SAND2015-9122C

Chip-scale Quantum Photonics

Paul S. Davids, Anthony Lentine, Chris DeRose, Doug Trotter, Andrew Starbuck, Nick Martinez, Andy Pomerene, Nick Boynton, Ryan Camacho

Sandia National Laboratories

LORD

SECANT QKD

U.S. DEPARTMENT OF ENERGY

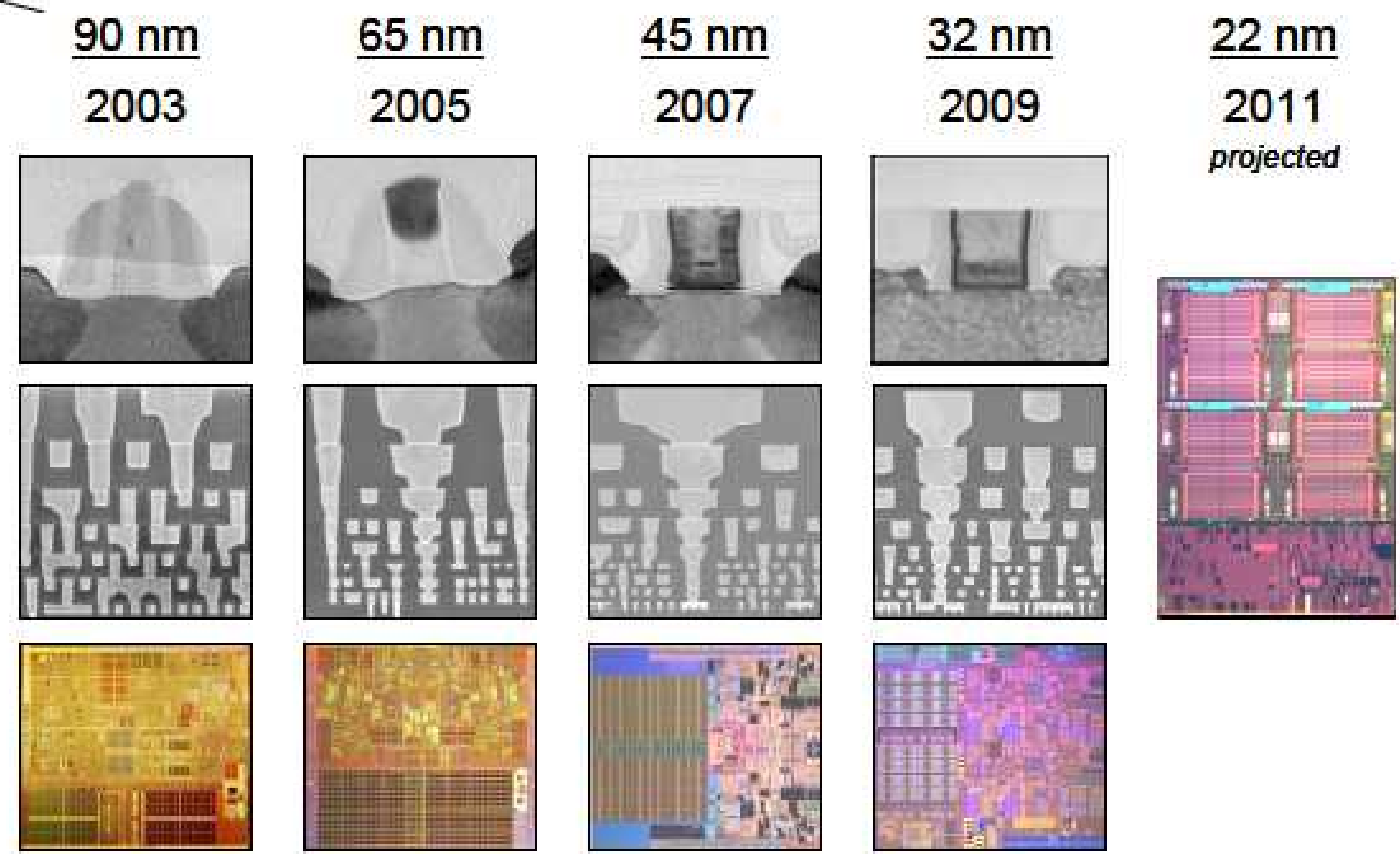
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Si Technology

