Electrical and optical Si SPAD simulation with Ansys Lumerical

Presenter: Bozidar Novakovic, Ansys

Collaborators:
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Dylan McGuire, Ansys

March 21, 2022

Ansys

Ansys Lumerical Application Spaces

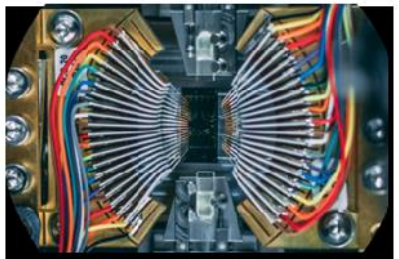
Datacom

- Circuit yield estimation
- Minimize bit error rate
- Thermal stabilization

LiDAR

- Grating coupler optimization
- Phased array design
- Metasurface design

Quantum



- Robust passive component design

PDK

- Passive component optimization
- IO port design
- Compact model

Sensing

- Custom component design with PDK

- Optimize pixel efficiency
- Minimize crosstalk

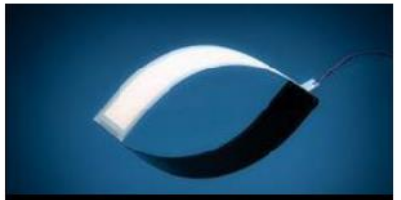
AR/VR

- Metalens design
- Display pixel design

Display

- Optimize pixel

Lighting



- Optimize efficiency

Metrology & defect

- Defect detection
- Optical metrology

Bozidar Novakovic, 2022 EPIC Online Technology Meeting on Single Photon Sources and Detectors

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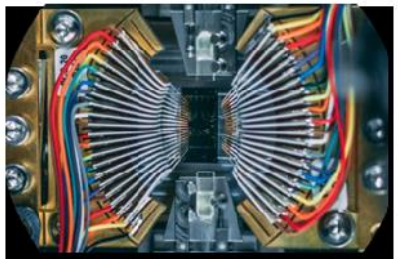

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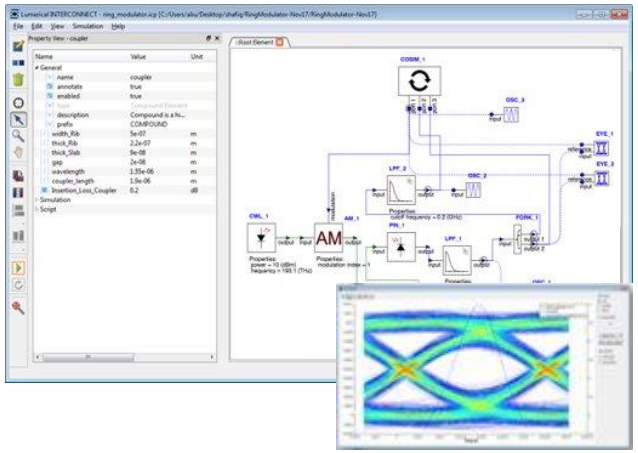
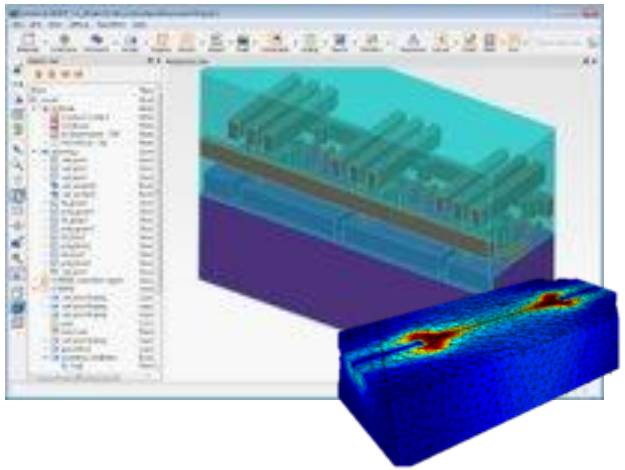
Ansys Lumerical:
A comprehensive set of tools and features for photonics





Photonic Integrated Circuit Simulation

INTERCONNECT Photonic Integrated Circuit Solver
Photonic Verilog-A Platform
CML Compiler Photonic Model Development

Photonic Multiphysics Simulation

FDTD 3D Electromagnetic Solver
MODE Waveguide Simulator
CHARGE 3D Charge Transport Simulator
HEAT 3D Heat Transport Solver
DGTD 3D Electromagnetic Solver
FEEM Waveguide Solver
MQW Quantum Well Gain Solver
STACK Optical Multilayer Solver

Interoperability, HPC & Cloud features

HPC & Cloud
Ansys Cloud, HPC clusters, AWS, Azure, schedulers, …

Automation APIs
Matlab, Python, Lumerical Script

Tool Integrations
IPKISS, Klayout, Matlab, Tanner, Virtuoso, ADE

Foundry Support
AIM, AMF, CompoundTek, HHI, imec, SMART, TowerJazz, …

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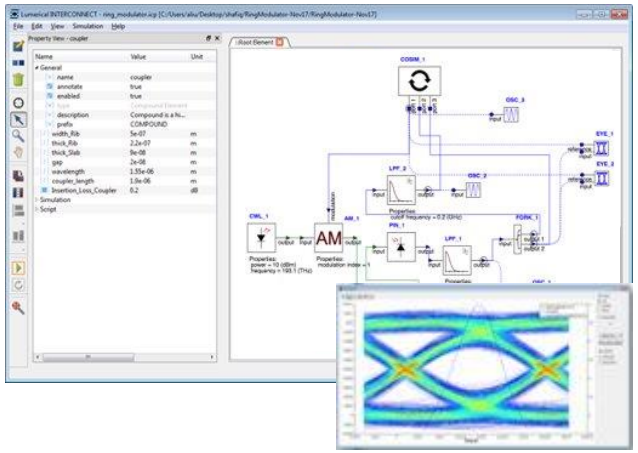

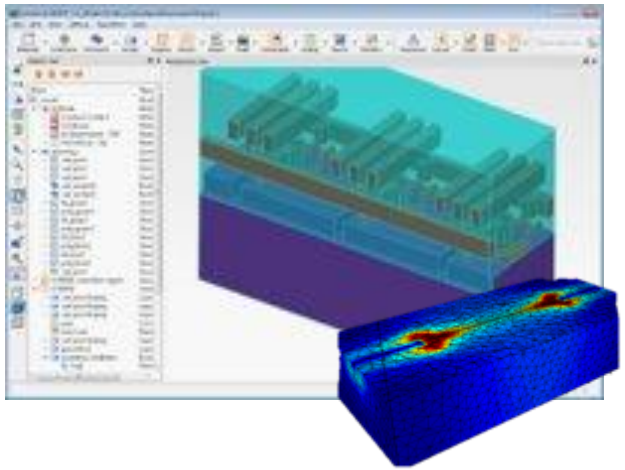

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Photonic Multiphysics Simulation	**Automation APIs** Matlab, Python, Lumerical Script
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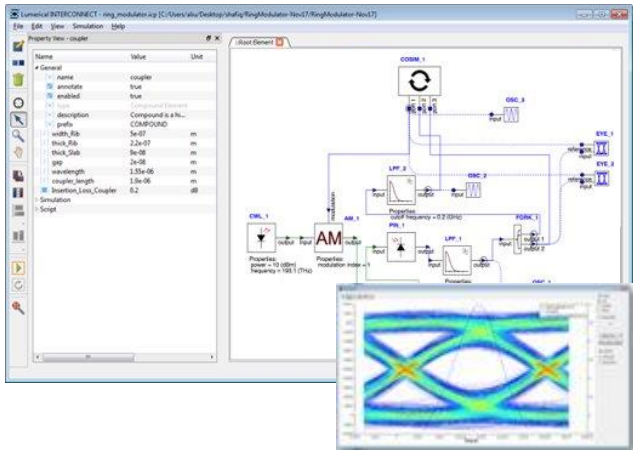

