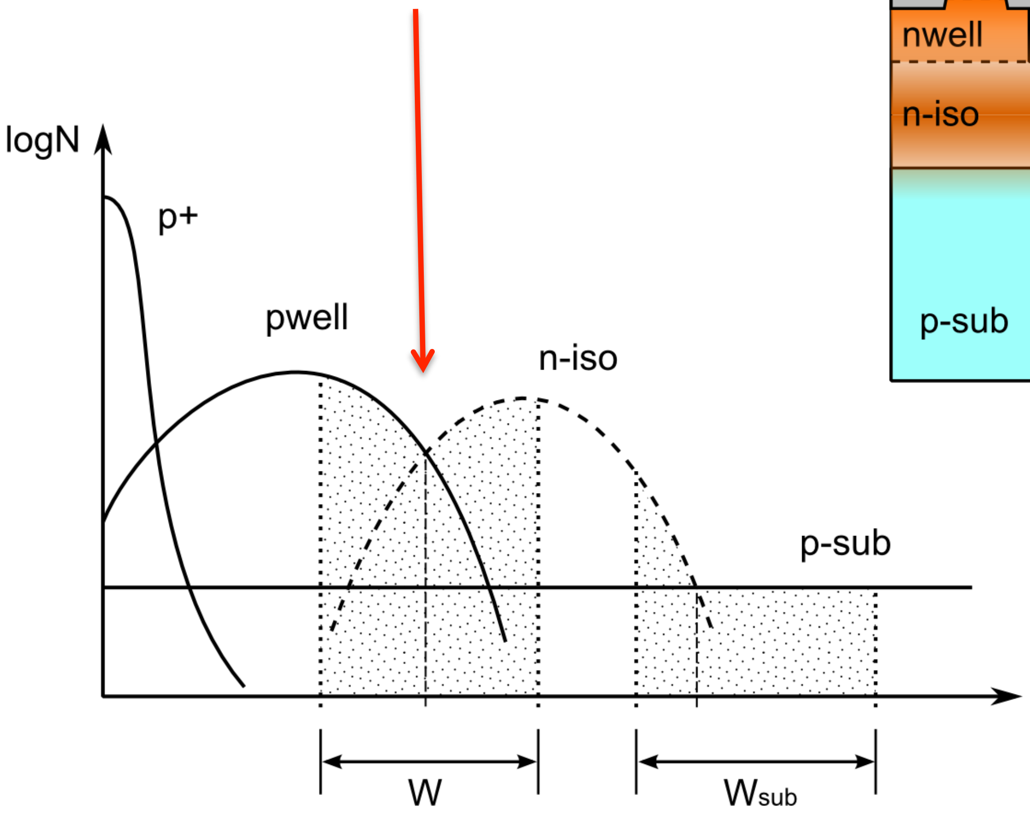


- Shallow junction ~ 0.2μm
- p-sub low-doped guard ring
- Active region: p+/nwell junction

