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High Performance integrated Ge on Si APDs

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Sandia National Laboratories

LDRD

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NNSA National Nuclear Security Administration

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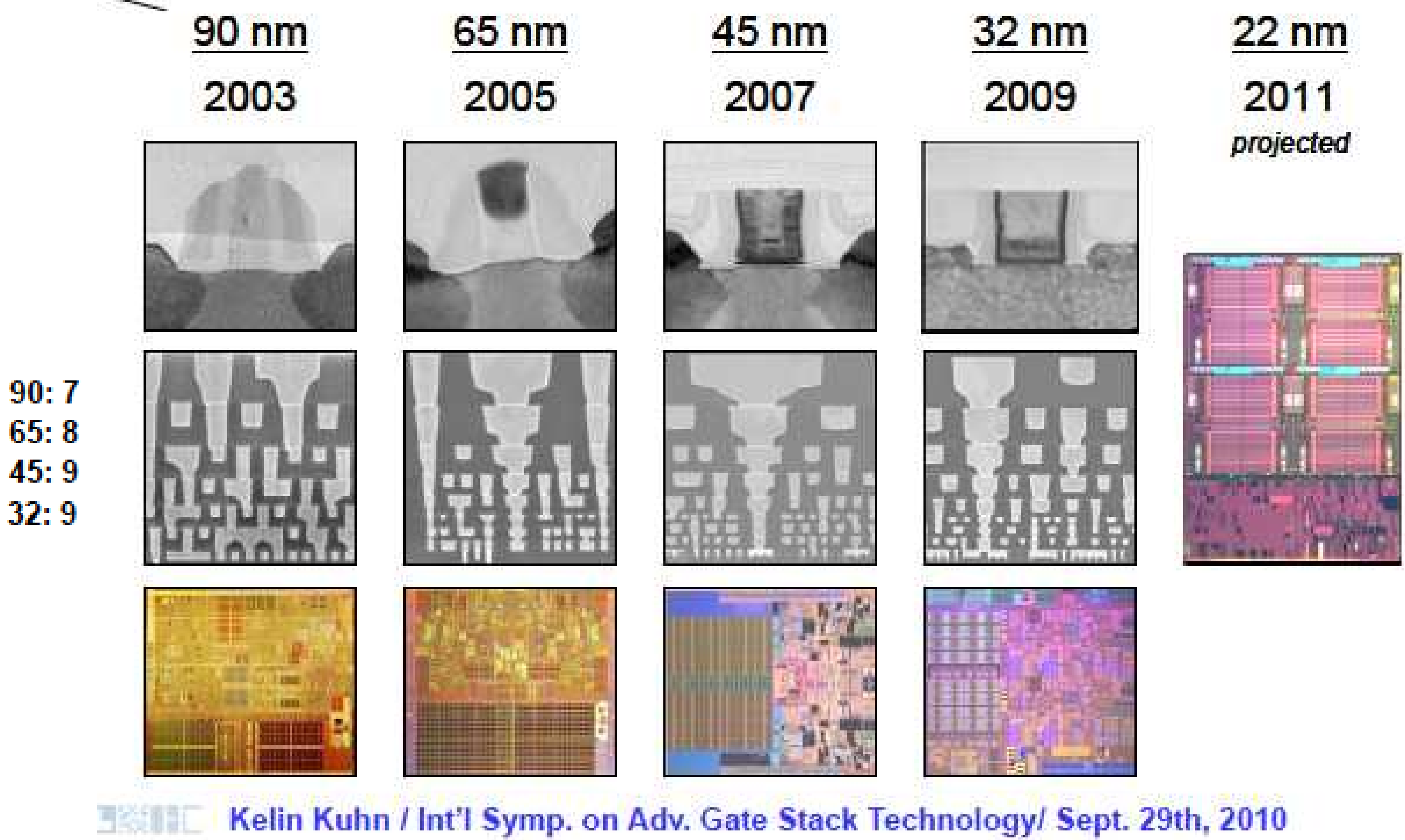
Outline

- Motivation
- Introduction to Selective Ge on Si integrate photonic devices
- Integrated Linear Mode APD
- Integrated Geiger Mode APD

Si Technology

G. Moore (Intel) " It should not be called Si technology but metal dielectric technology"



Dominated by interconnects

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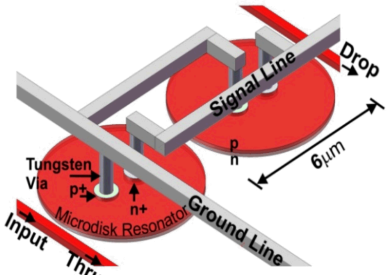
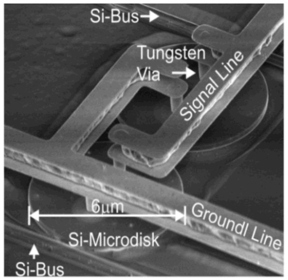
Core Silicon Photonics

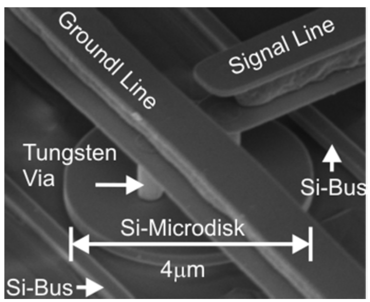
Free-carrier Effect (high-speed)



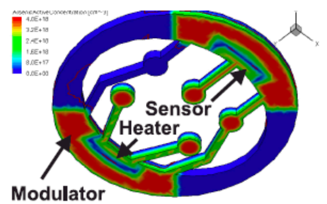


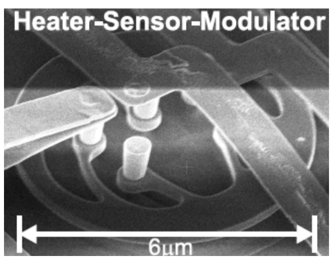
Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s



Resonant Optical Modulator/Filter

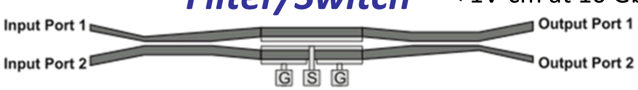




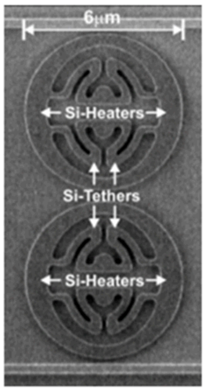
Thermally stabilized modulator

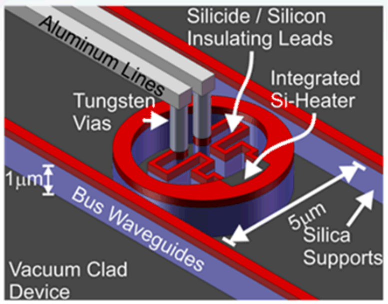
Broadband Mach-Zehnder Filter/Switch

< 1V-cm at 10 Gb/s

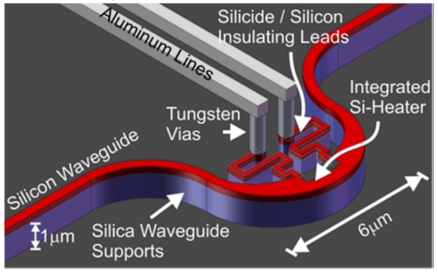


Thermal Optic Effect (wide-band)

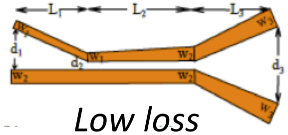




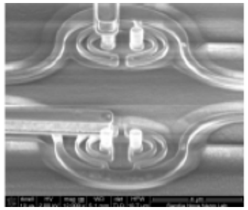
Tunable Resonant Filter



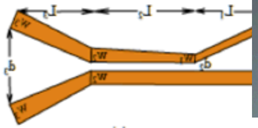
Thermo-optic Phase Shifter



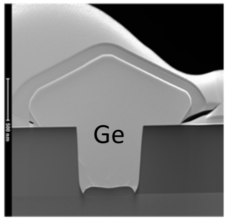
Low loss optical coupler



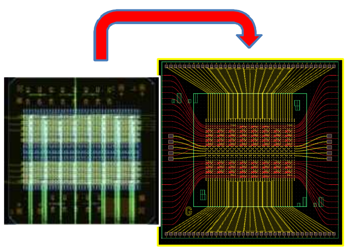
Switch Arrays

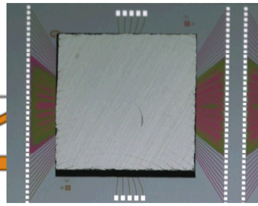


High-speed Ge Detector in Si



Si Photonics-CMOS Integration

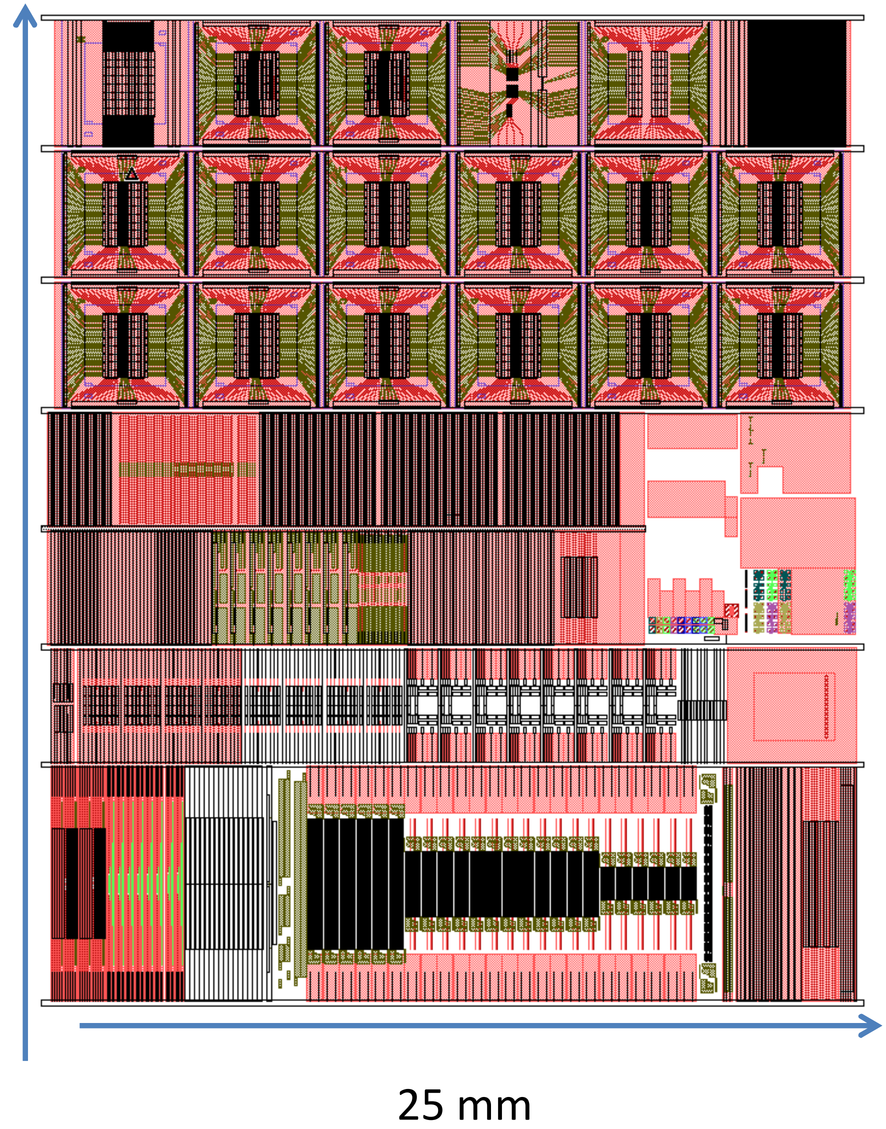




Integration Advantages

- High data rate – multiple wavelengths per channel
  - Requires dense integration.
  - High index contrast system – compact devices
- CMOS compatible photonics
  - Leverage existing infrastructure
  - Large number of active devices (SPAD's)
  - Low cost
- High efficiency
  - Compact devices – give lower dark current
  - Ge on Si offers best chance for integrated compact devices.