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

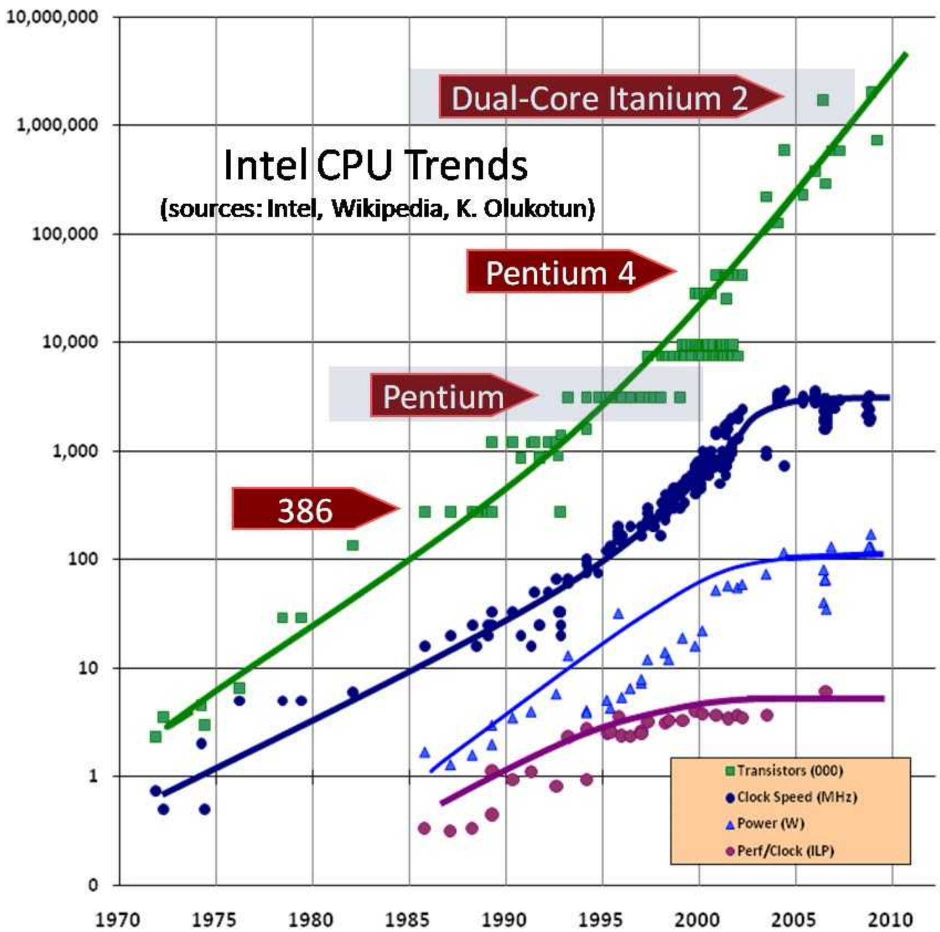
90: 7
65: 8
45: 9
32: 9



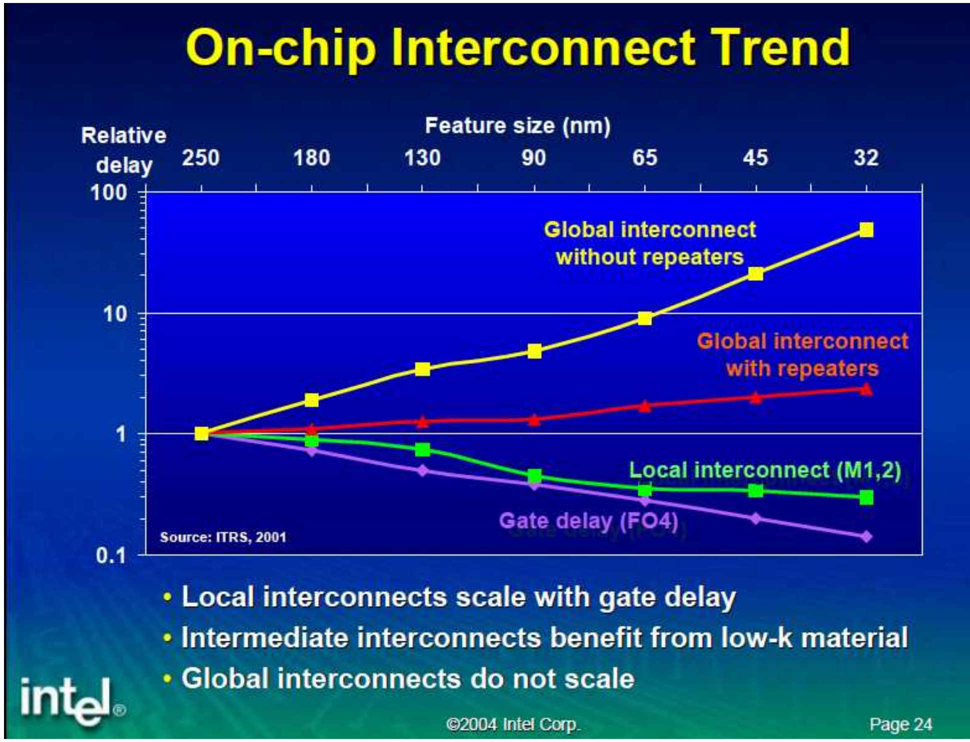
Kelin Kuhn / Int'l Symp. on Adv. Gate Stack Technology/ Sept. 29th, 2010