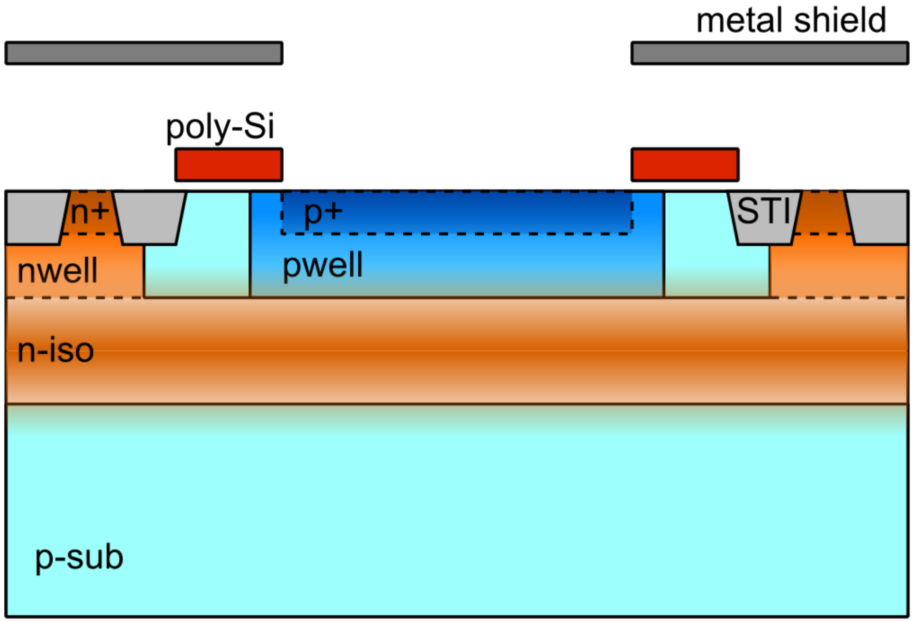
pwell/n-iso APD in 0.15μm CMOS

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

APD active region can be approximated with a **linearly graded junction**

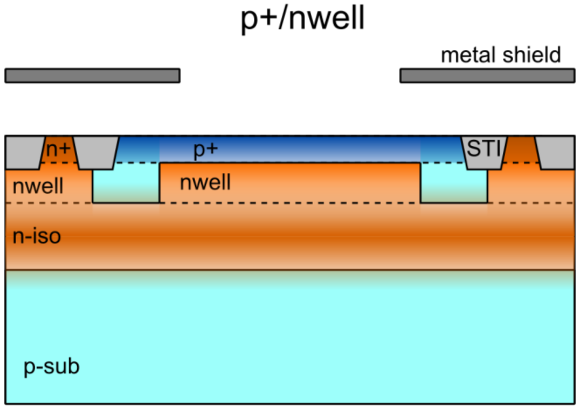


pwell/niso

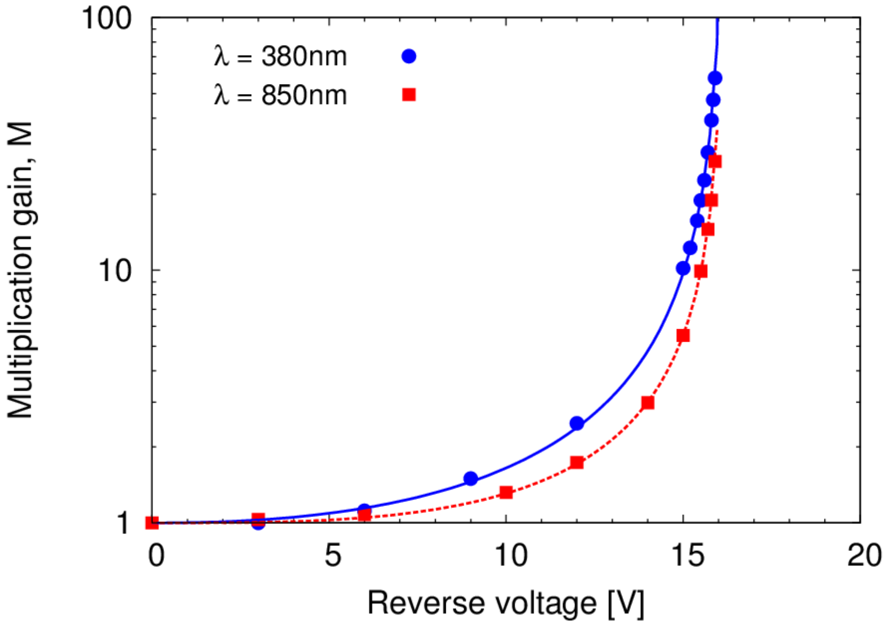


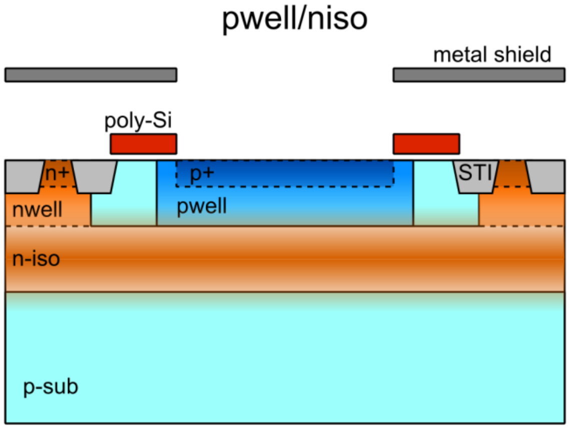
- Deep junction > 1μm
- p-sub low-doped guard ring
- Active region: pwell/n-iso junction