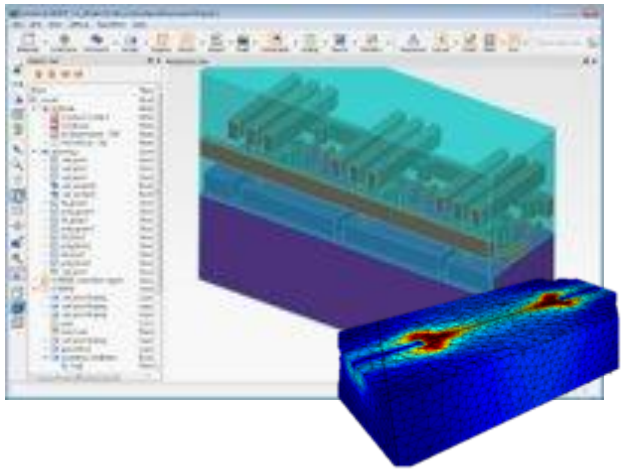

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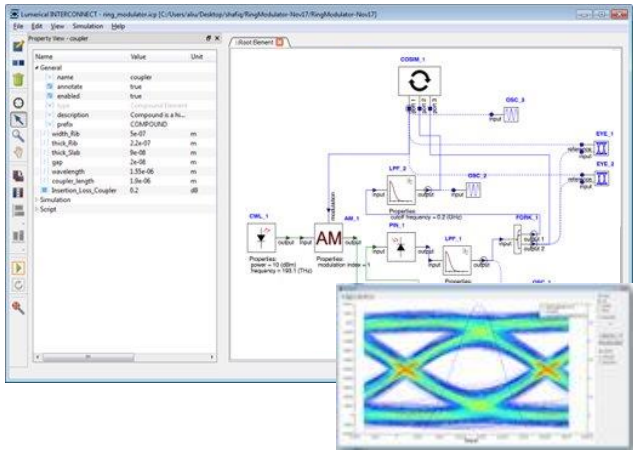

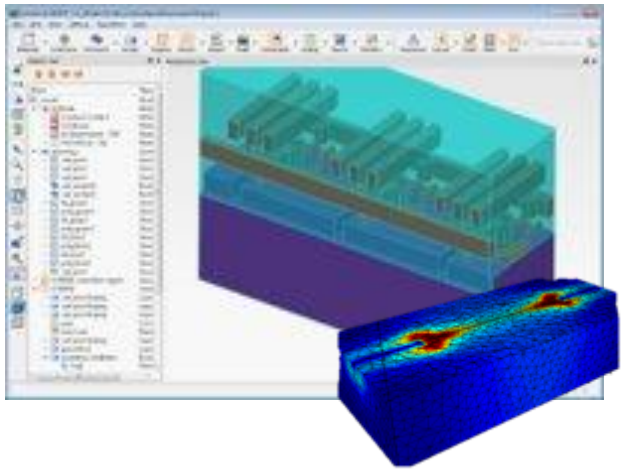

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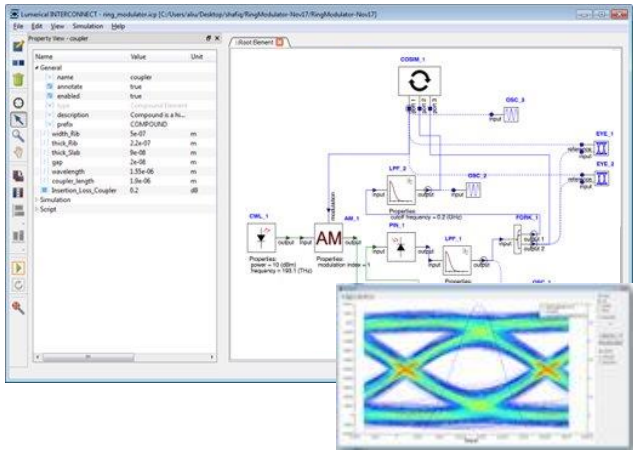

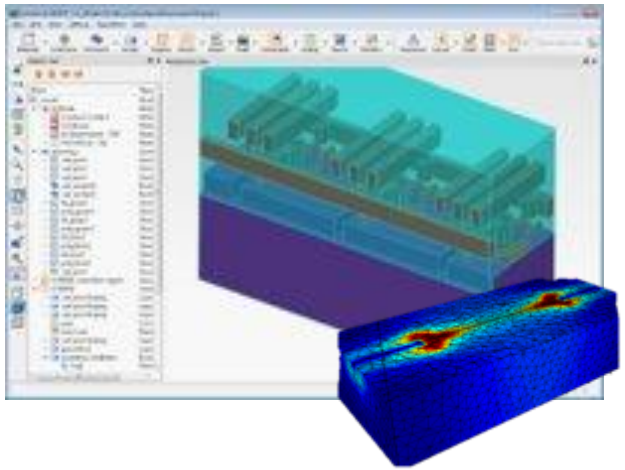

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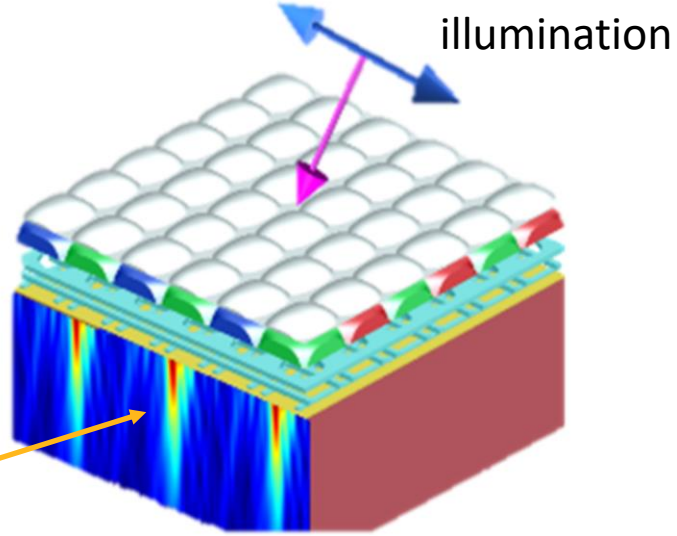
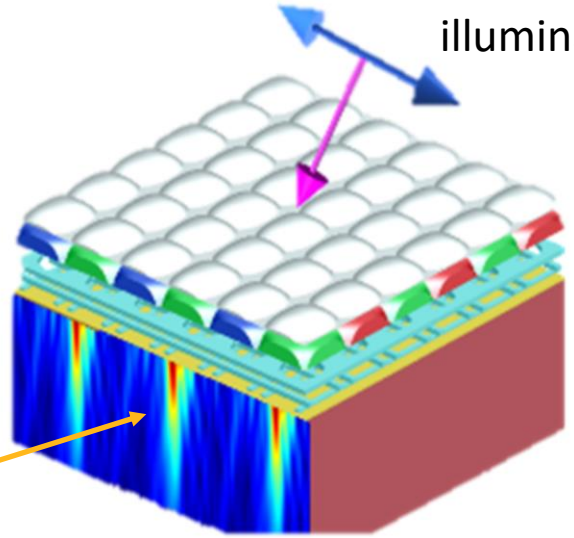
For the simulation of linear avalanche photodetectors, check this example:
https://support.lumerical.com/hc/en-us/articles/360042454814

Simulation workflow and SPAD figures of merit



- absorption
- avalanche triggering
- secondary emission

Simulation workflow and SPAD figures of merit



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CHARGE:

- internal electric field
- thermal electron-hole pair generation

→

- Avalanche triggering probability (ATP)
- Dark Count Rate (DCR)

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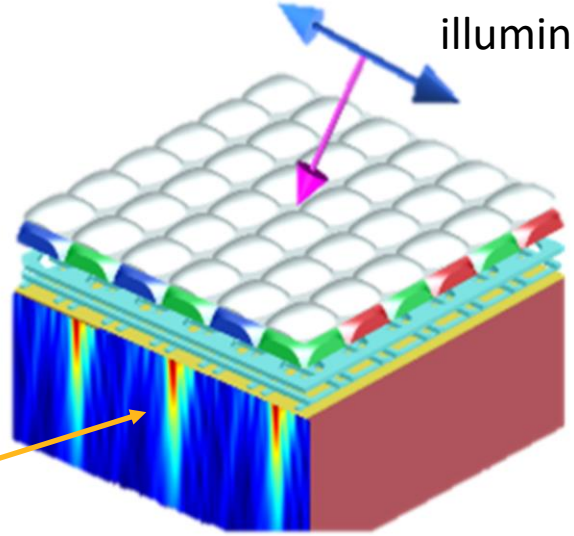

- absorption
- avalanche triggering
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STACK, FDTD:

- transmission
- absorption
- secondary emission

Optical Efficiency (OE)

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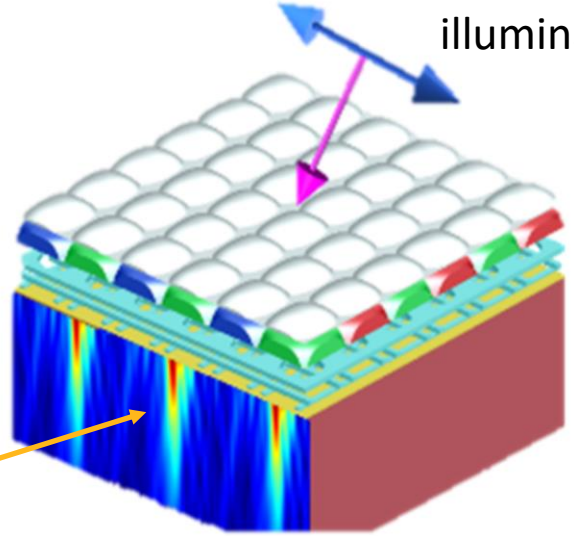