Optical Transceiver for Exascale



Detector development in Si Photonics Platform

- Key Platform Components
  - ***Linear mode APD for integrated photonic receievers***
  - ***Geiger mode APD for integrated photon counting applications.***
  - ***Single Photon Detection (SPD) Capability***
- Build on our high performance Ge on Si photodiode technology.
- Expand Si Photonics platform to Quantum Photonics using new and existing building blocks,.

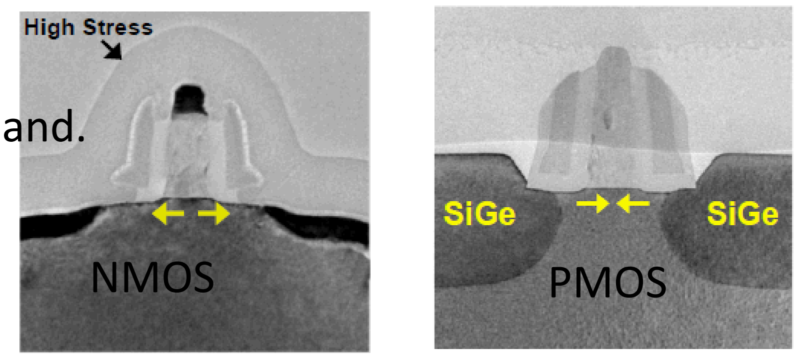
Ge in Modern CMOS

Germanium old semiconductor technology.

- Indirect Bandgap at 0.66 eV.
- Direct Bandgap at 0.8 eV (1550 nm) in telecom band.
- Not efficient optical emitter.

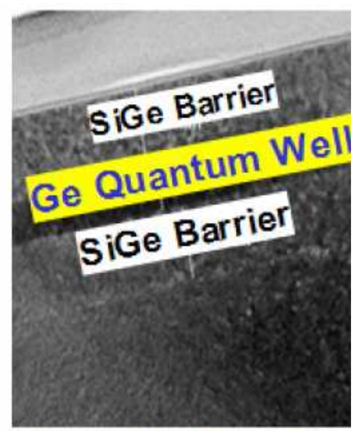
Strain engineering in CMOS

Intel 45nm

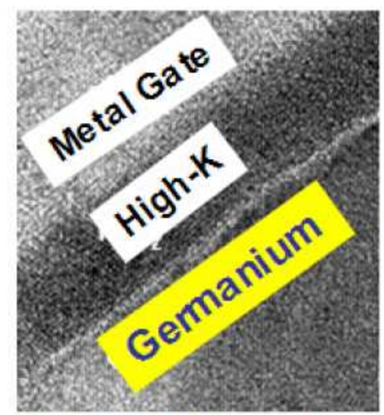


Selective epitaxial growth of Ge on Si has enabled advanced strain engineering in modern CMOS.
Fully CMOS Compatible.
High electron and hole mobilities.

Ge optoelectronics: direct bandgap at 1550nm implies good absorption.



Ge Quantum-well

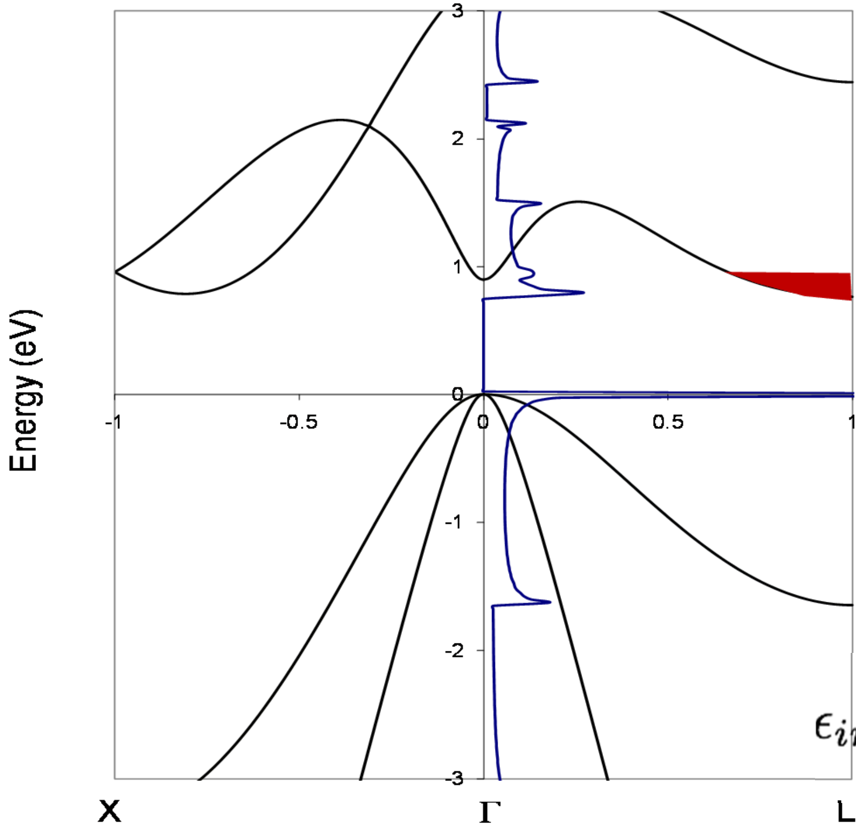


Ge MISFET Transistor

Sources: (1) ESSDERC 2008, (2) www.intel.com/silicon research/R&D pipeline

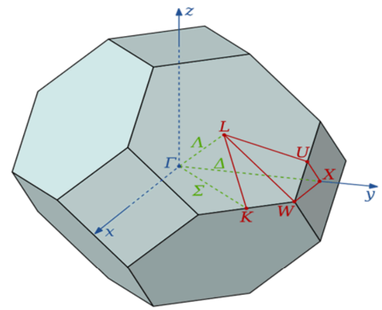
Optical Properties of Doped Ge

Tight binding band-structure



Can we determine validity of band-filling and strain models for PL & EL signatures?

Optical Properties of Heavily Doped Semiconductor



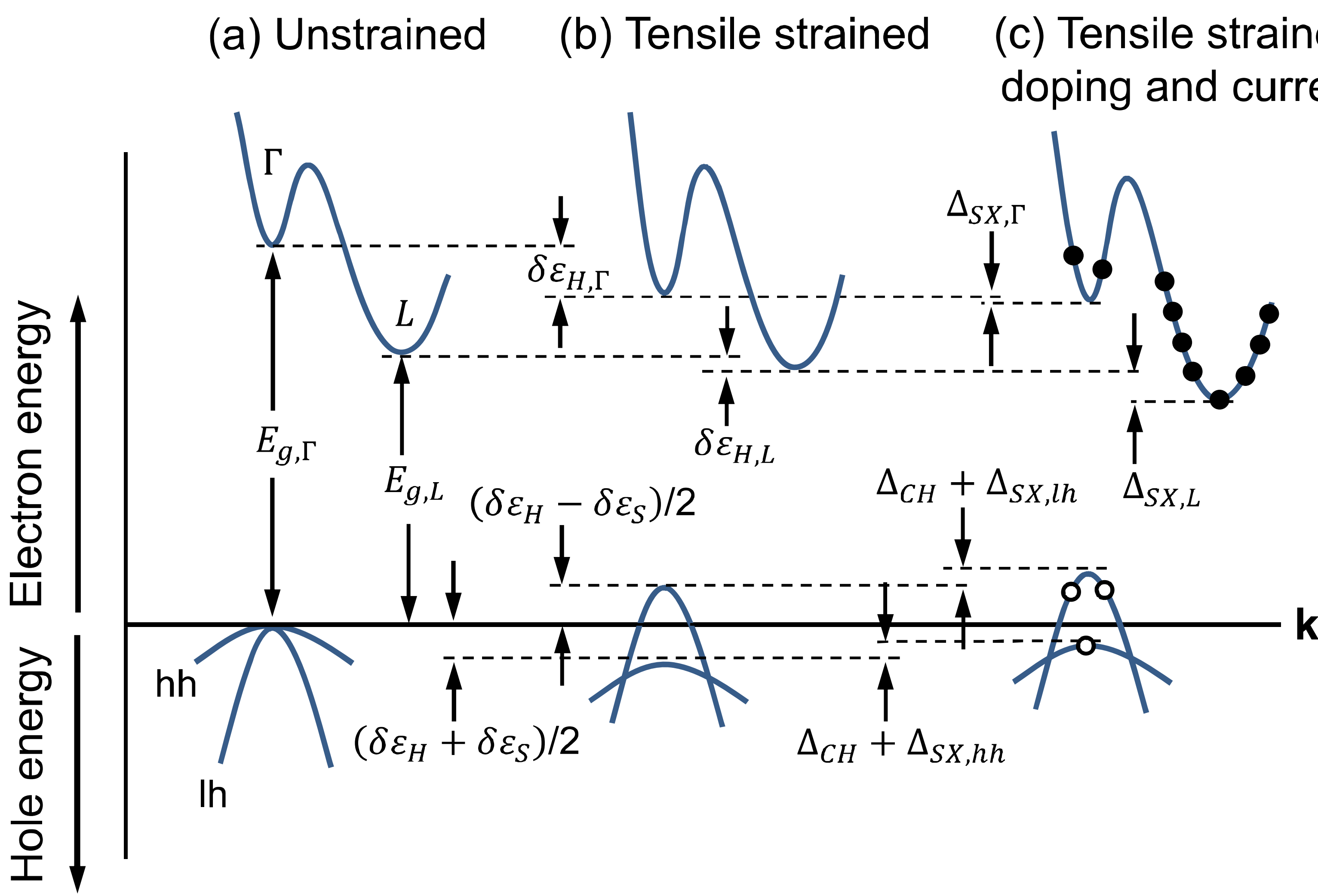
J. Jung, T. G . Pederson, JAP,113,114904,(2013)

$$\epsilon(\omega) = \epsilon_{inter}(\omega) + \epsilon_{intra}(\omega)$$

$$\epsilon_{intra}(\omega) = \frac{e^2}{8\pi^3\epsilon_0\hbar^2\omega^2}\sum_n \int \frac{\partial E_{n\mathbf{k}}}{\partial \mathbf{k}} f'(E_{n\mathbf{k}})d\mathbf{k}$$

$$\epsilon_{inter}(\omega) = 1 + \frac{e^2\hbar^2}{8\pi^3\epsilon_0 m^2}\sum_{n\neq m}\int \frac{f(E_{n\mathbf{k}}) - f(E_{m\mathbf{k}})}{E_{m\mathbf{k},n\mathbf{k}}[E^2_{m\mathbf{k},n\mathbf{k}} - (\hbar\omega)^2]} M_{m,n}(\mathbf{k})d\mathbf{k}$$