Gain vs Voltage

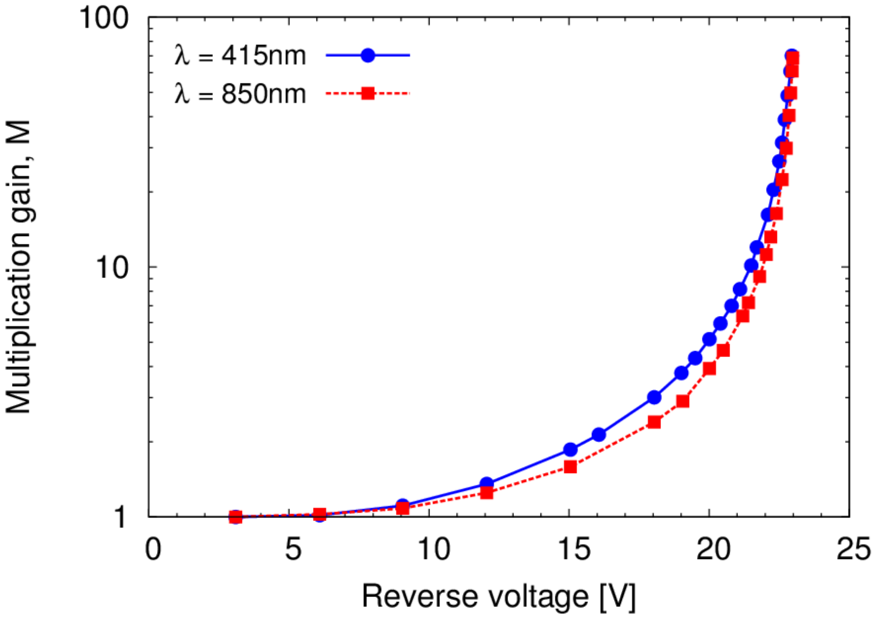


V_B = 16.1.V, σ = 90mV

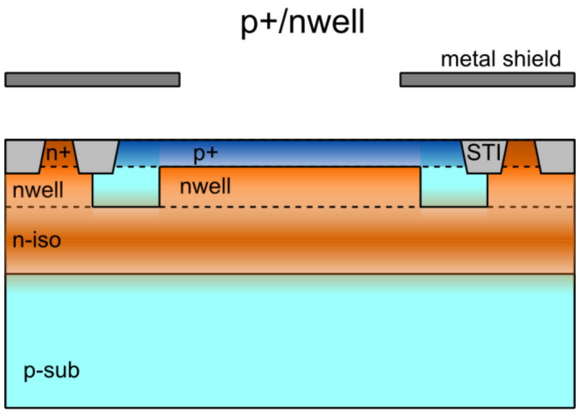




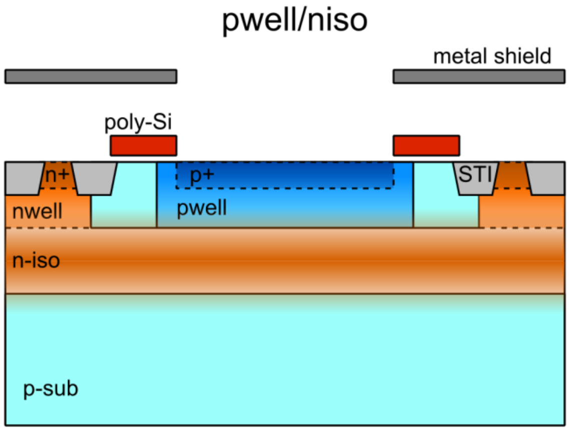
V_B = 23.1 V, σ = 260mV



Quantum Efficiency

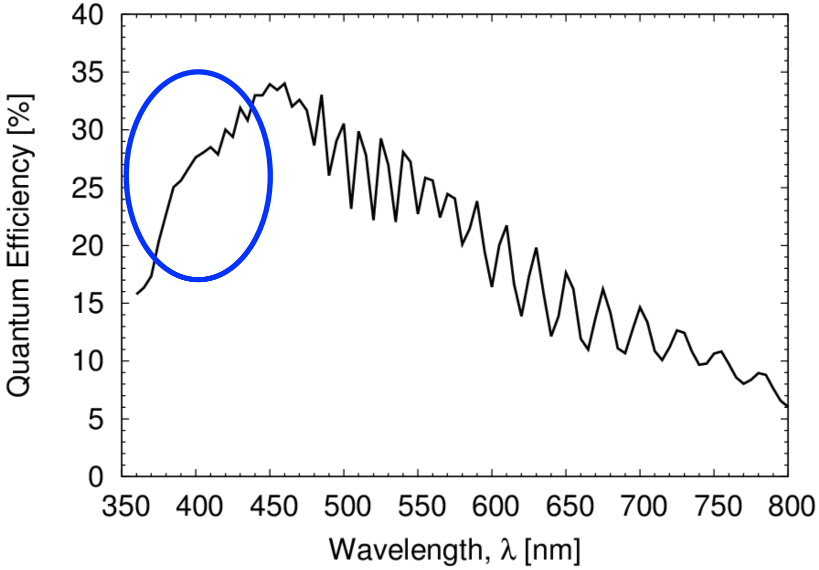