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STACK, FDTD:

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Optical Efficiency (OE)

CHARGE:

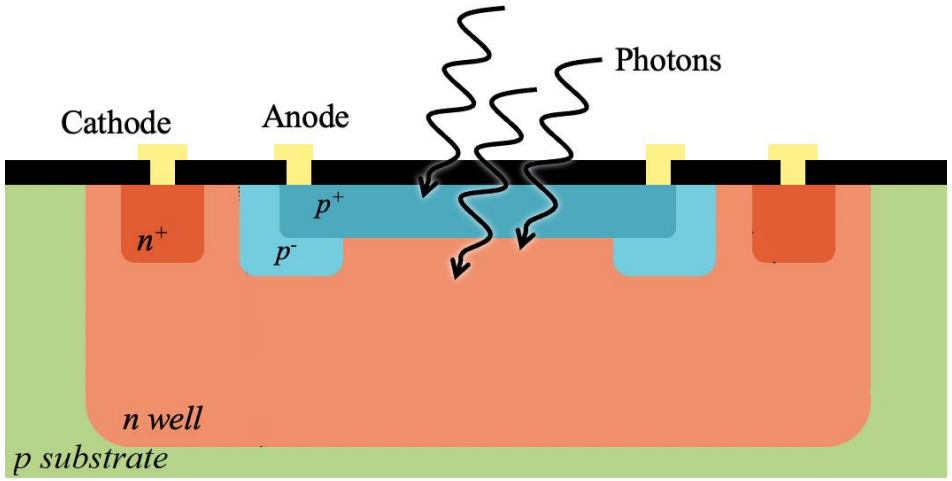
- internal electric field
- thermal electron-hole pair generation

- Avalanche triggering probability (ATP)
- Dark Count Rate (DCR)

- Photon Detection Efficiency (PDE)
- Cross-talk

Electrical simulation of ATP and DCR in a single SPAD

Custom fabricated Si SPAD:



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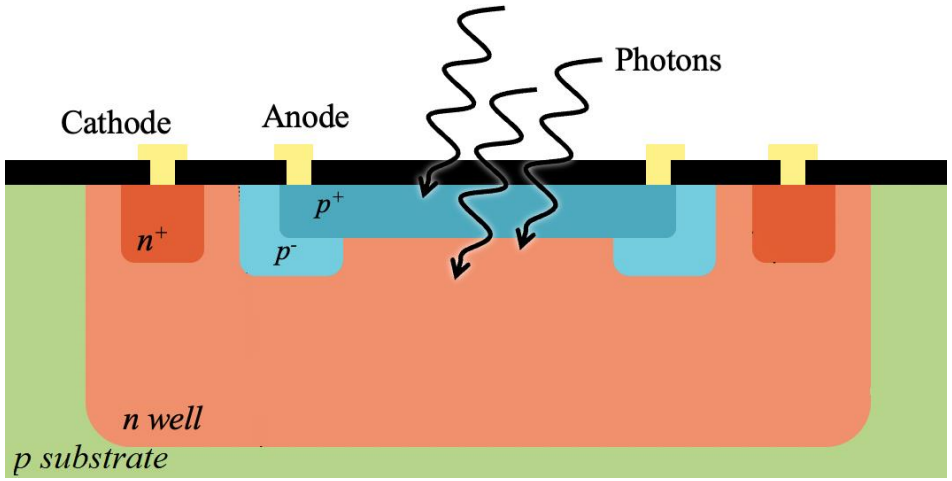
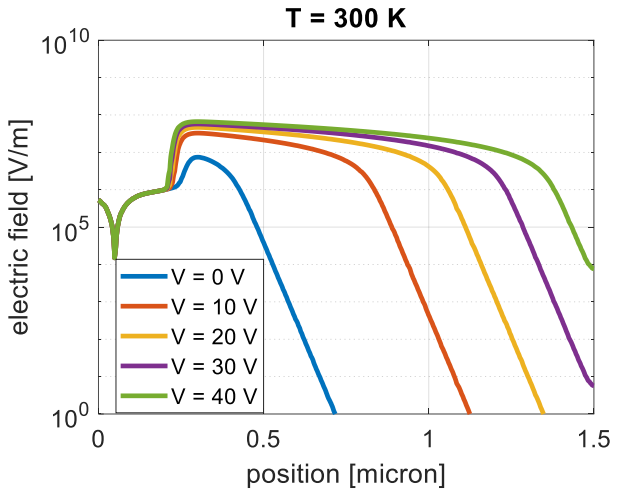
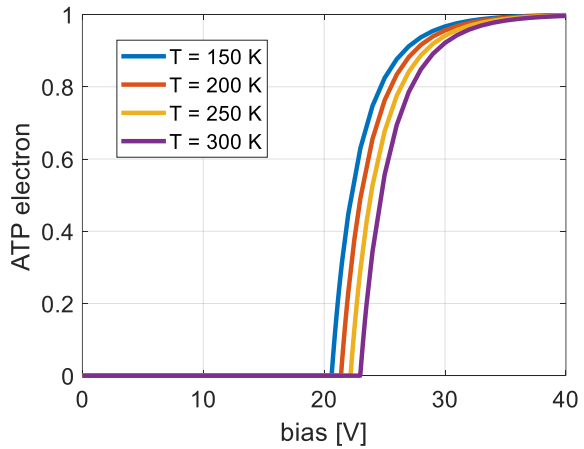
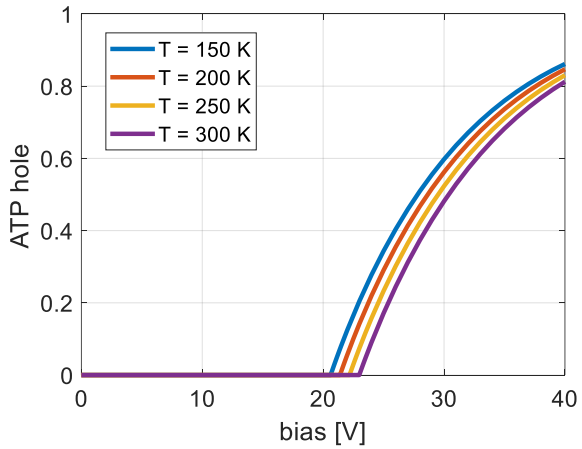




- Electric field simulation:
  - Doping profile:
    - Parameterized analytic (diffusive or implant)
    - Or imported profile on a mesh
- Avalanche triggering probability calculated from electric field and e-h location





