A New Model for Optical Crosstalk in Single-Photon Avalanche Diodes Arrays

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Outline

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- SPAD's array structure

Optical crosstalk theory
- Crosstalk phases
- Direct optical paths

Experimental characterization
- Crosstalk characterization
- SPAD emission spectrum
- Photon propagation inside the chip
- Quantum Efficiency

Numerical Model
- Model description
- Comparison with experimental data
In recent years SPAD's array were used for:
- Adaptive optics for astronomy
- 3-D imaging
- Parallel multichannel TCSPC
- Molecular dynamics (FCS)
- Microarray analysis: allergens, DNA, etc...
Like APD is a reverse biased **pn junction** but ...

Avalanche Photo-Diode
- Biased slightly *below* breakdown
- Linear-mode: it's an **AMPLIFIER**
- Gain: *limited* < 1000

Single-Photon Avalanche Diode
- Biased well *above* breakdown
- Geiger-mode: it's a **TRIGGER** device
- Gain: *meaningless*!
Double-epitaxy Single Photon Avalanche Diodes (SPAD)

- Good QE and low noise
- Picosecond timing
- Low voltage: 15 to 40V
- Low power: cooling not necessary
- Standard Si substrate
- Planar fabrication process **COMPATIBLE** with array detector and integrated circuits
- Robust and rugged
- Low-cost

**Planar structure:**
- typical active area 20–200 μm diameter
Device structure and Arrays

- Timing resolution (~30 ps)
- High PDE (peak ~ 50%)
- Internal noise (dark counts, afterpulsing, crosstalk)

- Epi-layer (5 μm) over n-type substrate (500 μm, ~10^{17} cm^{-3})
- n++ isolation region (~10^{20} cm^{-3}) between SPADs
When an avalanche is triggered in one SPAD we have:
- Secondary photons emission due to the avalanche current
- Photons propagation throughout the chip
- Secondary photon detection by a nearby detector
Optical Crosstalk Theory

When an avalanche is triggered in one SPAD we have:

- Secondary photons **emission** due to the avalanche current
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Direct optical paths

Dependence of the emitted optical power

- $1/R^2$ attenuation due to geometrical propagation
- Silicon absorption $\sim e^{-\alpha R}$

We expect at least an $1/R^2$ dependence
Experimental characterization

Two possible measurements:

- **Coincidence Measurement**
  - Two SPADs operate *simultaneously*
  - Output signals are *time-correlated*

- **Pseudo-crosstalk**
  - *Emitter* biased with a constant current above breakdown
  - *Detector* counts the photons emitted by the emitter

*Pseudo-crosstalk* gives only a quantity *proportional* to crosstalk *but* is useful to study the crosstalk as function of the distance.
 Dependence of crosstalk on the distance

- Does not follow an $1/R^2$ behavior
- Is not either monotonous
Dependence of crosstalk on the distance

- Does not follow an $1/R^2$ behavior
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Direct optical paths are not able to explain the phenomenon
Reflections off the bottom?

Hypothesis

- Reflections off the bottom do contribute to the crosstalk

Proof

- Measurements of emission from the backside prove the existence of photons hitting the bottom

Reflected optical paths can contribute to the crosstalk
Importance of the reflections off the bottom

Hypothesis

- Is there the contribution due to the bottom reflection *dominant*?

Proof

- Measurements with a reflective layer on the backside show a *marked increase in the crosstalk intensity*

Notwithstanding the small fraction of re-injected photons we recorded a crosstalk increase of 10–20%

Optical paths reflected off the bottom give a *dominant contribution*
We need to study

- **SPAD emission spectrum**
- **Photons propagation throughout the chip**
- **Photon Detection Efficiency (PDE)**
Measured emission spectrum of our SPAD

SPAD spectrum extends well beyond a wavelength of 1100 nm

These components can contribute to the crosstalk
Absorption coefficients

Silicon absorption coefficients:

- Intrinsic edge
- Free–carrier absorption (doping dependent)

Our SPAD process

**Isolation:** doping level \( \sim 10^{20} \text{ cm}^{-3} \)

**Substrate:** doping level \( \sim 10^{17} \text{ cm}^{-3} \)

- The *isolation* acts like trenches blocking the direct optical paths
- **Minimum** absorption coefficient in the 1100–1200 nm range
PDE decreases more than an order of magnitude from 1100 to 1200 nm.

Crosstalk is due to a narrow wavelength range (<100 nm).
- **Emitter:** isotropically emitting cylindrical volume
- **Isolation:** absorbing surface around each SPAD
- **Substrate:** uniform material (n-type silicon, $\alpha = 3 \text{ cm}^{-1} @ 1100 \text{ nm}$)
- Crosstalk becomes higher increasing the distance from the emitter!
Crosstalk becomes higher increasing the distance from the emitter!
Due to *total internal reflection* ...

- Single reflection \( \rightarrow \) peak at distance \( d_1 \)
- Double reflection \( \rightarrow \) peak at distance \( d_2 \)

*We observe a non monotonous dependence!*
### Bottom reflections

Total internal reflection causes a first strong peak at a $d_1$ distance and a second weaker peak at $d_2$.

### Edge effects

Reflections on the lateral surfaces cause an asymmetric crosstalk behavior.
Simulation–Measurements Comparison

- The x axis indicates the SPAD position.
- The arrow marks the detector position (1).
- Continuous line: measured crosstalk.
- Dashed line: simulated crosstalk.
Simulation–Measurements Comparison

- The $x$ axis indicates the SPAD position
- The arrow marks the detector position (1)
- Continuous line: measured crosstalk
- Dashed line: simulated crosstalk

Excellent agreement with experimental data
Conclusions

- Crosstalk can’t be eliminated simply by means of trenches
- Main contribution to crosstalk comes from bottom reflections (using trenches)
- Total internal reflection can occur, so photons reflecting with angles of incidence greater than critical angle are dominant for crosstalk
- The optical model we proposed explains both the spatial and the spectral dependence of the crosstalk.
Thank you for the attention!
Spectrum analyzer

Input Achromatic Doublet (AC254-030)

SPAD

Diaphragm

Prism (PS855)

Hamamatsu CCD C4880

Output achromatic doublet (AC254-075)
Pseudo-crosstalk Measurement Description

- Performed for all the emitter-detector pairs
- Collected data were filtered using digital lock-in
- 100 to 10000 measurement cycles per emitter

**Measurement Cycle**

- Detector working in normal operation mode
- Emitter is turned ON (biased at constant current) and OFF alternatively
- Counts measured with emitter OFF are subtracted from counts measured with emitter ON and results for different cycles are averaged (*digital lock-in filtering*)
Measurement-Simulation comparison