Dominated by interconnects

Paradigm Shift



Transistor count scaled but not frequency.
"Power Wall"



Frequency constant multiple cores → Enter optical interconnects for global interconnects

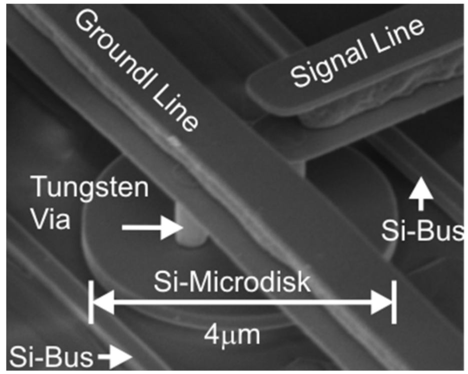
Enter Si Photonics

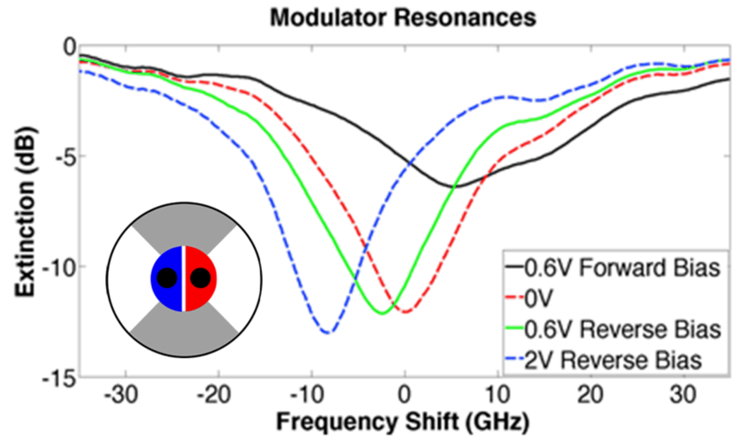
- Si Photonics for optical interconnects.
- Si Photonics Philosophy (Borrowed from Si IC's)
  - Building block devices : modulators, switches, filters, detectors, …
  - Arrange into complex circuits
- Problem we are solving is power and bandwidth, so
  - Make sure Si photonics is low power & high bandwidth.

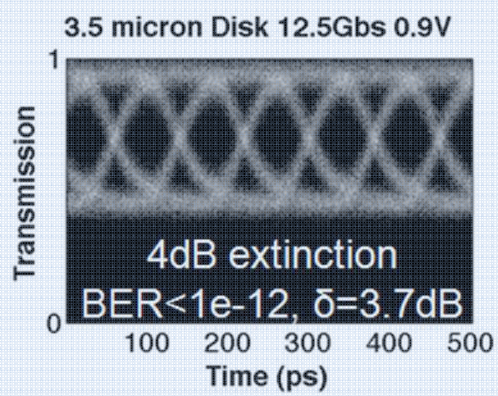
Low Power Modulator Switch

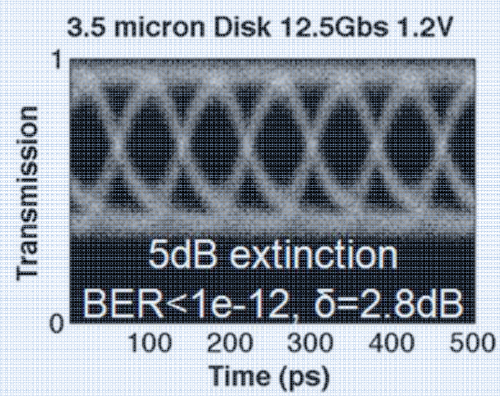
<u>Si disk resonators:</u>

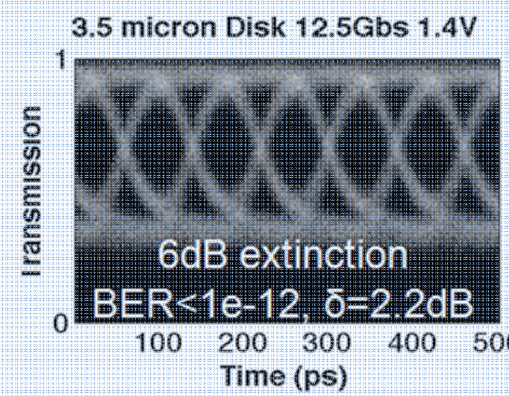
- very small device
- limit doping in ring
- differential Operation