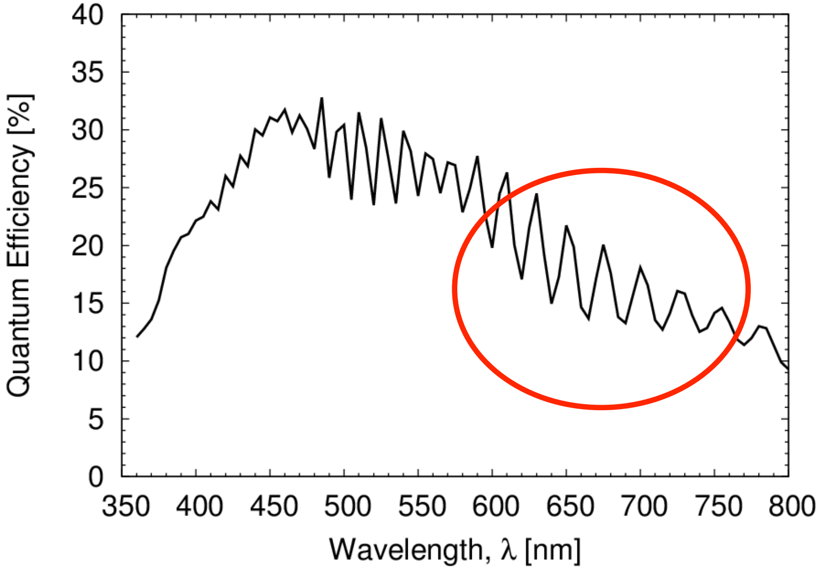
Better in the UV and blue



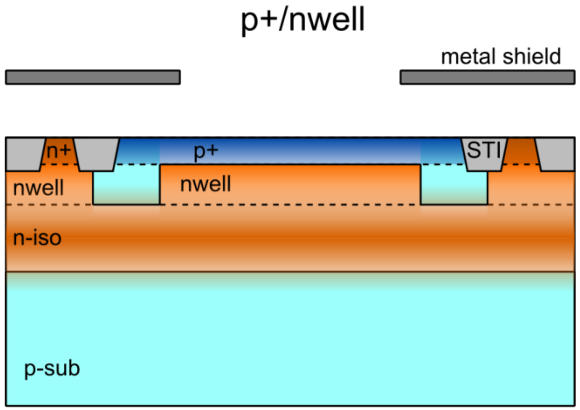
Better in the NIR

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

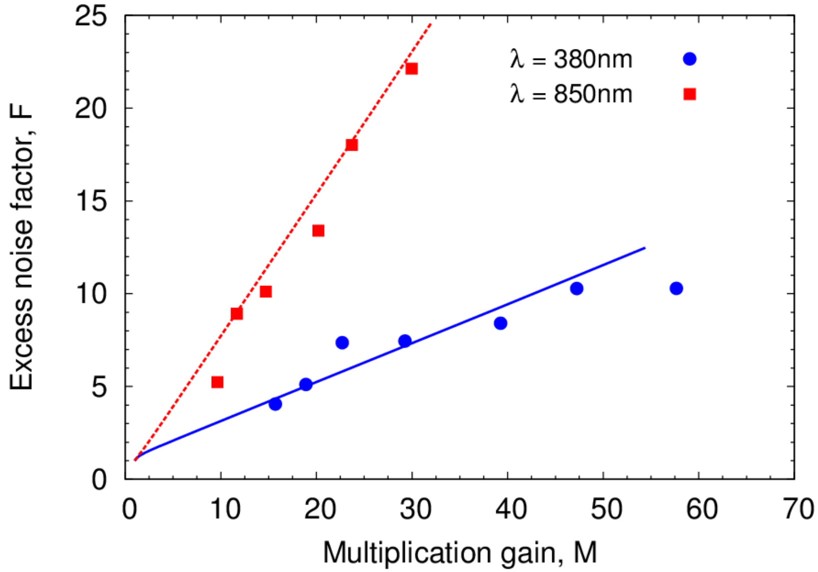