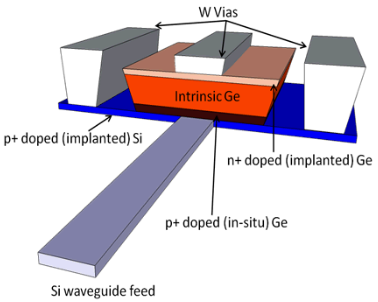
Indirect Bandgap in Strained Ge

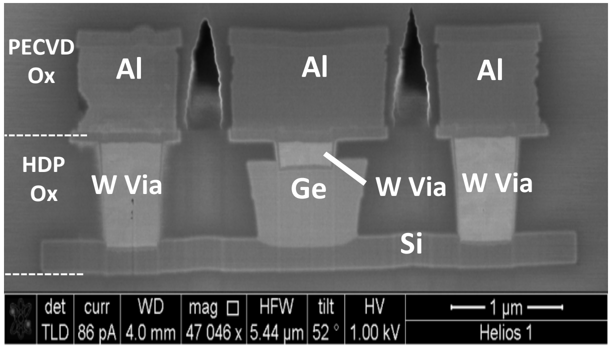


Ge on Si Detector Development

Compact high speed photodiode

<u>Sandia</u>





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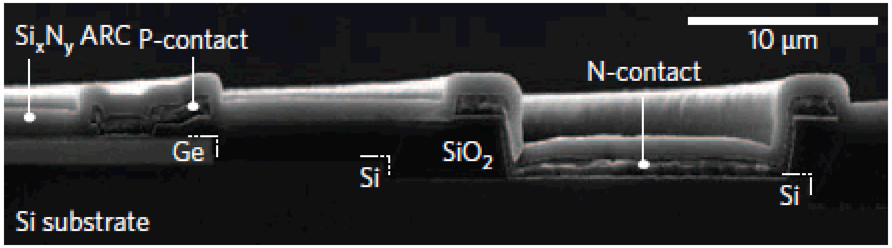
Ge on Si Avalanche Photodiode

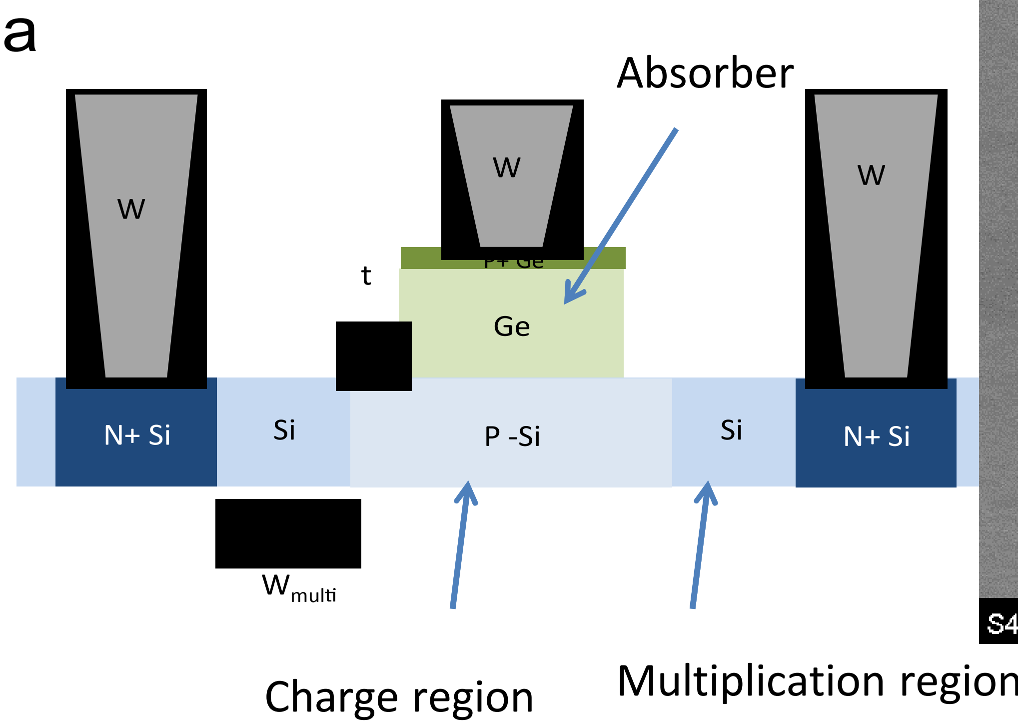
<u>Intel, UCSB, UVa</u>

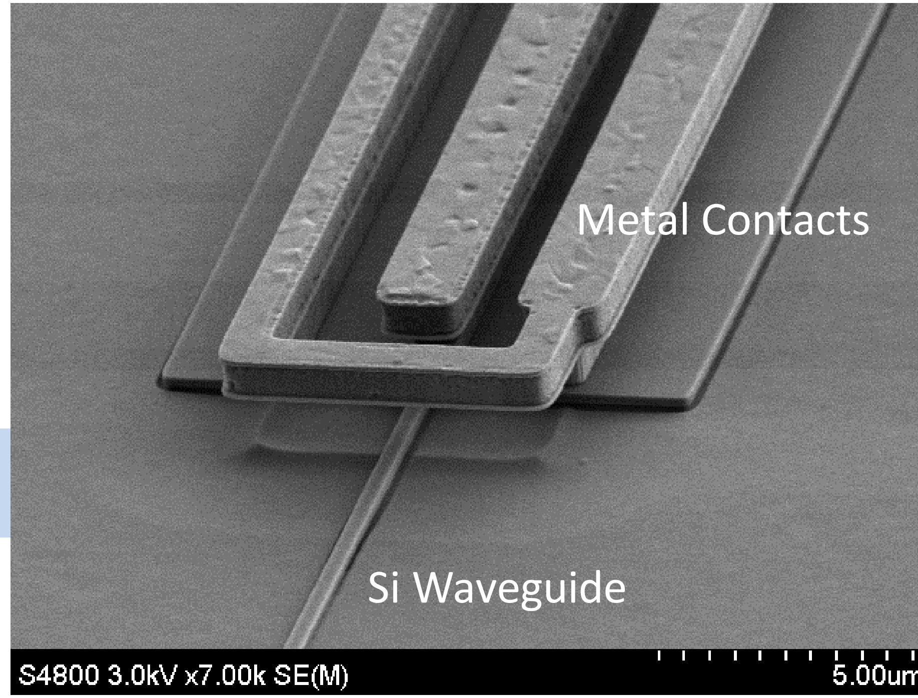


NATURE PHOTONICS | VOL 3 | JANUARY 2009 | www.nature.com/naturephotonics

- Integrated waveguide Ge on Si photodetector demonstrated best in class performance.
- Ge on Si linear mode separate absorption multiplication avalanche photodiode demonstrated 340 GHz gain bandwidth product.
- **Combining new device concepts would enable integrated single photon detection and launch Quantum Si Photonics.**

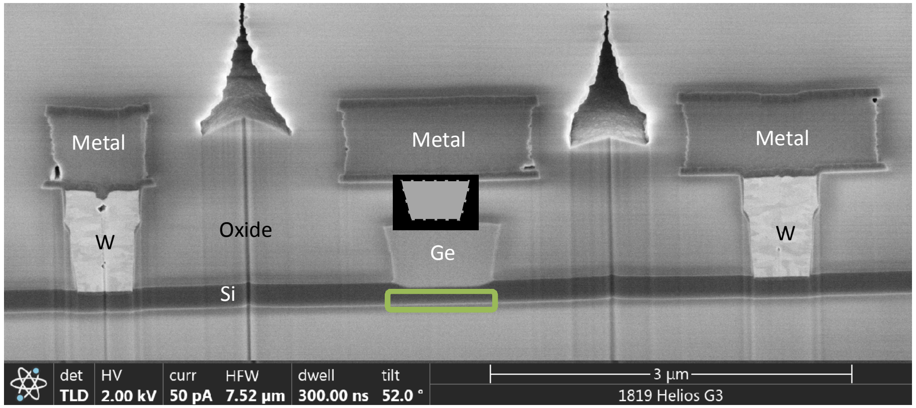
Integrated SACM APD

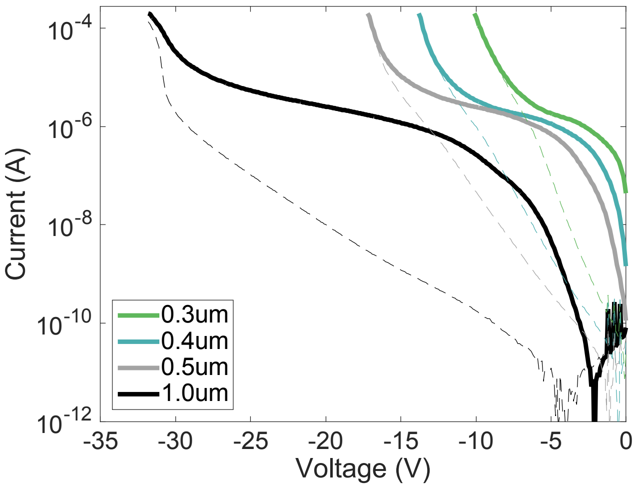


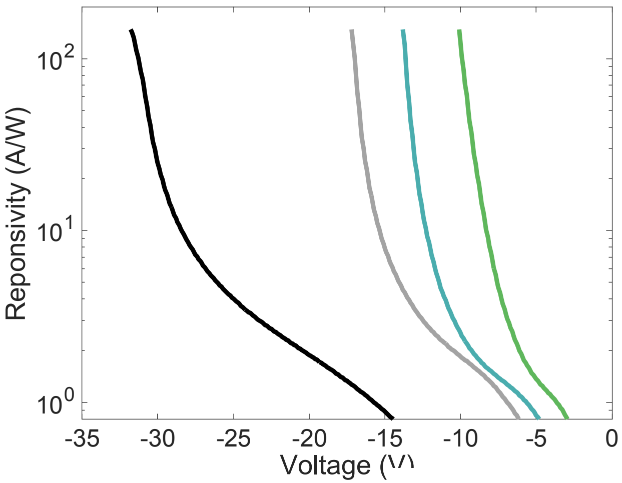


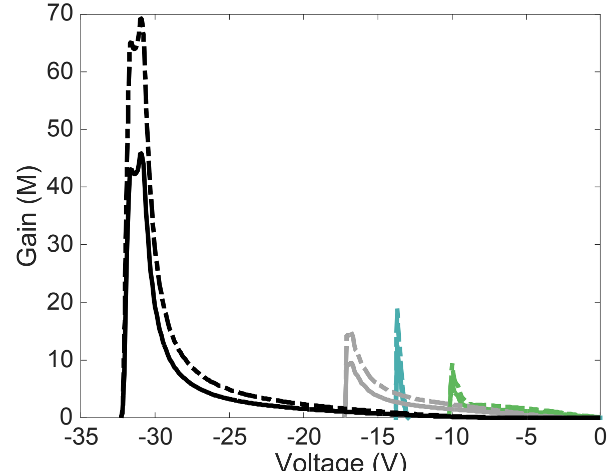
- Lateral Multiplication region in Si
- Waveguide entry into Ge absorber.