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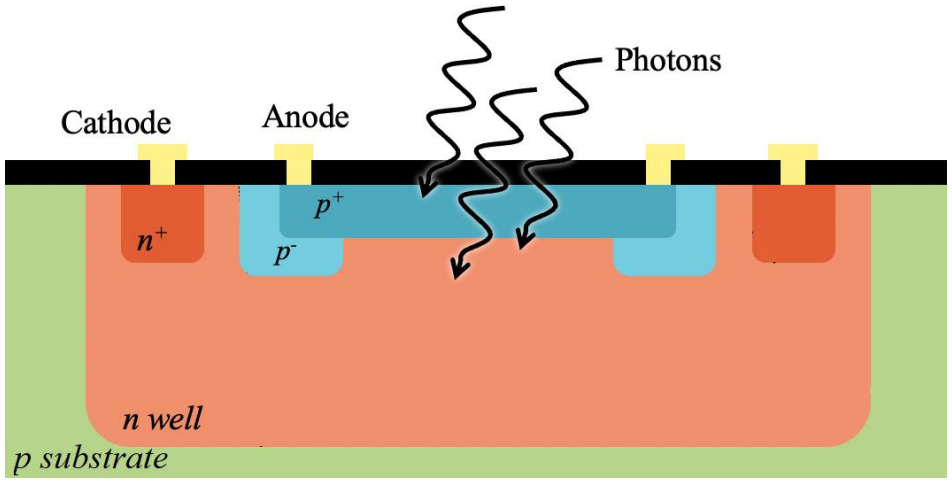
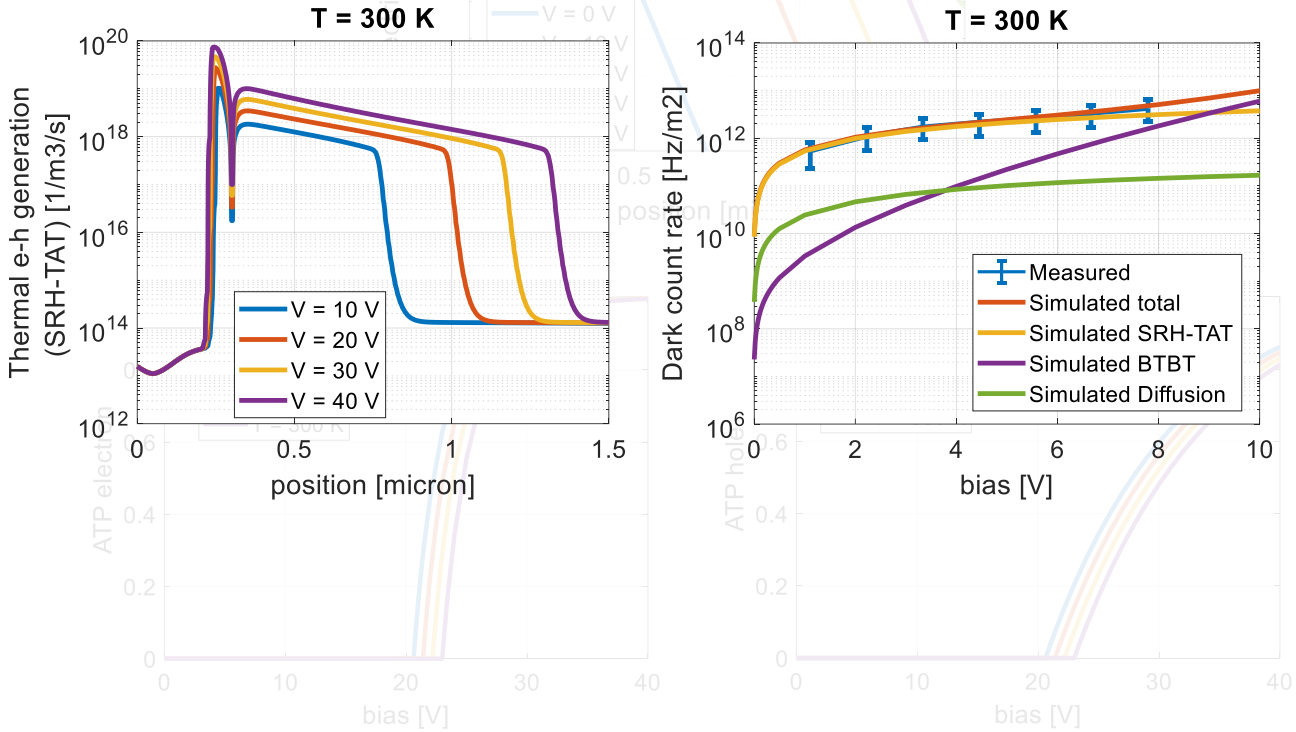


- Dark e-h generation:
  - Thermal:
    - SRH with TAT
    - Diffusion from outside the high field region
  - Band-to-band tunneling
- DCR has a good match to measurement



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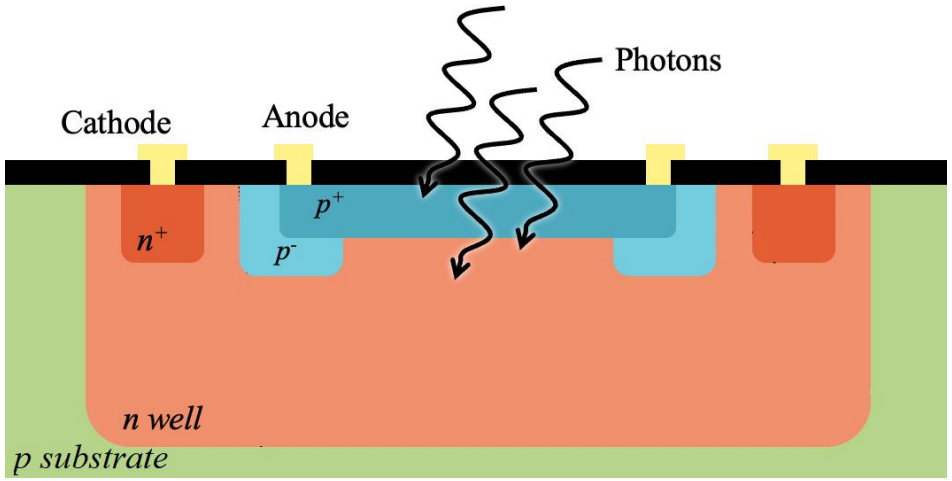
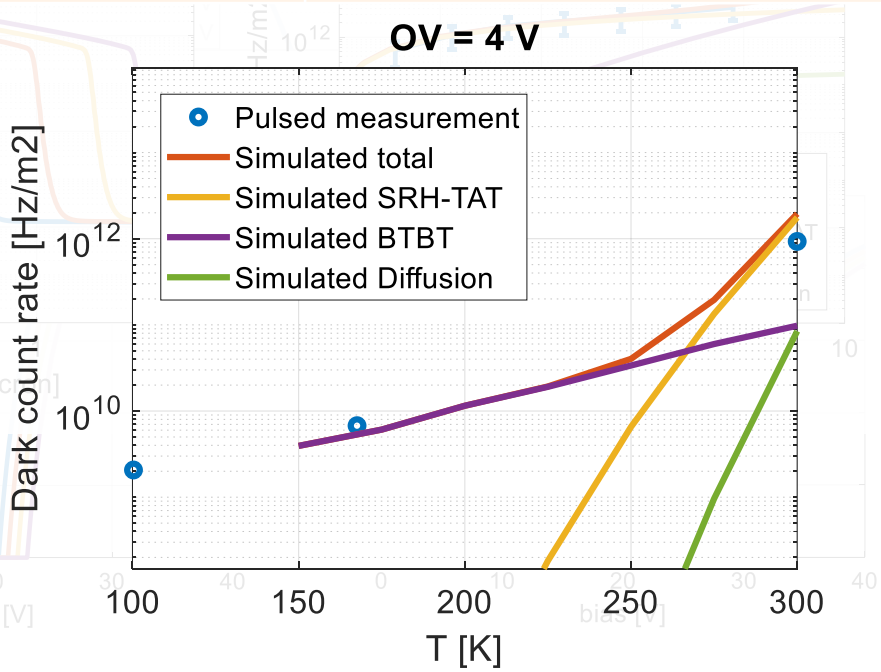


Fitting parameter	Name
C_{bbt}	Band-to-band-tunneling prefactor
τ_n, τ_p	Electron and hole lifetime at room T and low doping
E_t	Trap level
v^n_{surf}, v^p_{surf}	Surface recombination velocity



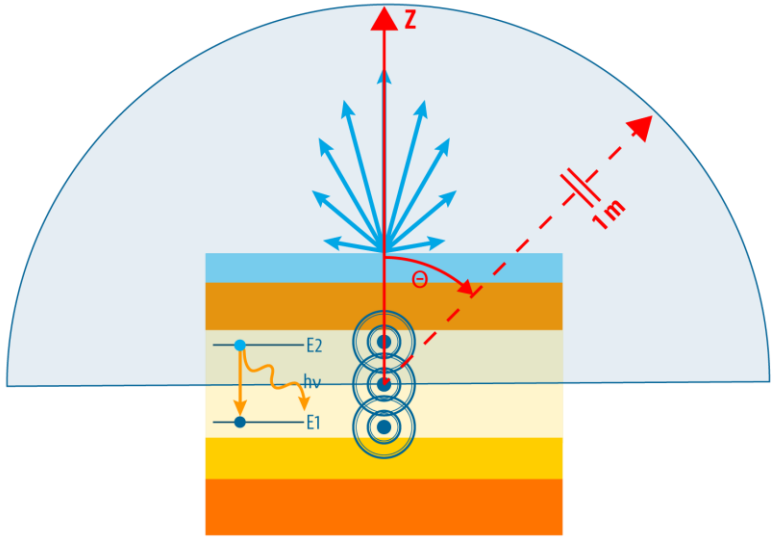
Takeaways from correlating measurement to simulation:

- Some minimum set of process-dependent fitting parameters exists
- SRH-TAT has a higher T slope and dominates at higher T in a good design
- BTBT has a lower T slope and dominates at lower T
- Time-based pulsed measurement and analysis preferrable to frequency counter to filter-out after-pulsing and cross-talk[1]

[1] G. Gallina et al., Nuclear Inst. and Methods in Physics Research, A 940 (2019) 371–379

Optical simulation of the secondary emission in a single SPAD

Avalanche causes secondary emission responsible for external and internal cross-talk



FBK VUV-HD3 SPAD measurements:
J. B. McLaughlin et al., Sensors 2021, 21(17), 5947; https://doi.org/10.3390/s21175947