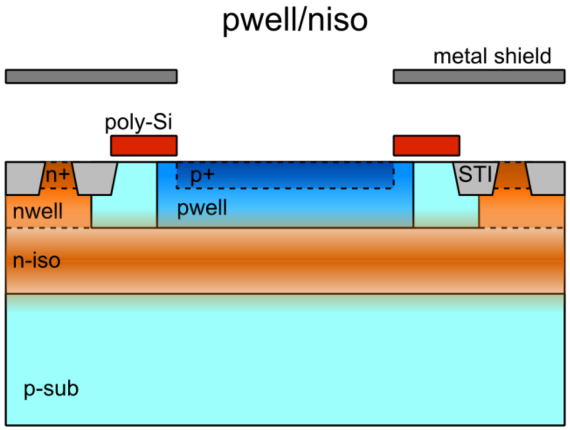


Excess Noise Factor



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





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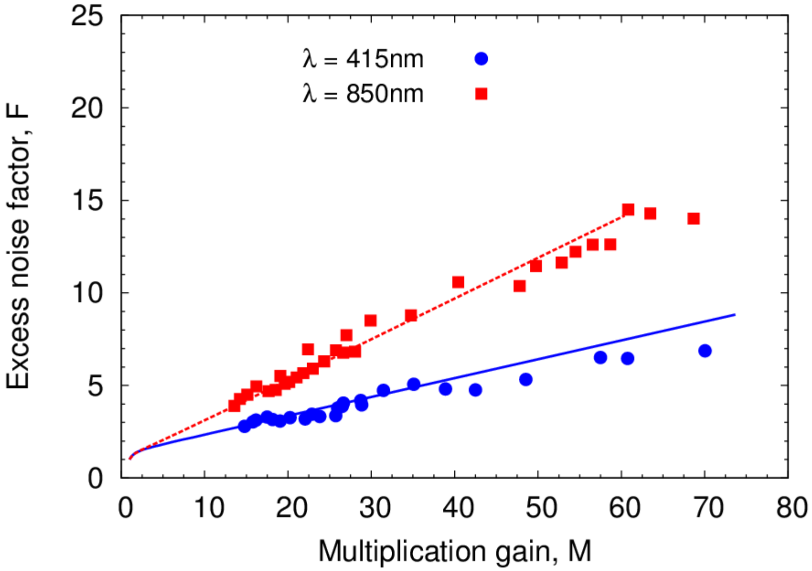
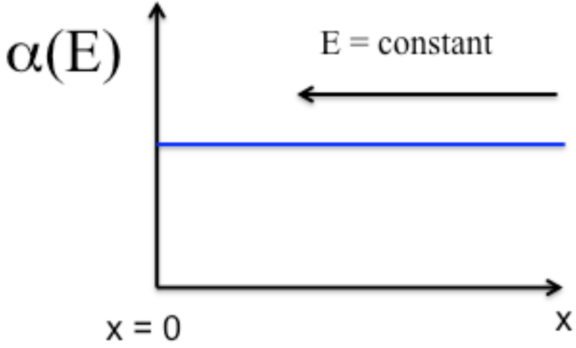