LIV Characteristics







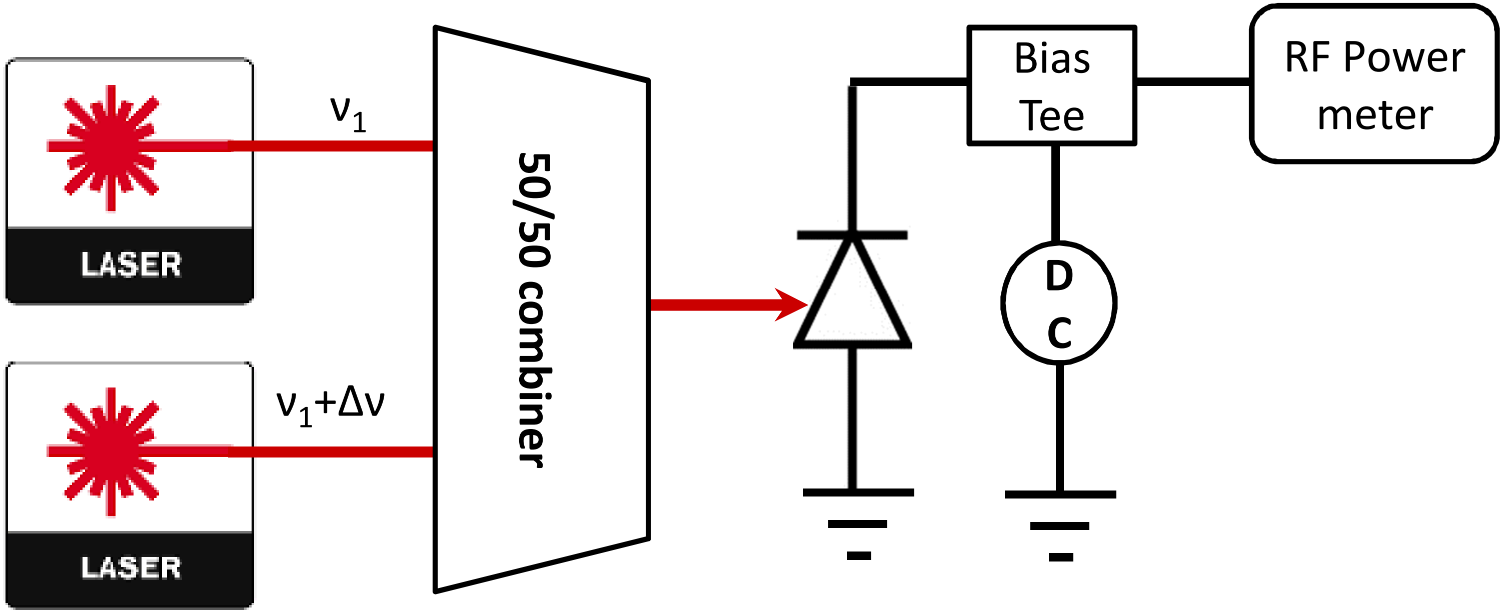


$$I_{photo} = RP_{opt} \qquad R = e\eta G\frac{\lambda}{hc}. \qquad G = \frac{I_{photo}(V) - I_{dark}(V)}{I_{photo}(V_{G=1}) - I_{dark}(V_{G=1})},$$

Estimate unit gain voltage from measured responsivity of Ge p-i-n device.

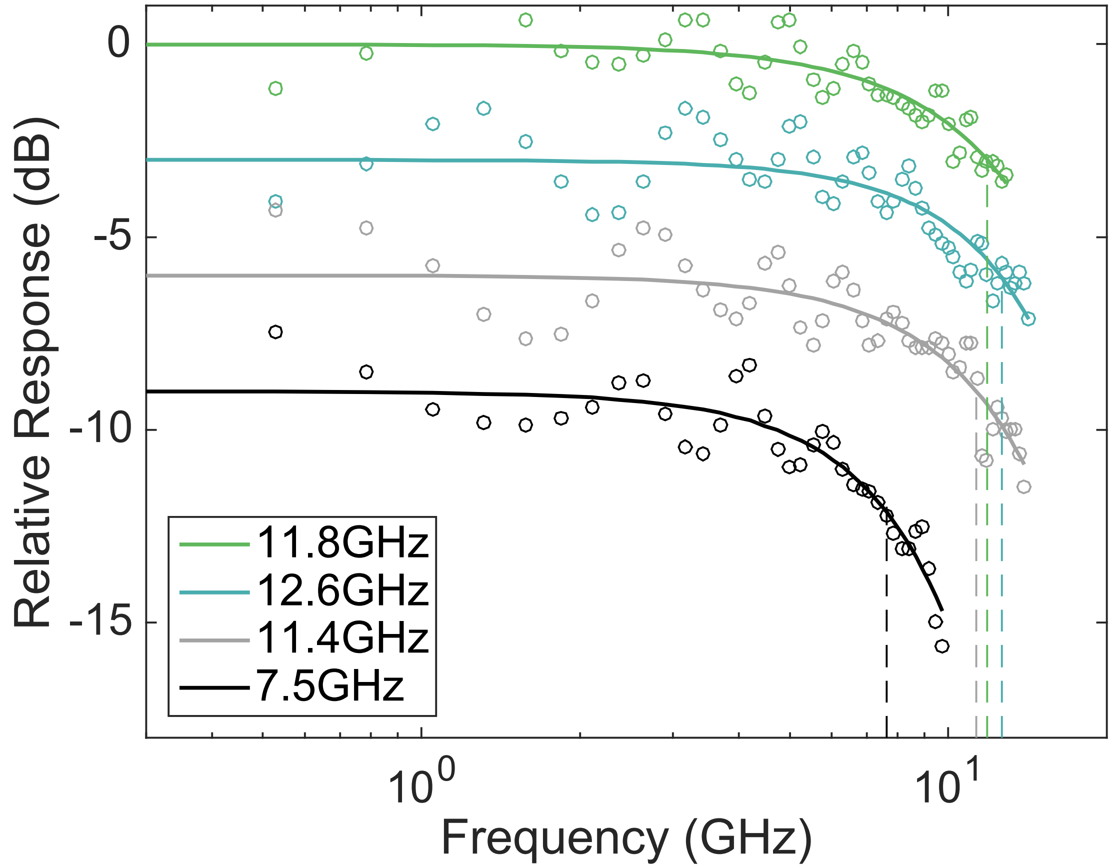
Studied impact of overlap and found best devices had t=0 nm.

Bandwidth Measurements



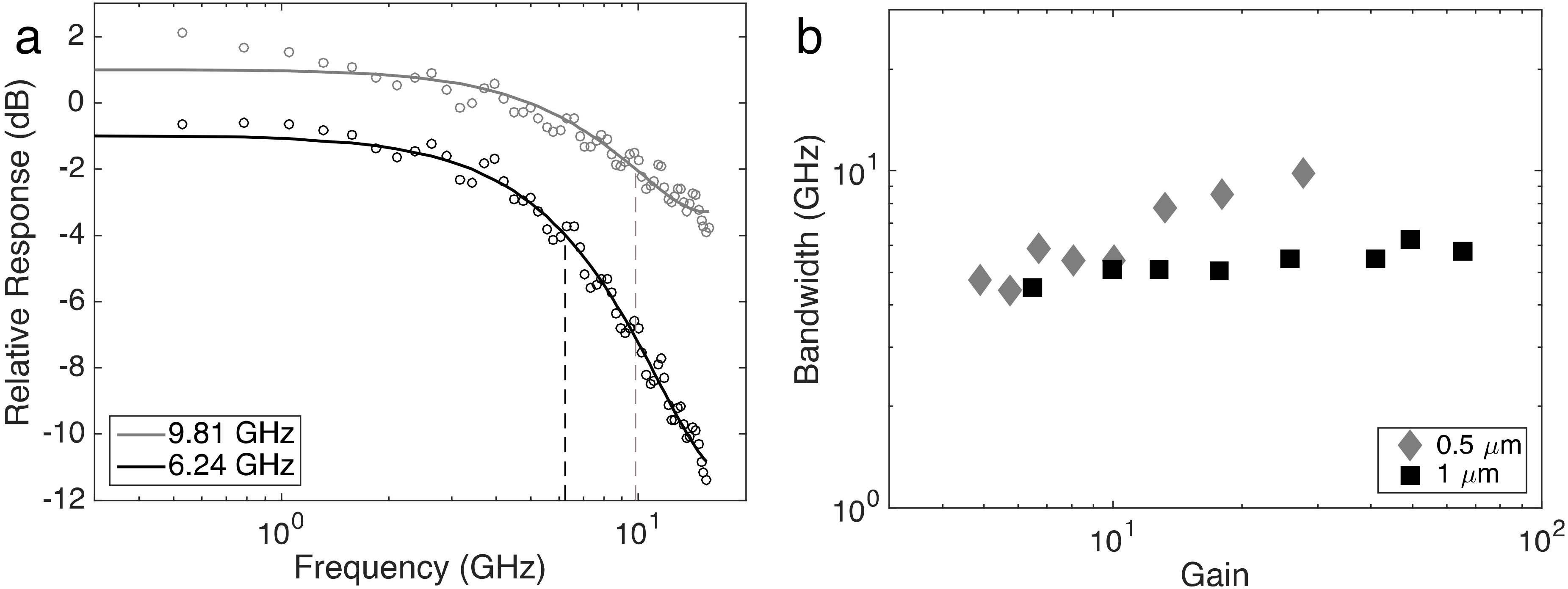
- Heterodyned bandwidth measurements
- Use fixed and tunable laser and calibrated with commercial detector in RF spectrum analyzer.