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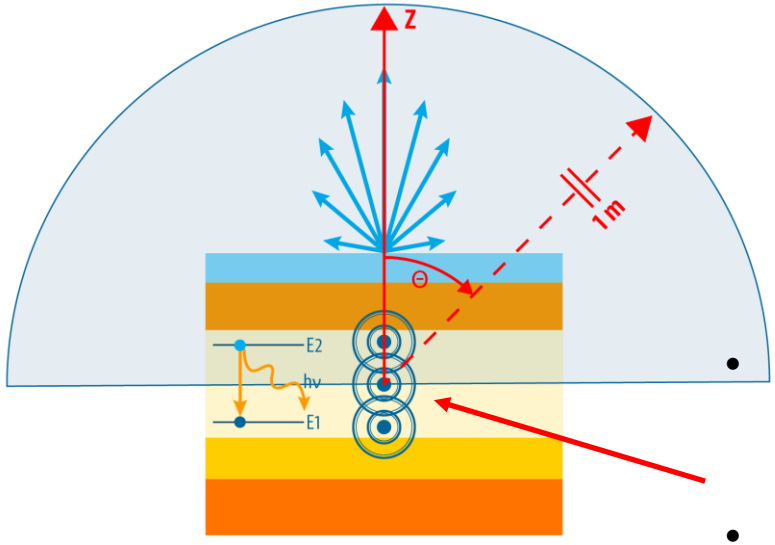

- Random dipole sources placed in a high field region
- Complex index of refraction in each layer

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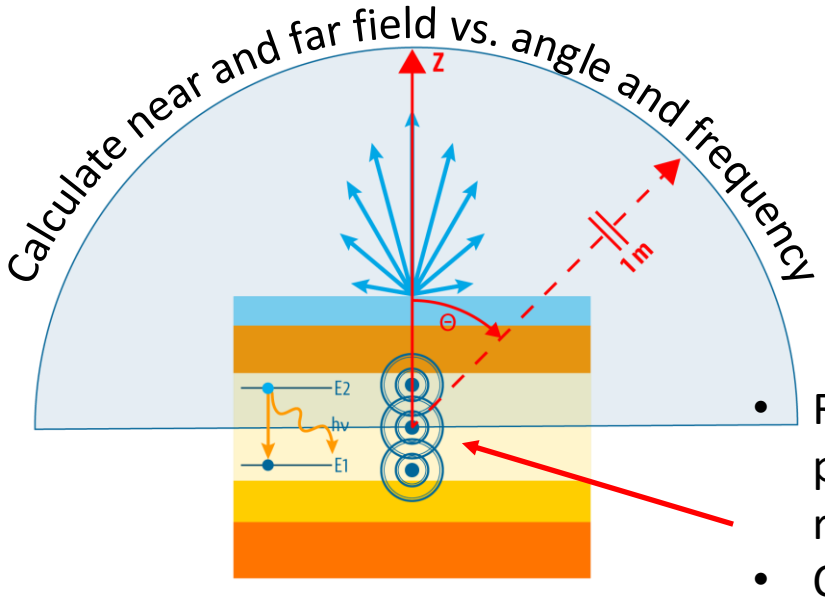

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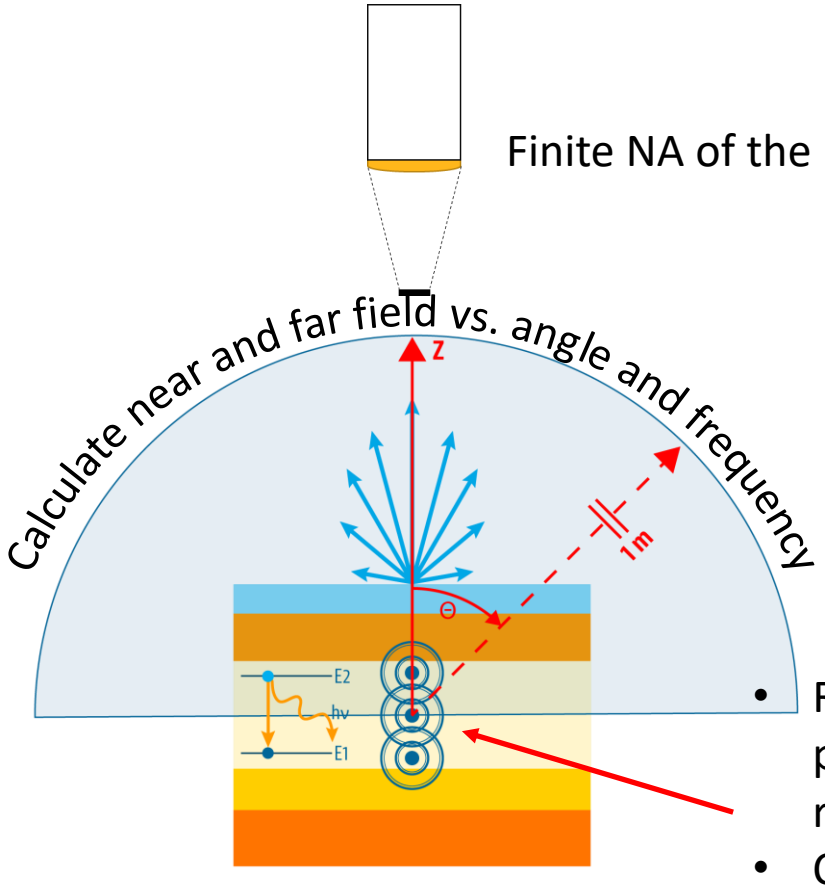

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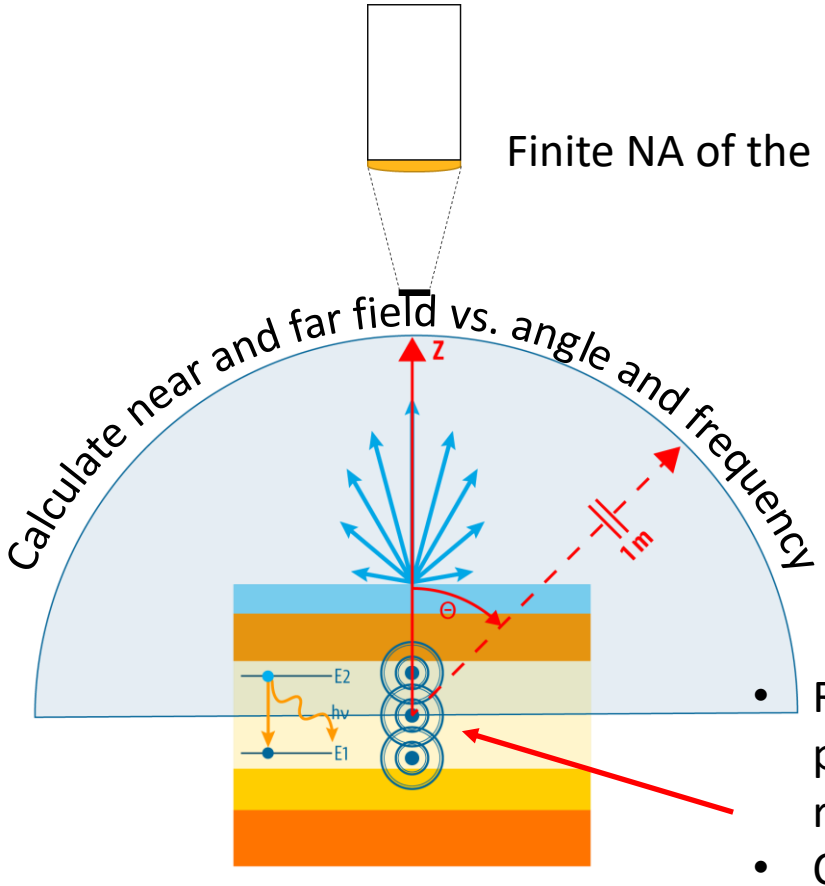