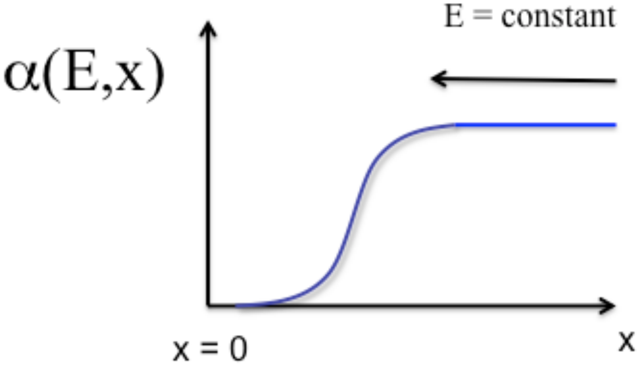
Ionization Rate Models



1) Local model:

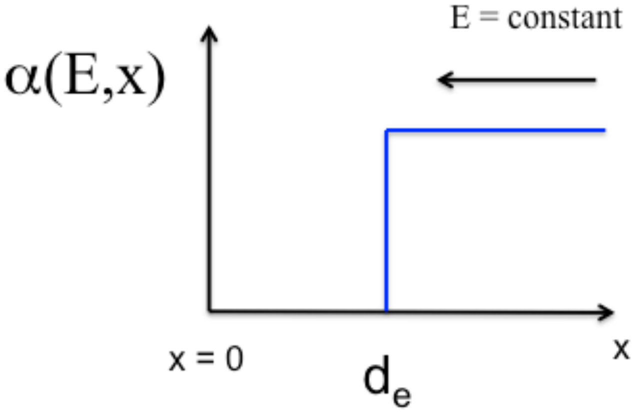
α depends only on the electric field E

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
- α depends on electric field E and position x

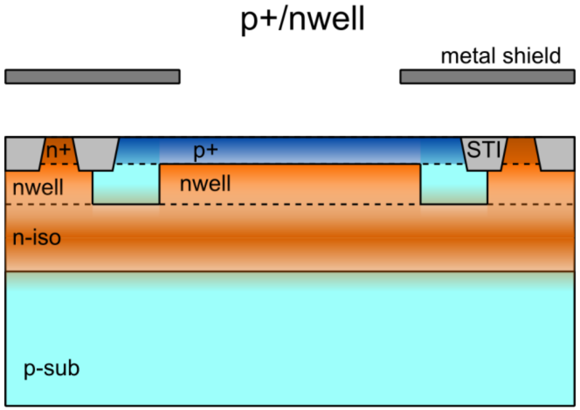


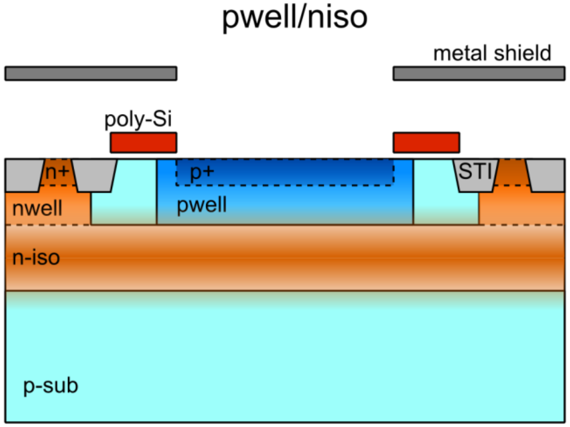
3) Simplified non-local model:

- Dead-space d_e defines a sharp transition
- d_e proportional to ionization threshold energy