Bandwidth



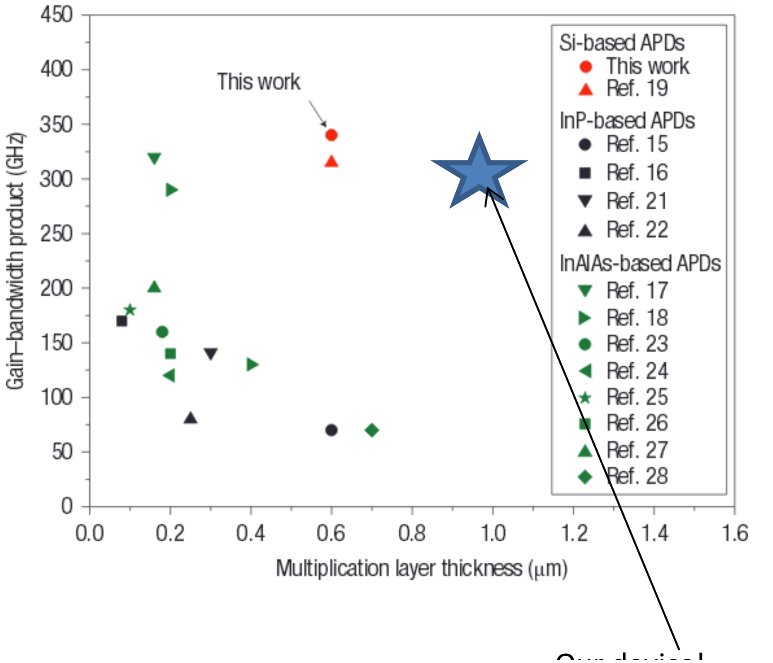
- Measured at low gain away from breakdown
- Parameterized multiplication widths.

Gain Bandwidth Product



- Response and maximum gain for 500 nm and 1000nm wide multiplication region.
- Gain-Bandwidth product of ***311 GHz*** for 1 micron wide muliplication region.

Comparison



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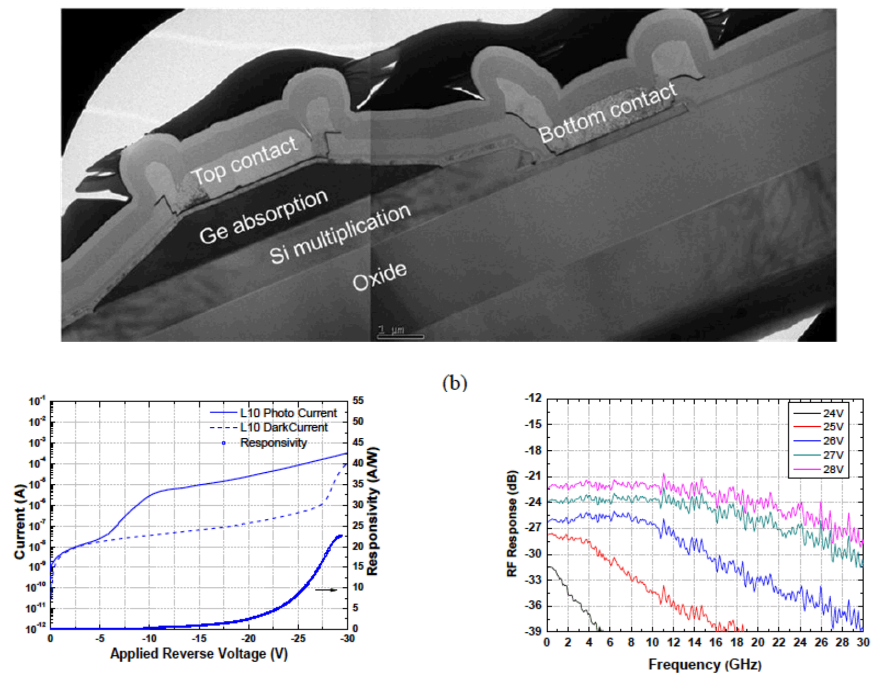
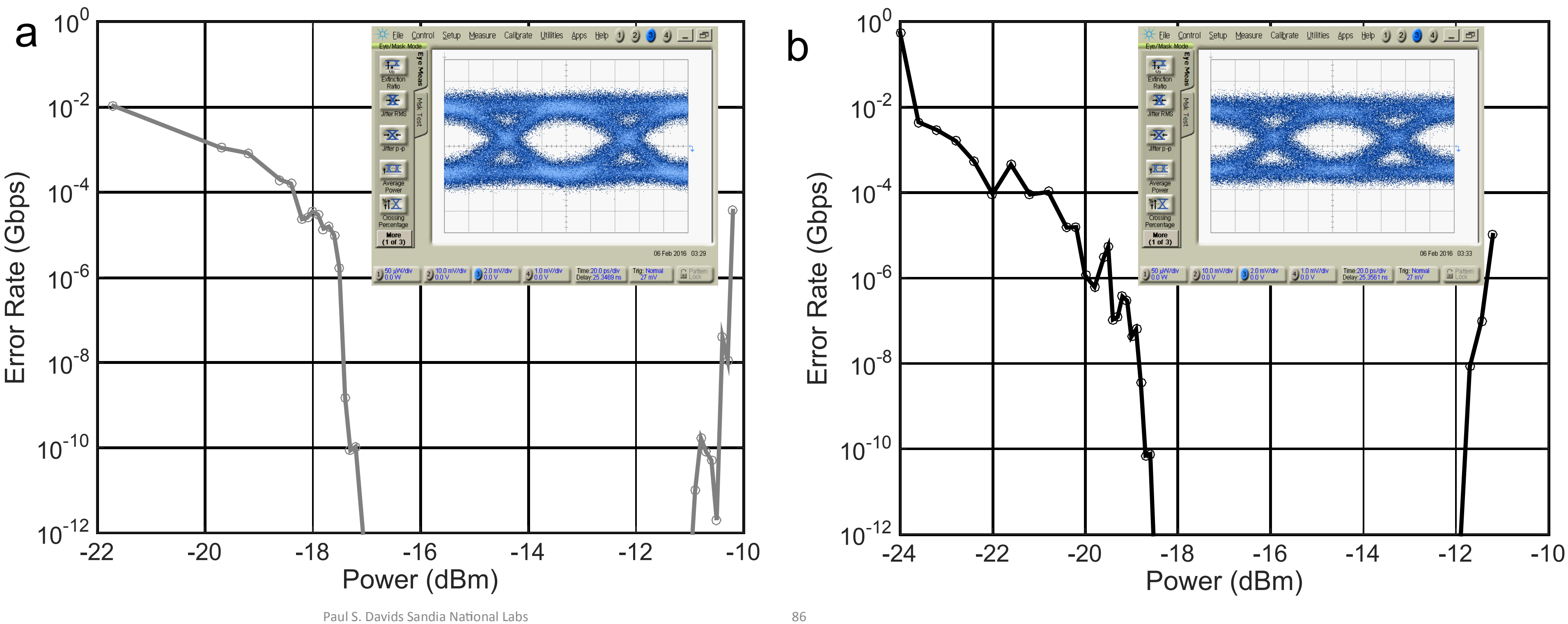


Fig. 3 (a) Measured total photocurrent (solid curve) under 1550 nm illumination, dark current (dash curve), and responsivity vs. bias voltage at room temperature of a 8 μm x 10 μm APD. (b) Measured frequency response at different bias voltages at 1550nm input wavelength.

[1] K.-W. Ang, J. W. Ng, A. E.-J. Lim, M.-B. Yu, G.-Q. Lo, and D.-L. Kwong. Waveguide-integrated ge/si avalanche photodetector with 105ghz gain-bandwidth product. In Optical Fiber Communication Conference, page JWA36. Optical Society of America, 2010.

Previous results at 1550 nm in waveguide coupled Ge on Si showed ***105 GHz*** Gain-Bandwidth product.

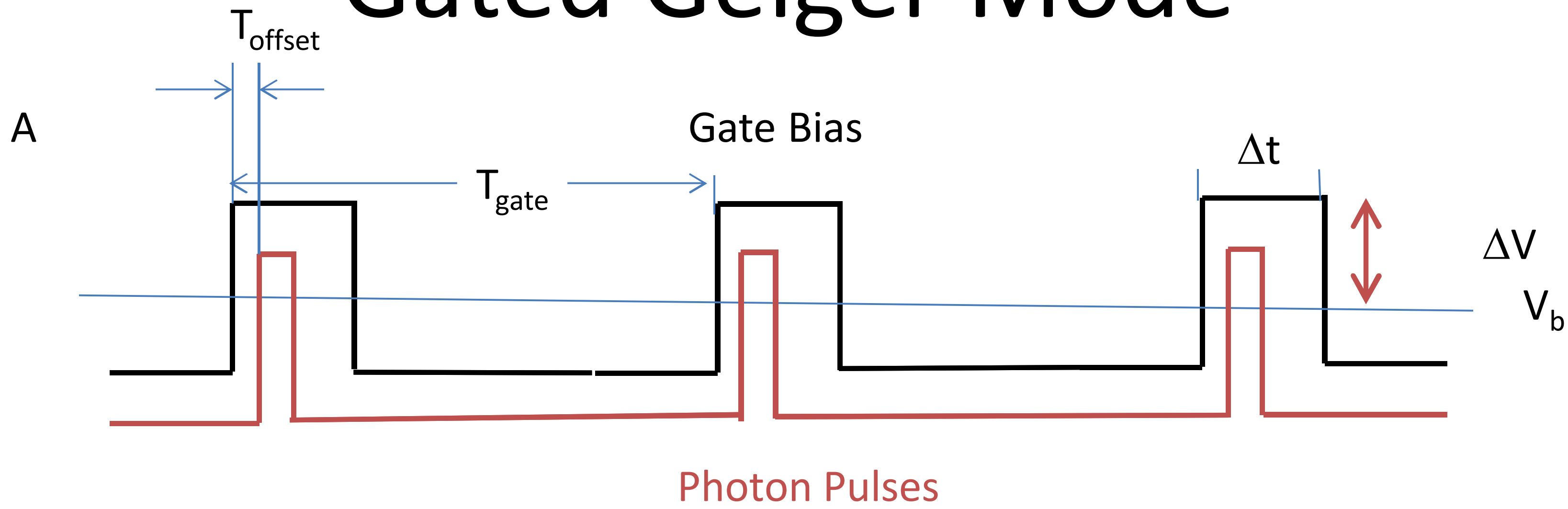
Receiver characterization



Integrated Geiger Mode APD

- Develop a new Geiger mode APD and try and run as a ***Single Photon Detector***.
- Use same general structure as Linear mode APD.
- Optimize implant and E-field profile in device.
- Minimize Dark Current if possible.