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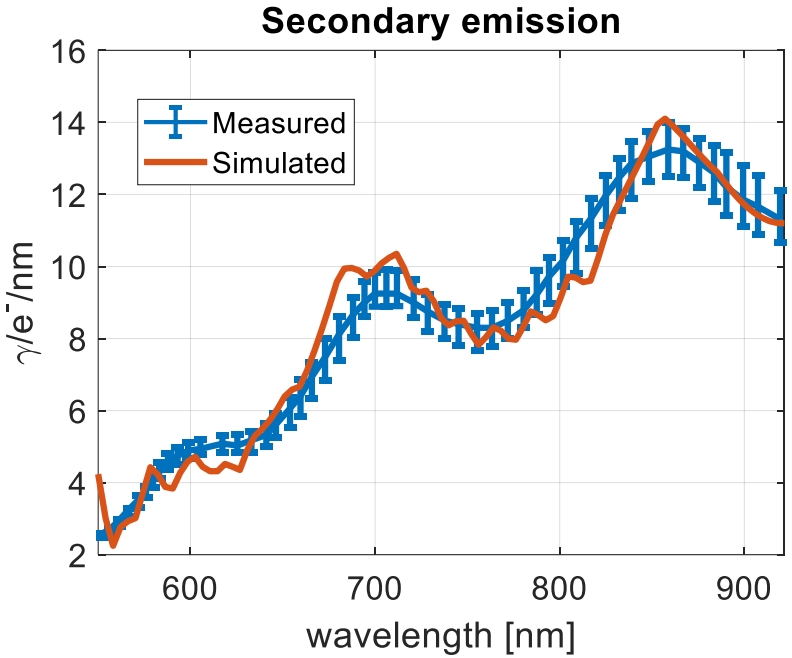

Takeaways:

- Dipole power may need to be correlated to the average measured emission power
- Optical simulation can reproduce the transmission/absorption patterns very well

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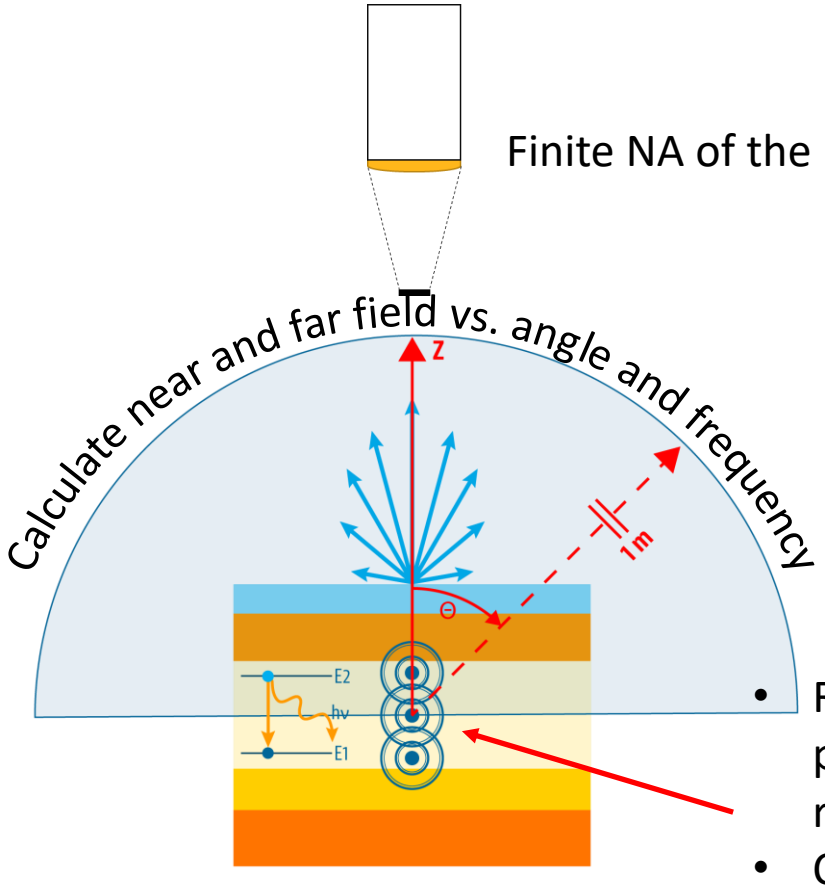

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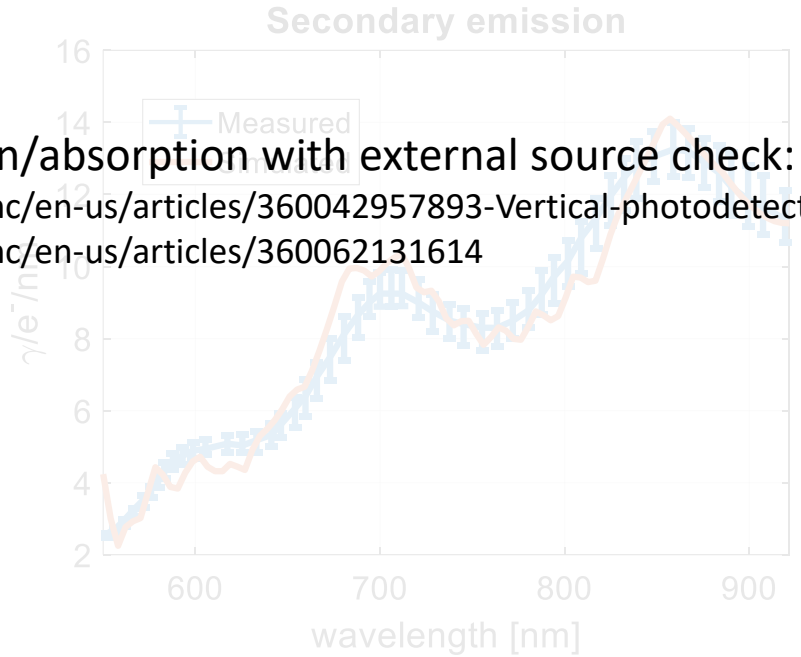

For examples of transmission/absorption with external source check:

- https://support.lumerical.com/hc/en-us/articles/360042957893-Vertical-photodetector
- https://support.lumerical.com/hc/en-us/articles/360062131614

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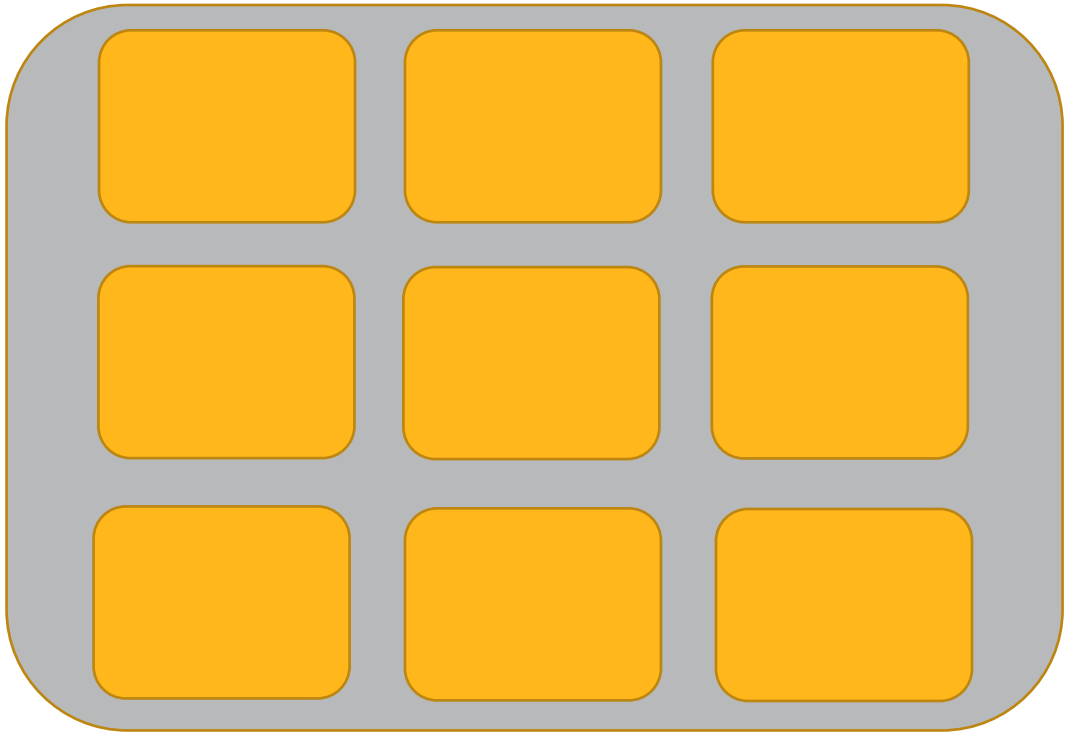
Cross-talk simulation in SPAD arrays: near-term vision