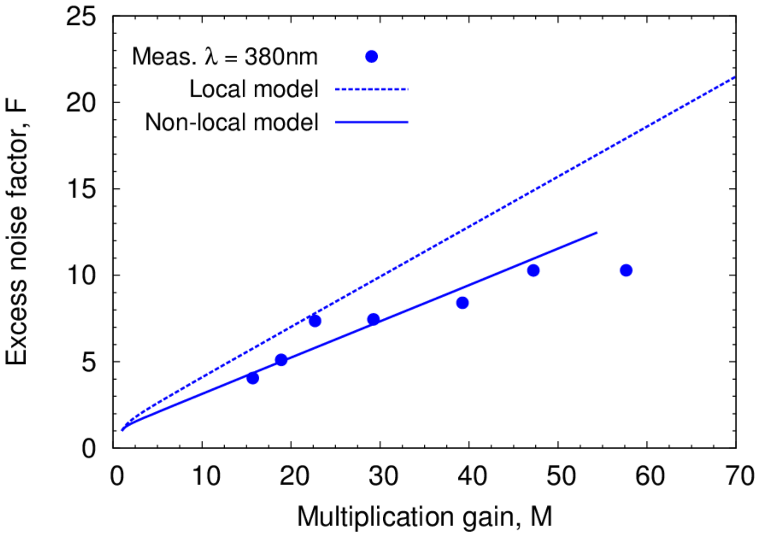
Non-local (dead-space) model: Hayat et al., IEEE JQE, 1992
Ion. rates (nonlocal): Okuto and Crowell, Phys. Rev. B, 1974