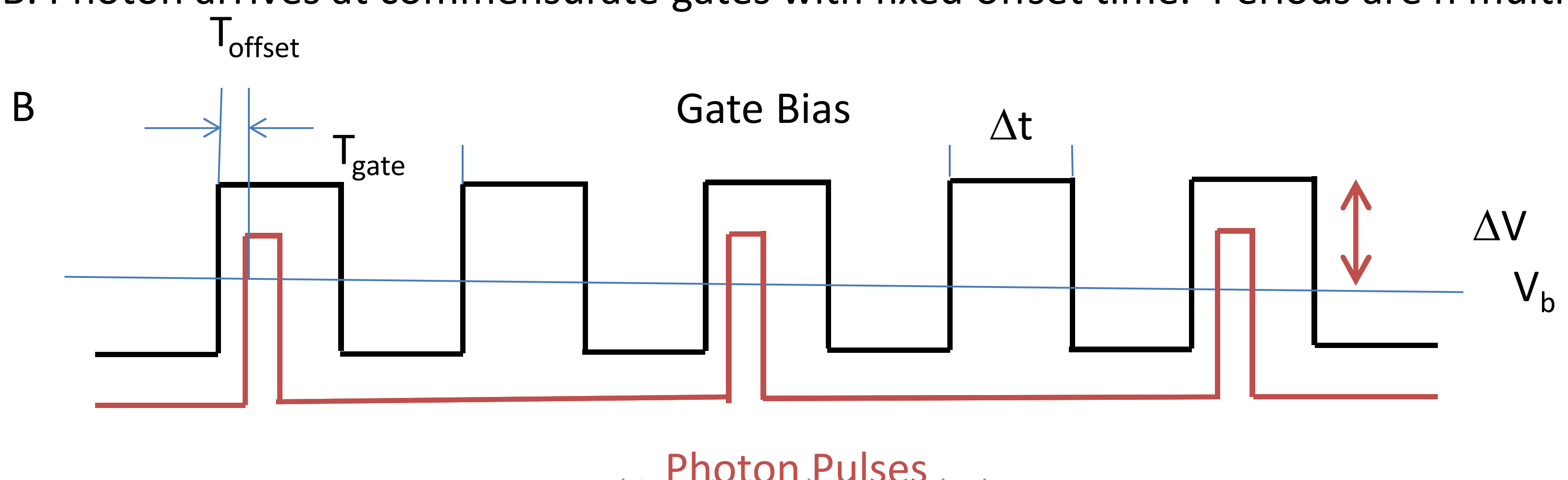
Gated Geiger Mode



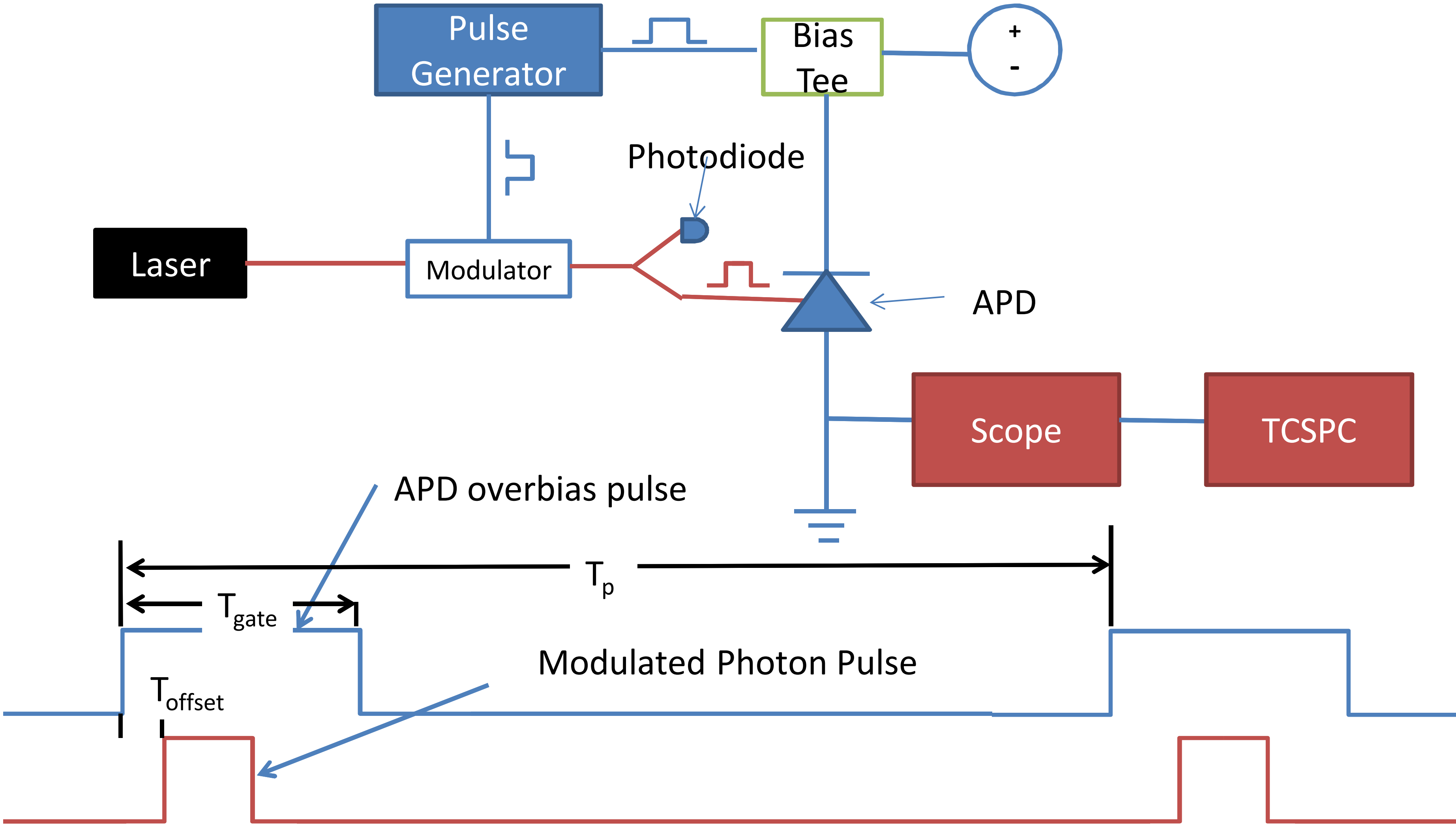
A. Photon arrives each gate with fixed offset time. Periods are equal

OR

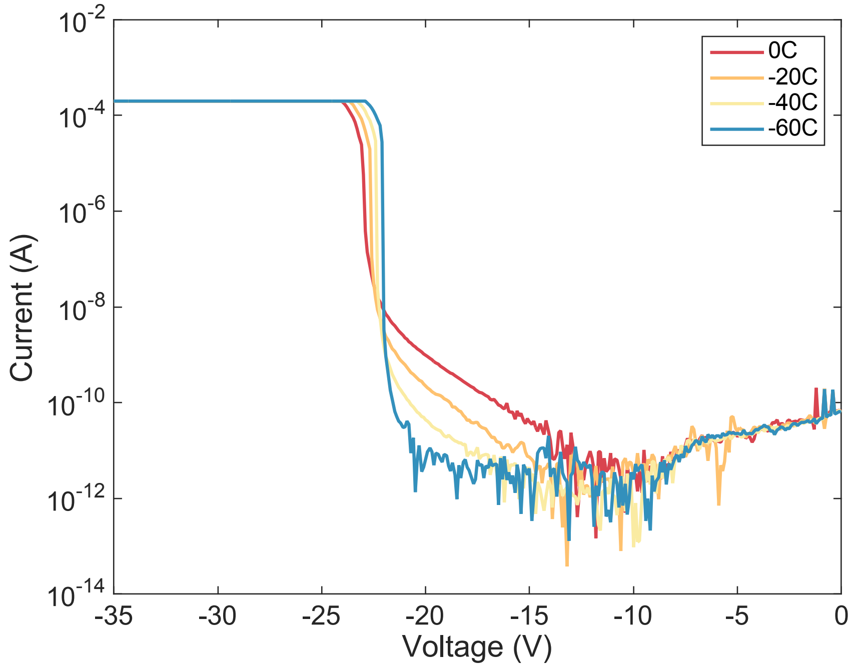
B. Photon arrives at commensurate gates with fixed offset time. Periods are n multiple



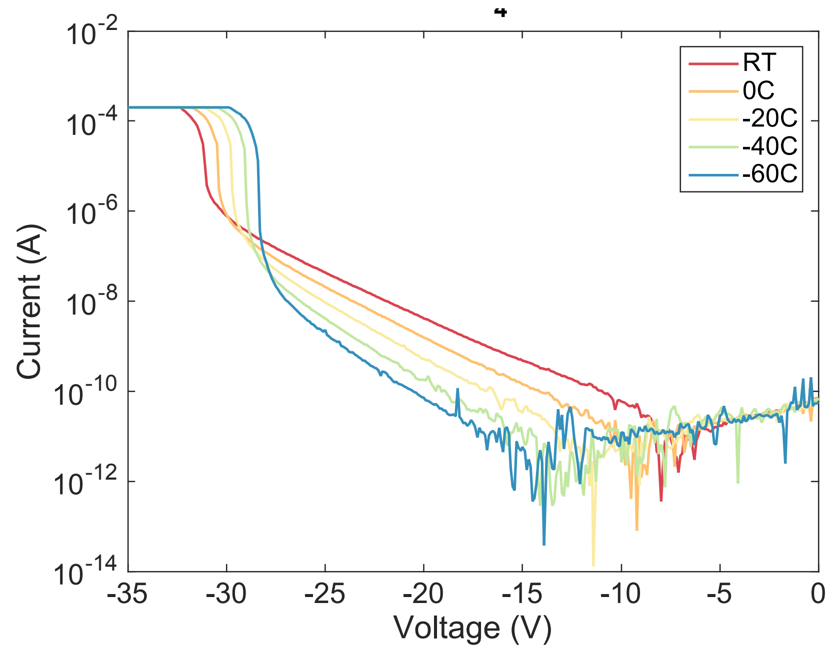
Gated Geiger Mode Setup



Dark IV vs. Temperature



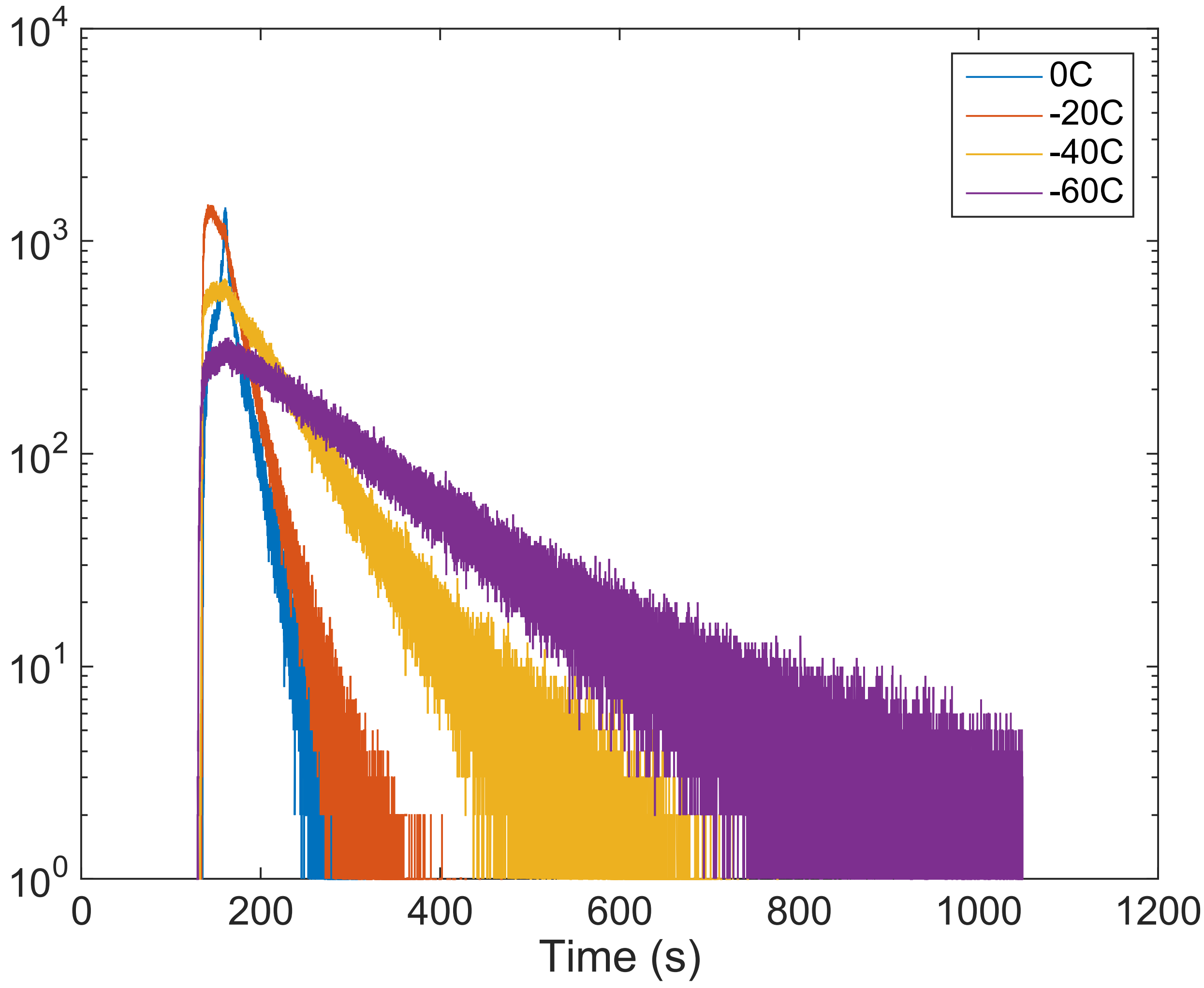
New design (Buried channel)