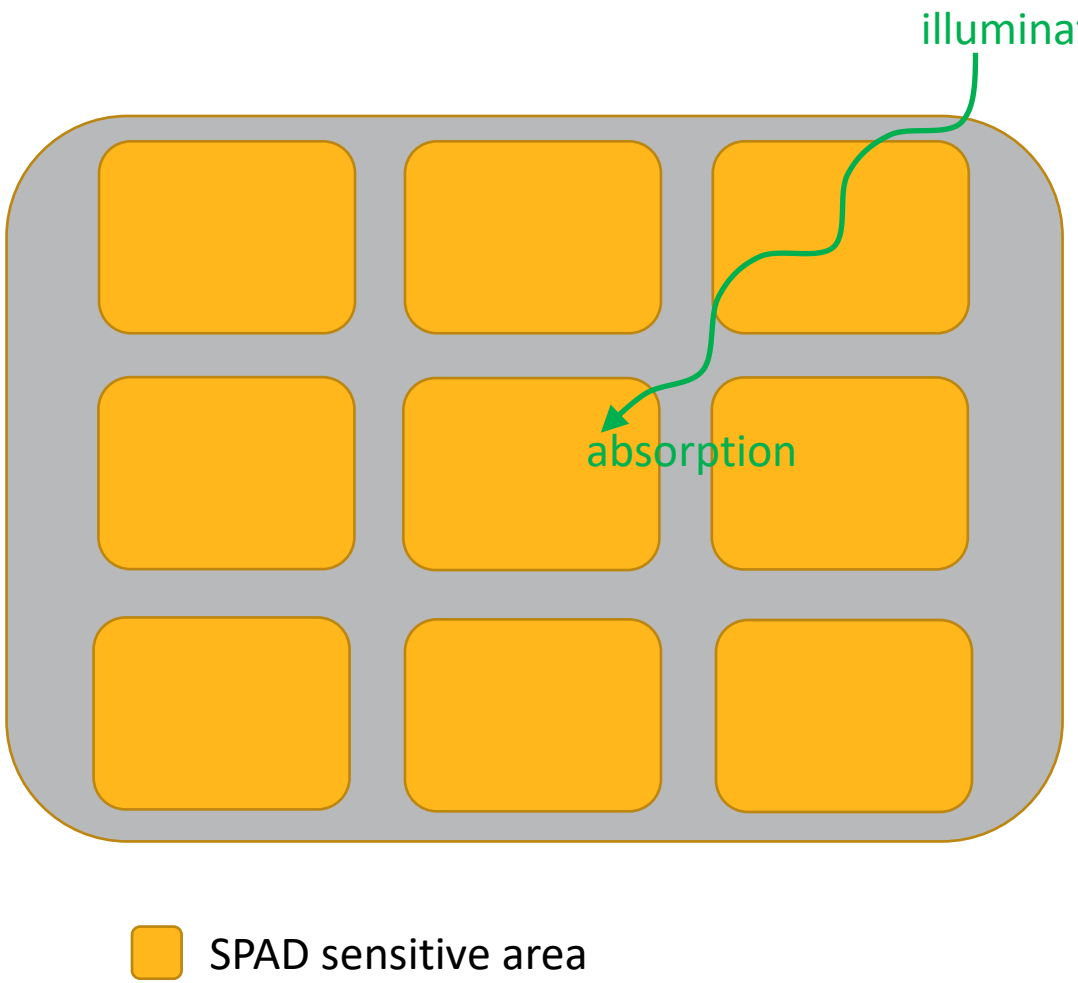


SPAD sensitive area

Origin of cross-talk:

- Upon detection, the resulting avalanche current is the source of secondary photons.
- Secondary photons may trigger avalanches in neighboring SPADs (spurious detection).

Cross-talk simulation in SPAD arrays: near-term vision



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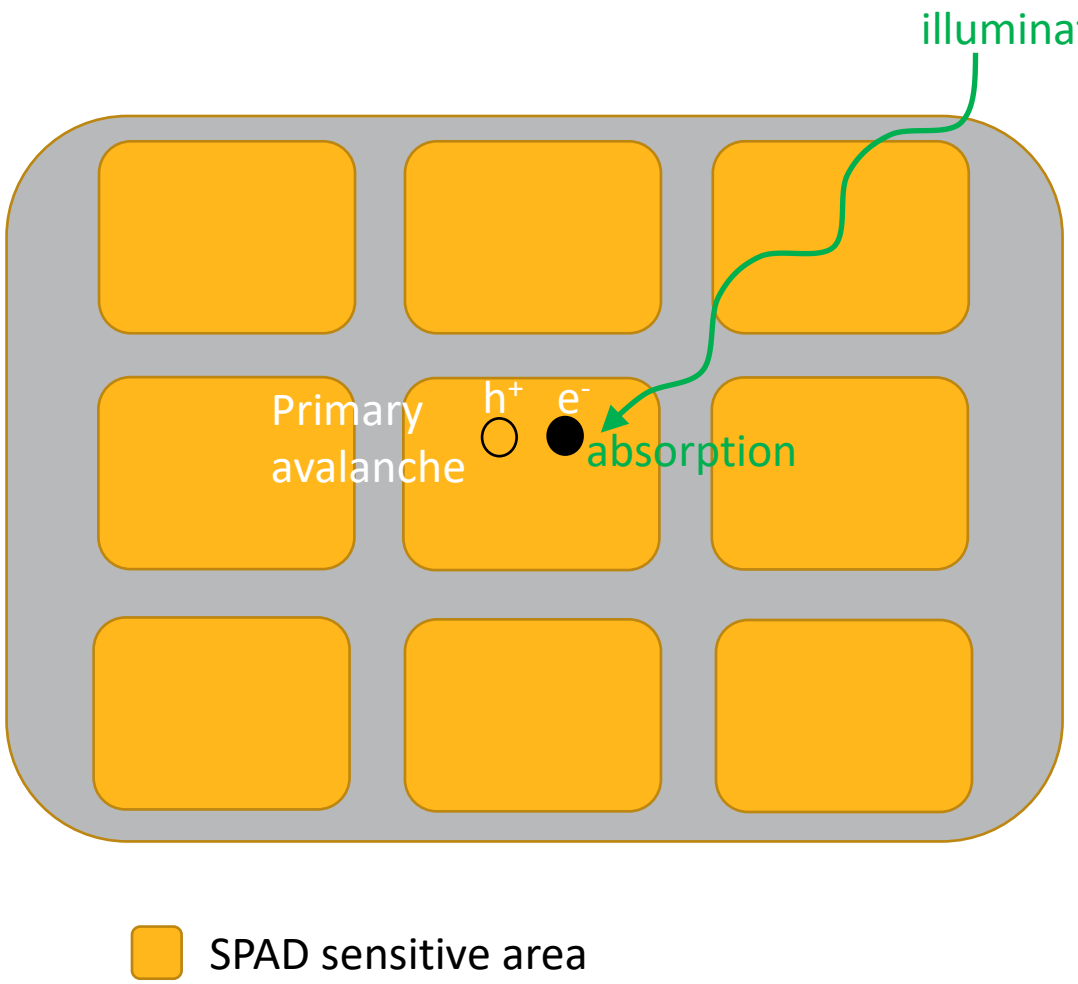

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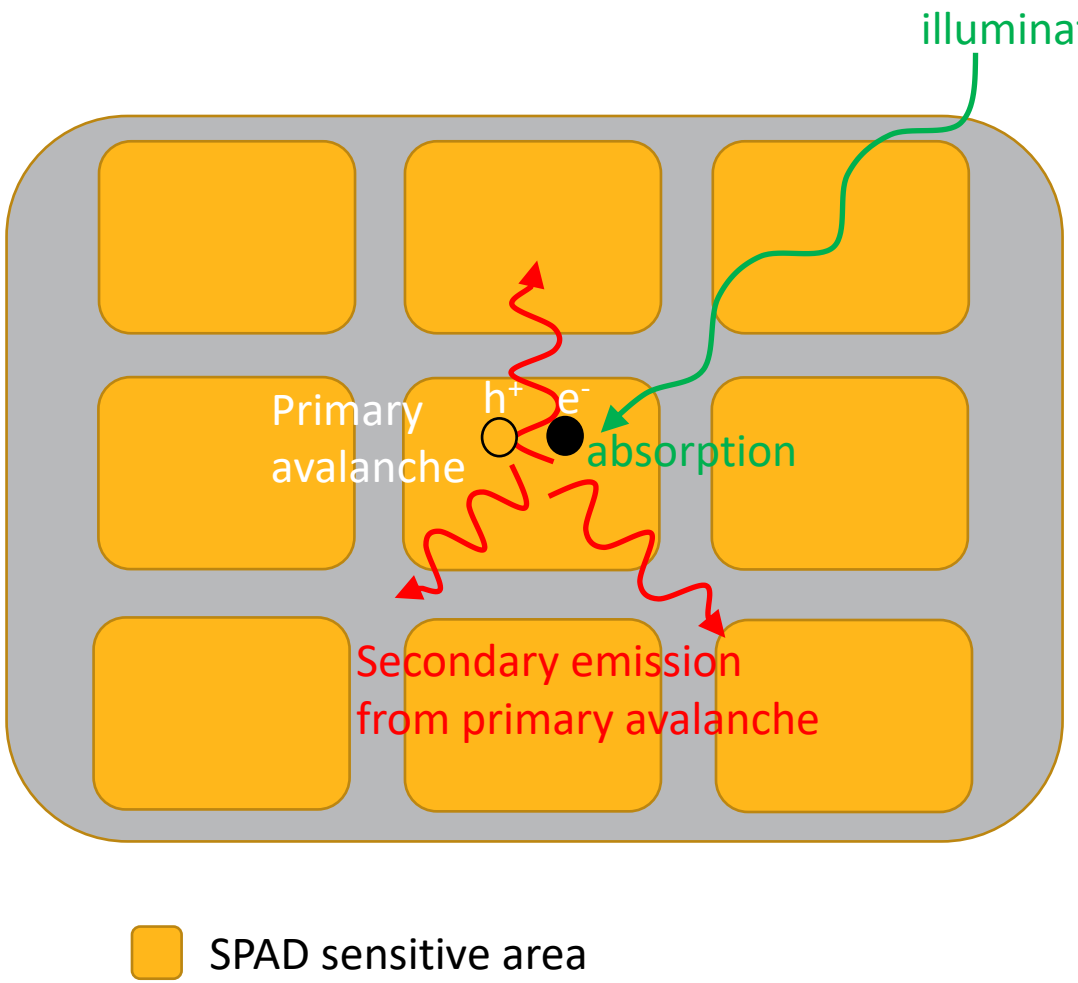