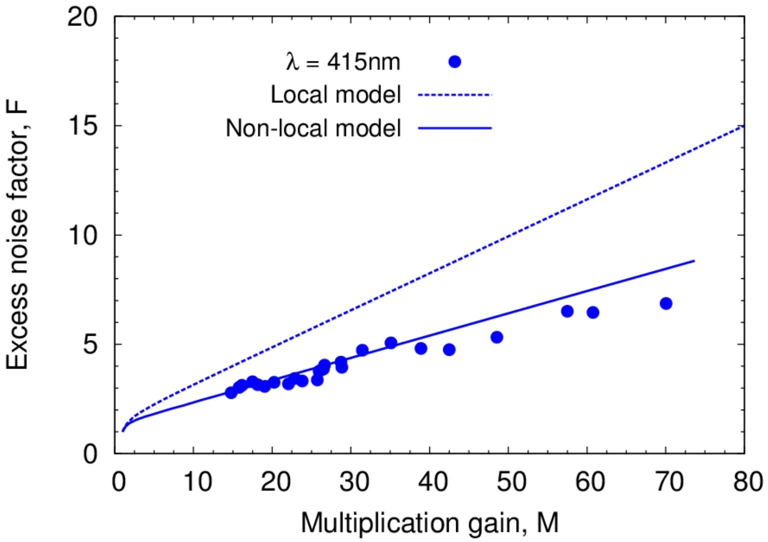
F vs M: model comparison



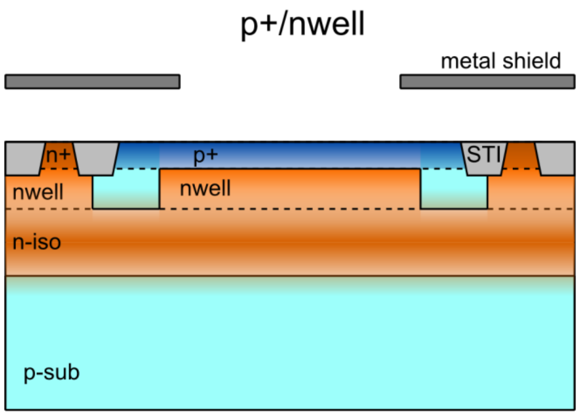


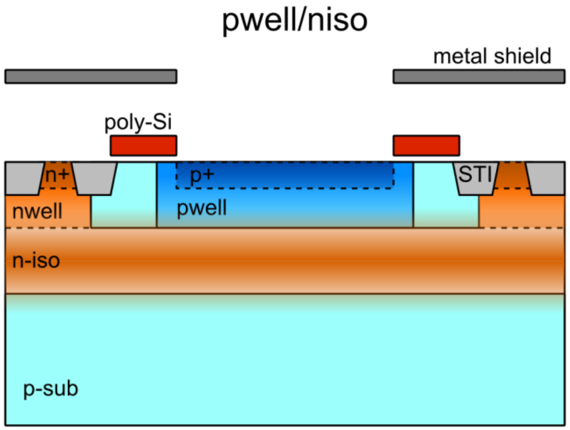
- Local model not suitable due to high electric field and narrow space-charge regions
- Very good agreement with non-local models for electron-initiated avalanche



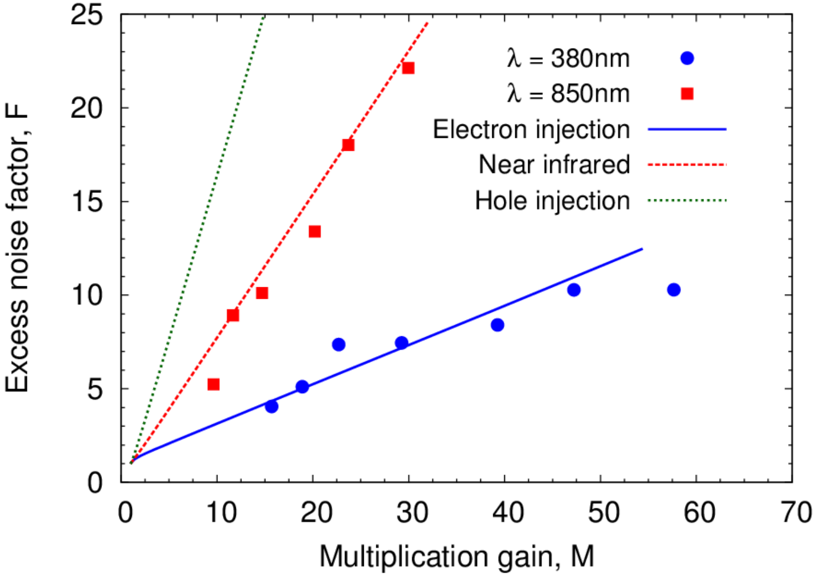


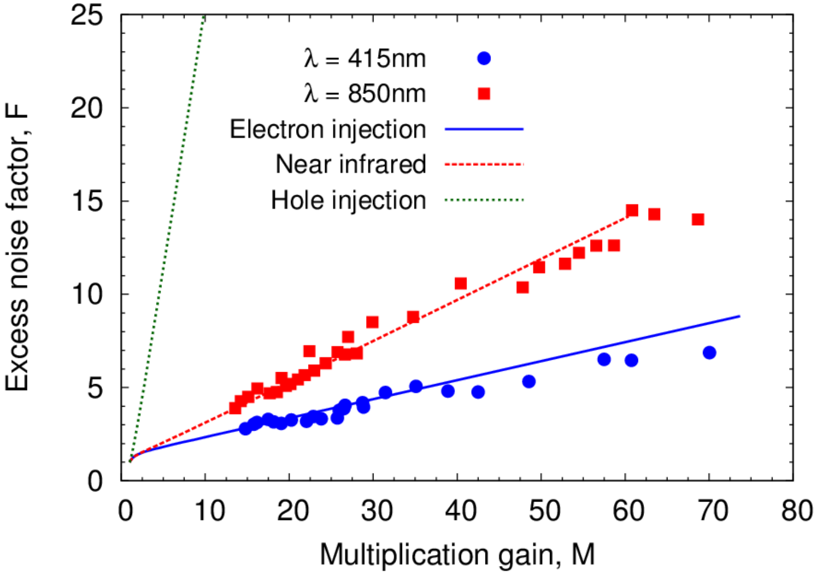
F vs M: non-local model





- Also non-local model with hole-initiated avalanche overestimates F
- Good agreement with NIR approximation (mixed injection) with Xj 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

Acknowledgement

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