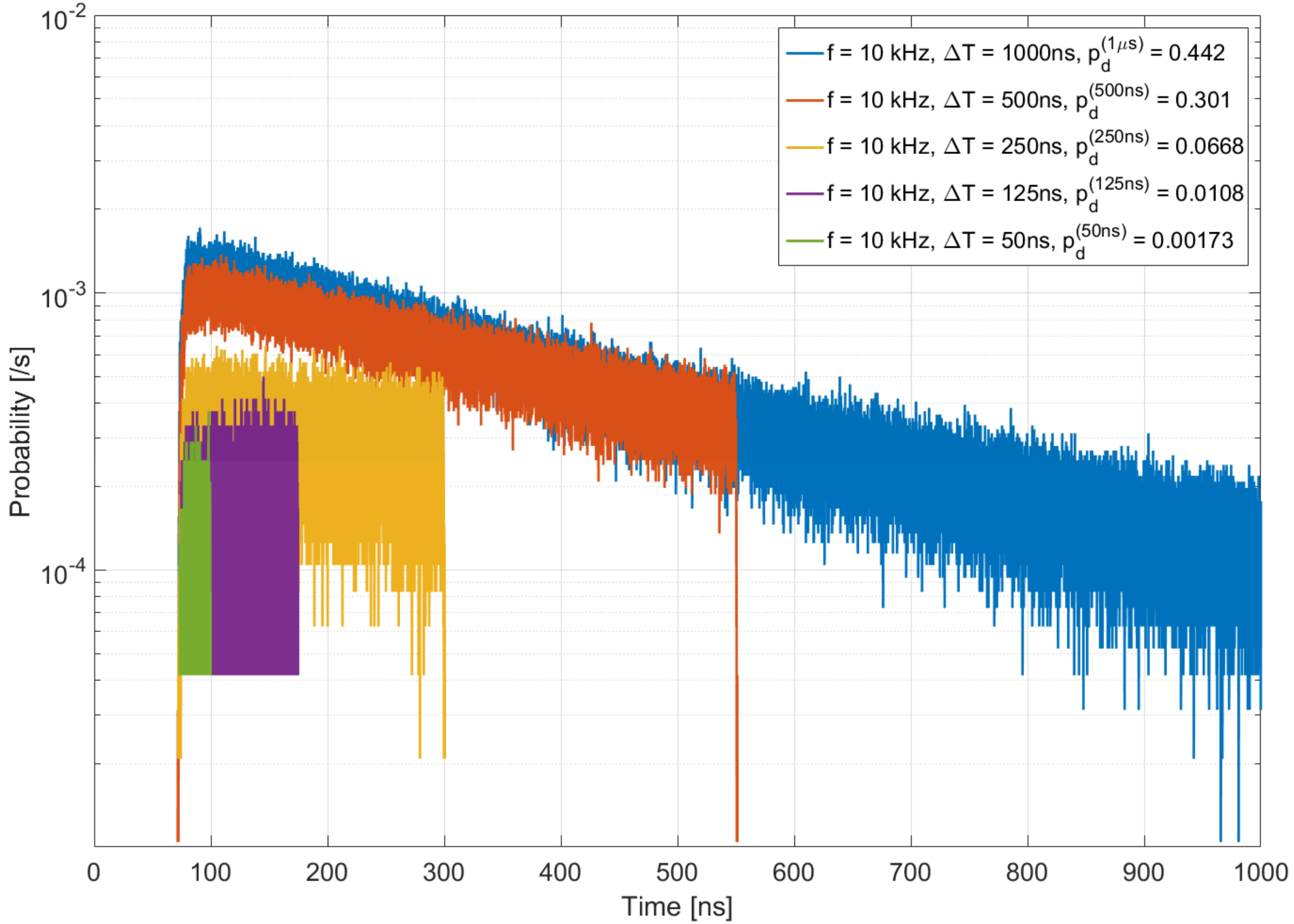
Linear mode APD

SACM lateral APD

Dark Counts vs. Temperature



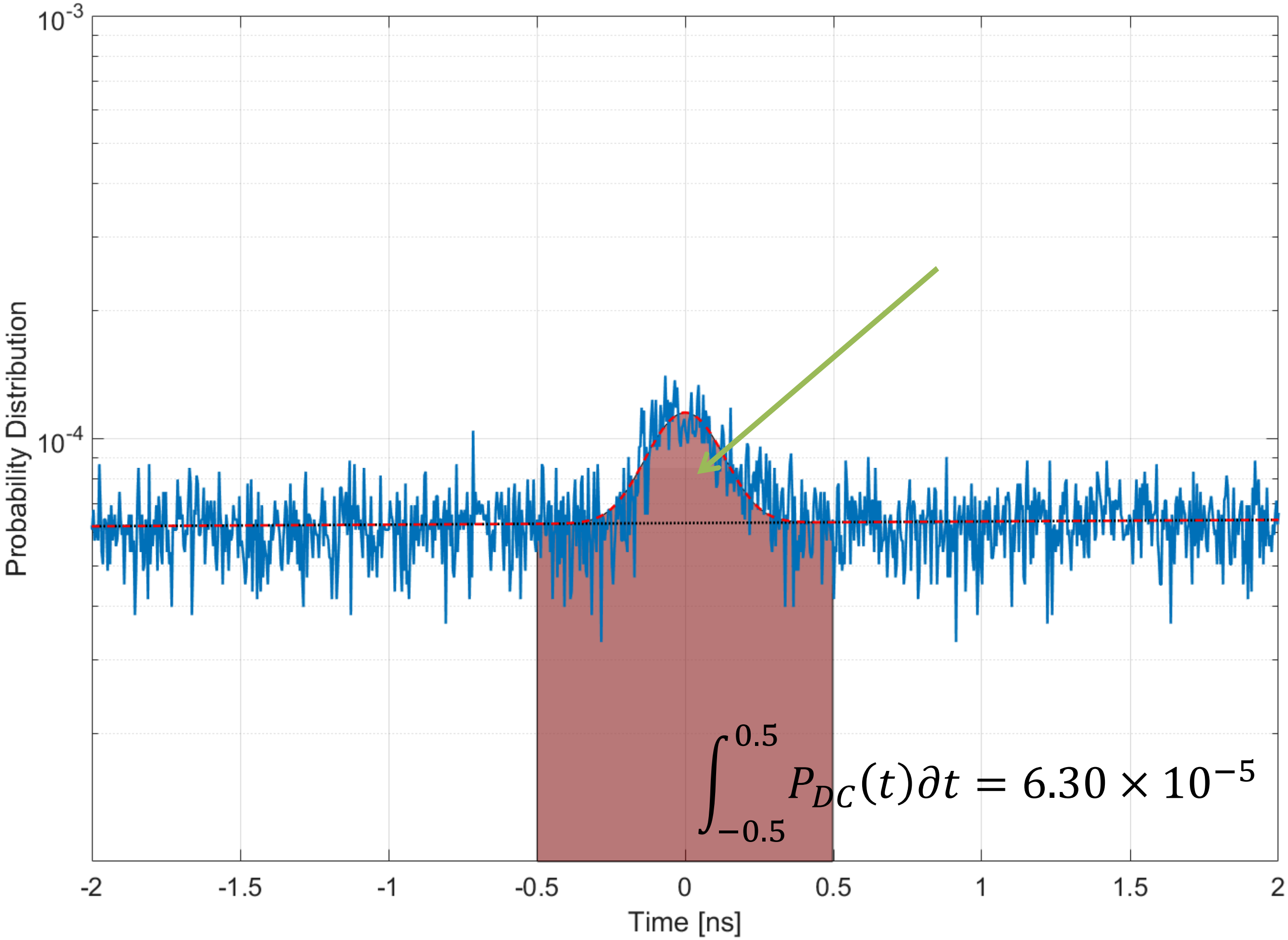
Geiger Mode Dark Count Rate



Dark count *probability per time period* decreases with decreasing gate time

Geiger Mode Single Photon Detection

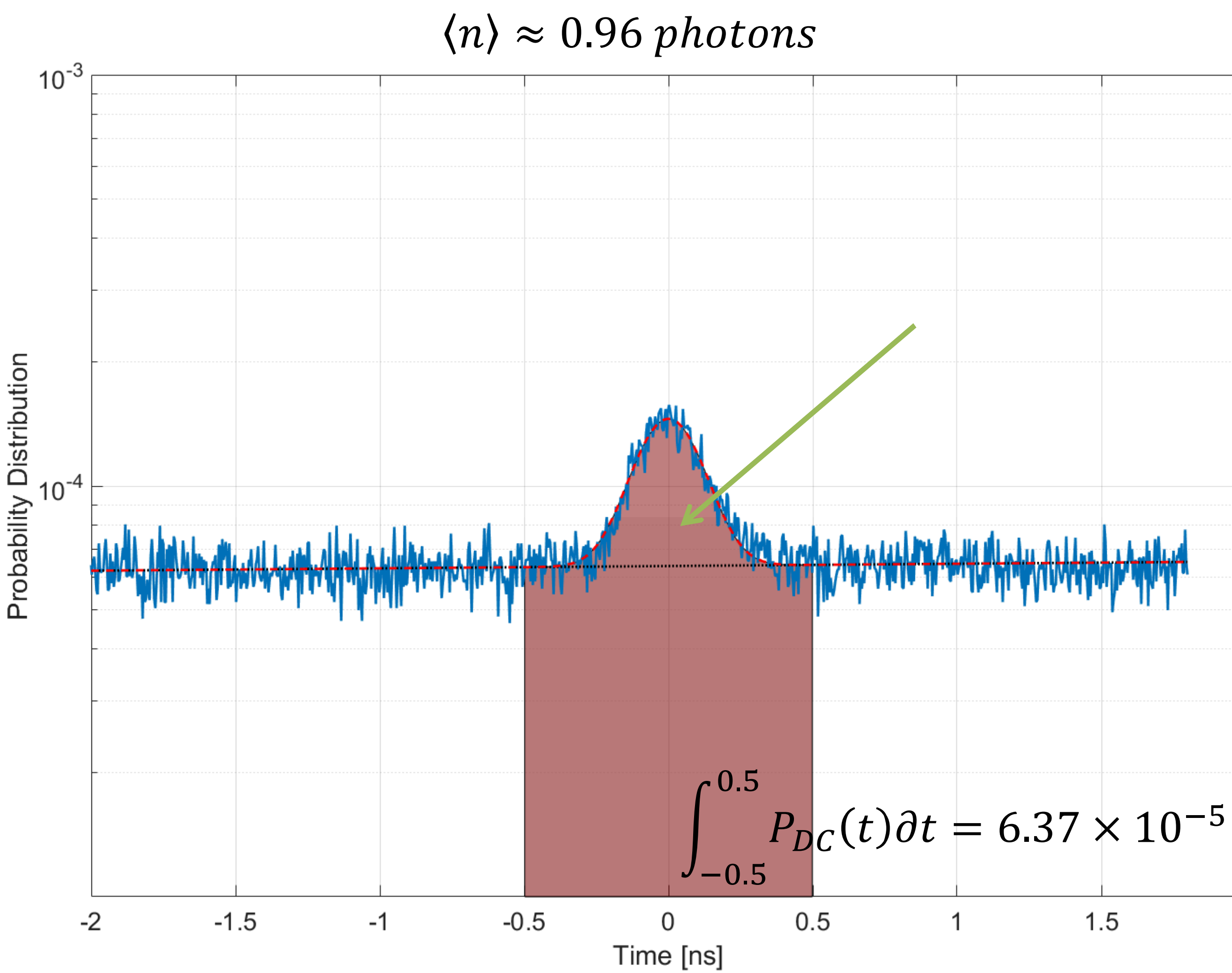
$\langle n \rangle \approx 0.76\ photons$



$$\int_{-0.5}^{0.5} P_{DC}(t)\partial t = 6.30 \times 10^{-5}$$

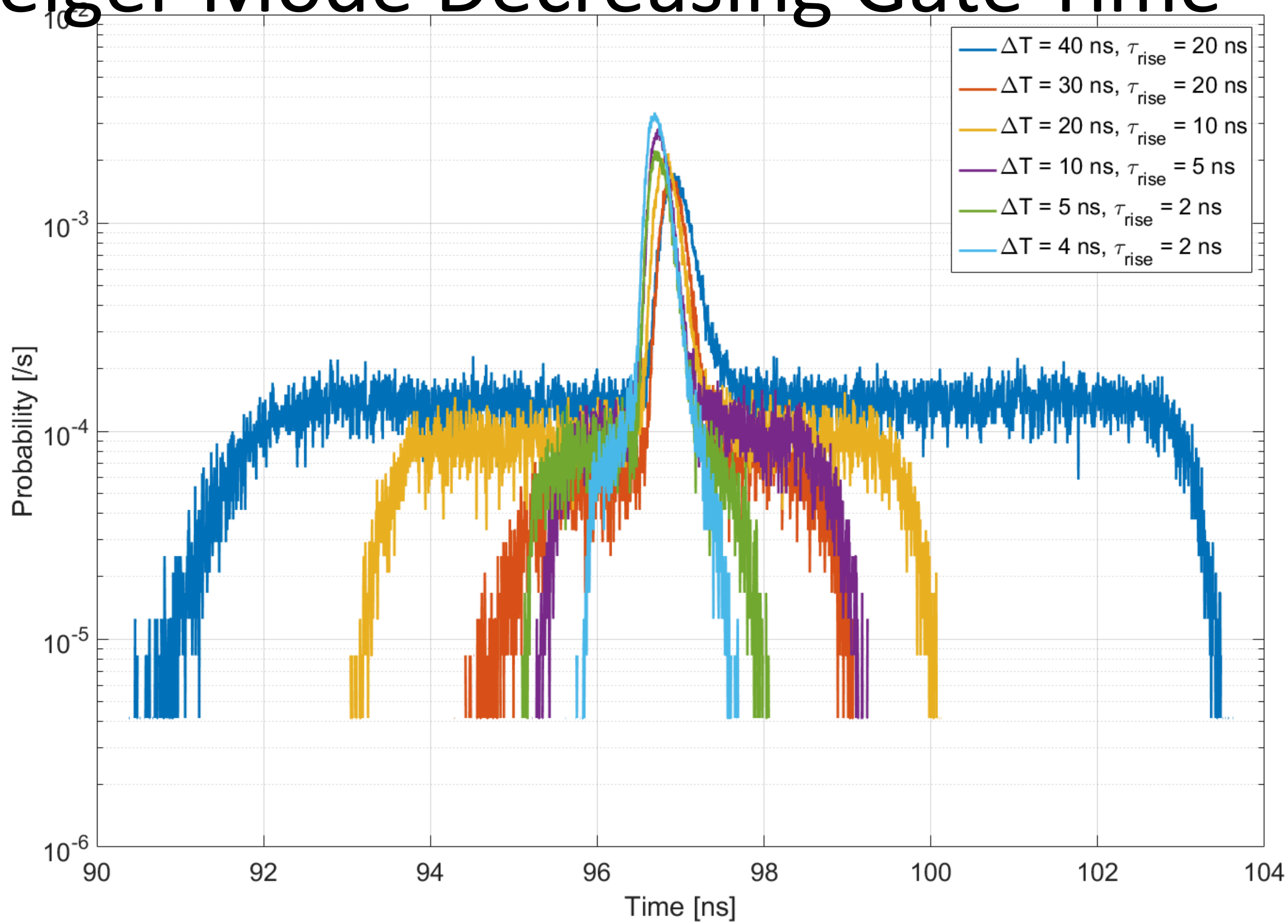
In a 1 ns window, an average photon number of 3.17 is needed in order to make the probability of a count from a photon equal to the probability of a dark count

Geiger Mode Single Photon Detection



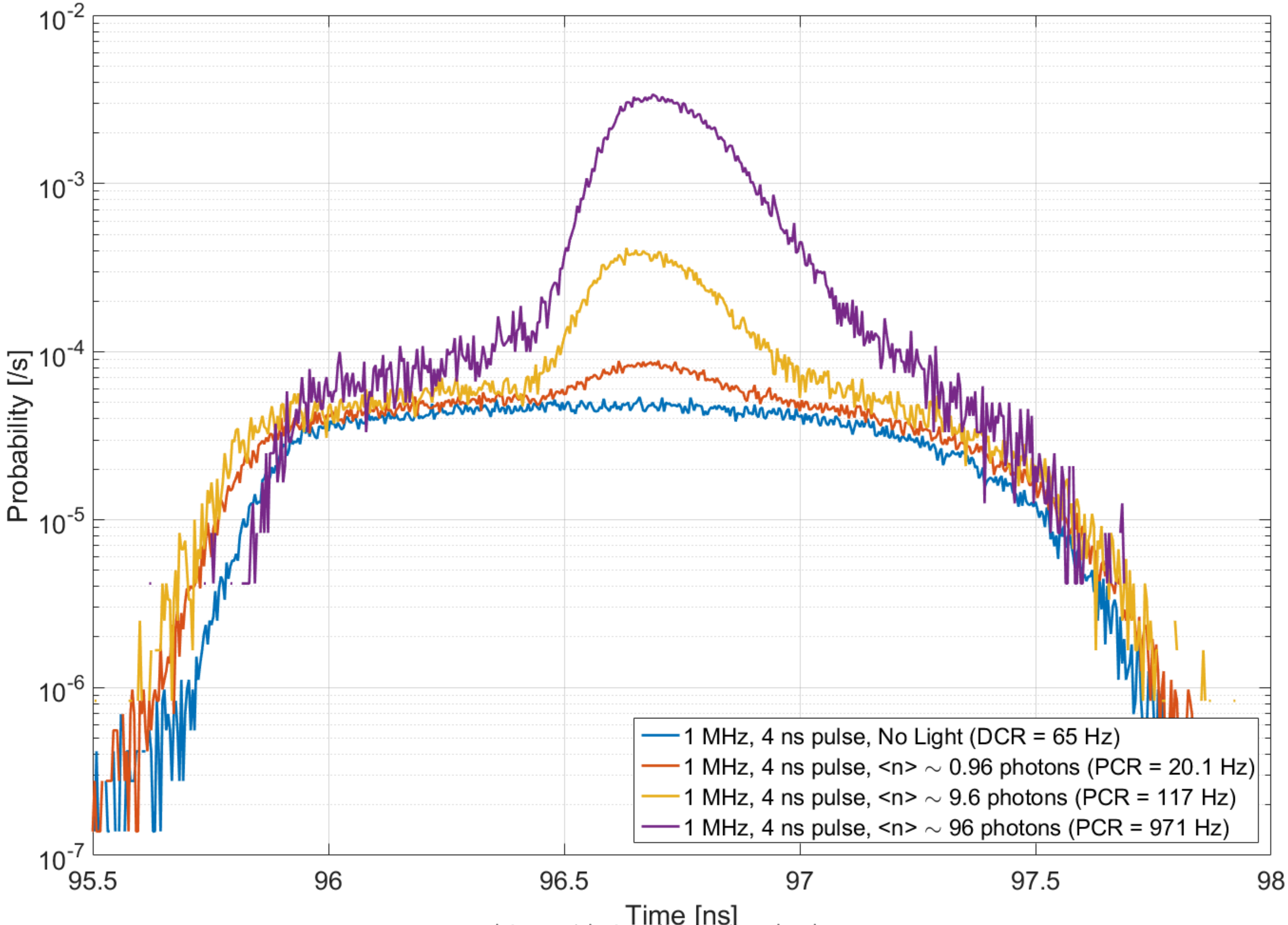
In a 1 ns window, an average photon number of 2.58 is needed in order to make the probability of a count from a photon equal to the probability of a dark count

Geiger Mode Decreasing Gate Time



Slight decrease in dark count probability and increase in photon count probability, but it's not clear if this is real or variation between measurements

Geiger Mode Photon Count Rate vs. <n>



Summary

- Demonstrated integrated Linear mode APD with Gain-Bandwidth product of 311 GHz.
- Showed BER<10^{-12} at 10Gbps with good receiver sensitivity.
- Demonstrated integrated gated Geiger mode performance with low dark count vs. temperature.
- Showed single photon sensitivity.
- Need further improvement through design and optimization.