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- Upon detection, the resulting avalanche current is the source of secondary photons.
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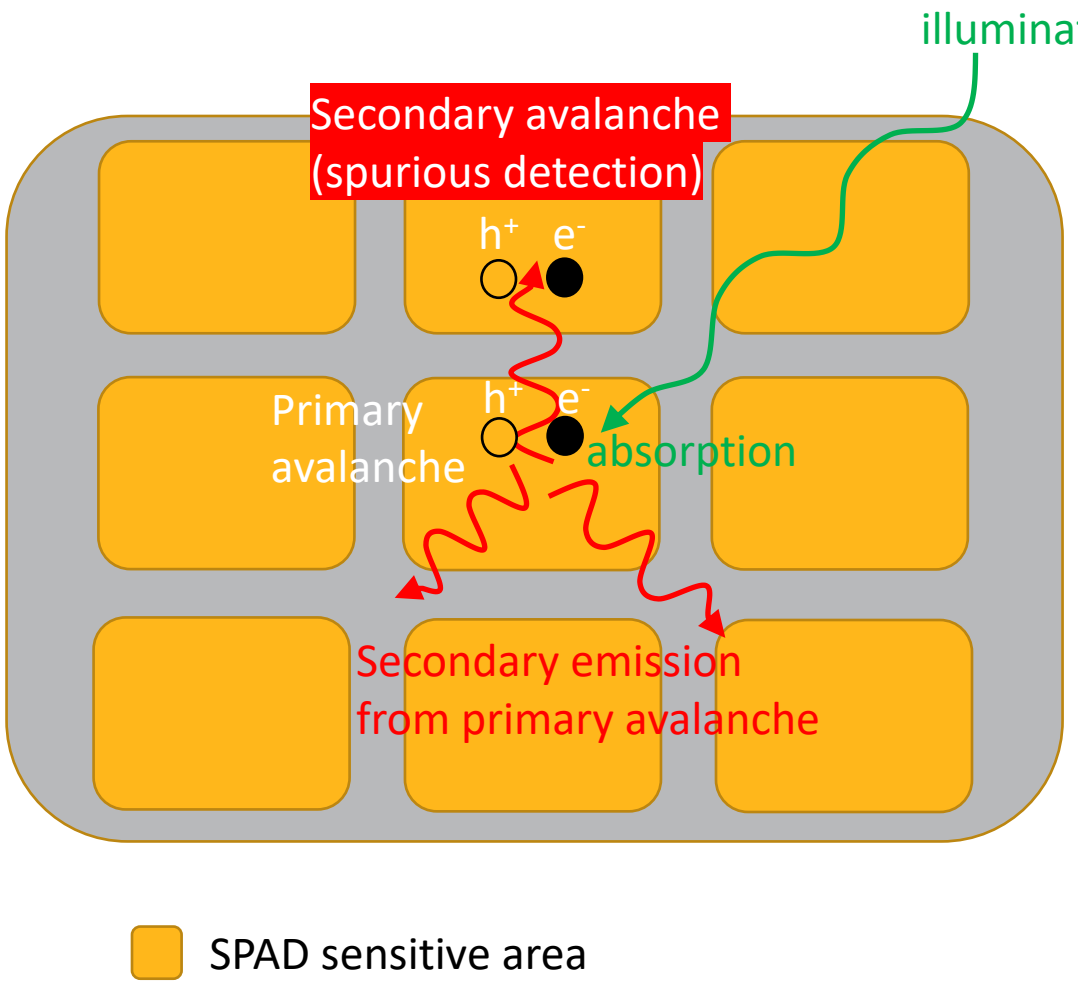

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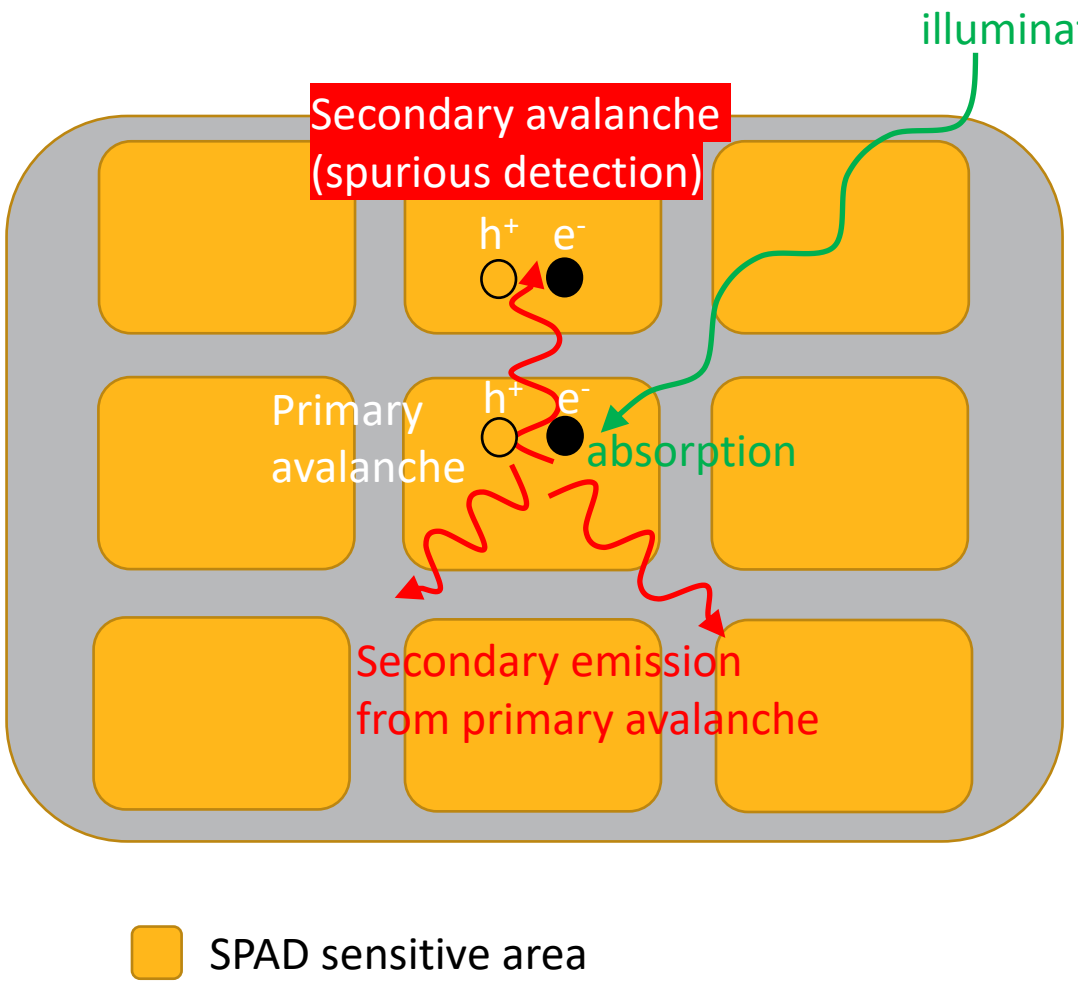

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Workflow (ongoing collaboration with TRIUMF):

- Light transmission, absorption, and secondary propagation relies on Ansys Lumerical FDTD
- Primary photon detection and secondary photon generation and detection relies on Ansys Lumerical CHARGE


Ansys