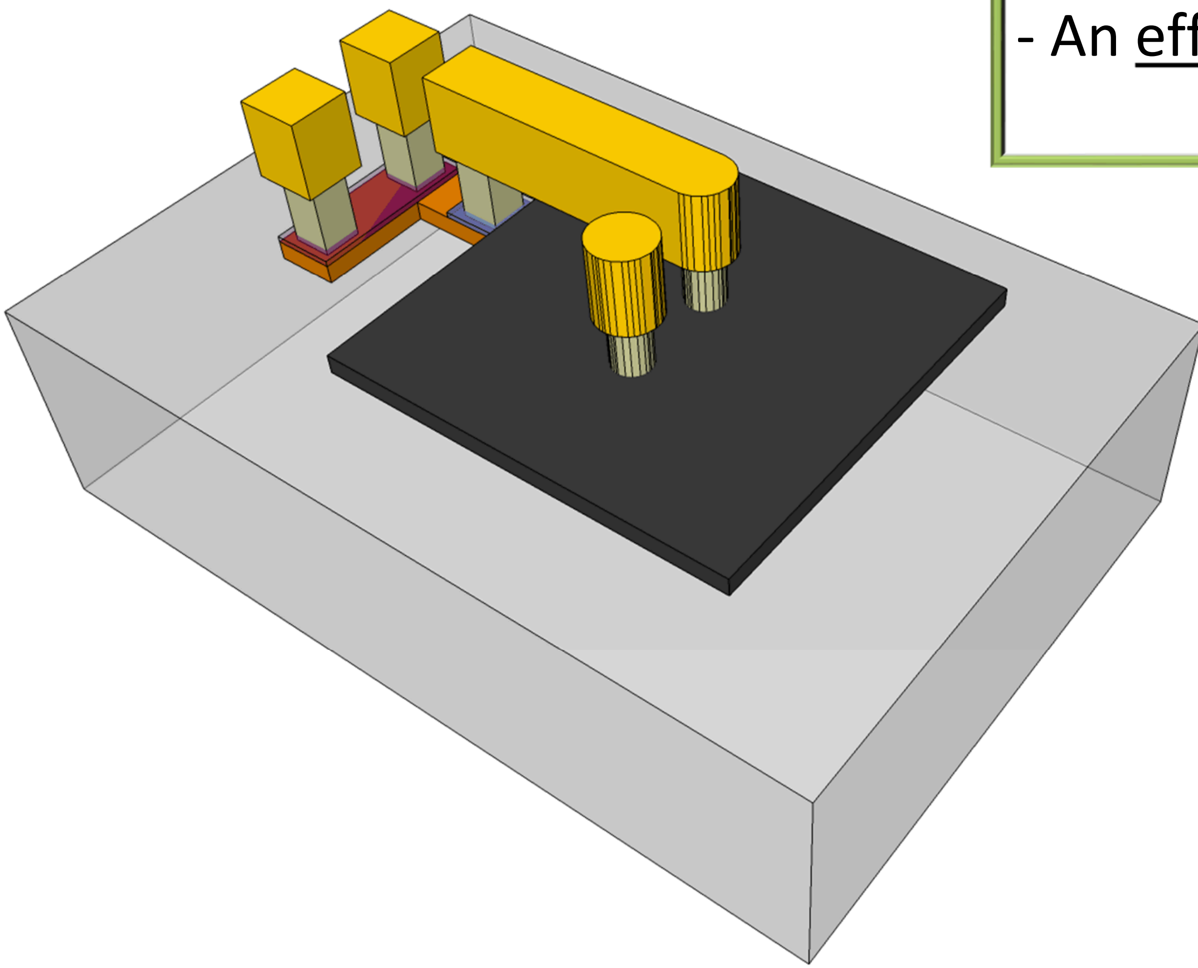


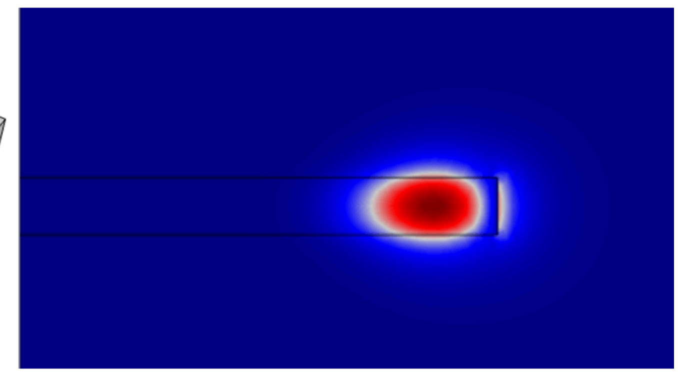
Energy / bit:	0.9V	1.2V	1.4V
Analysis:	3.8fJ/bit	6.8fJ/bit	10.6fJ/bit
Measured:	3.2fJ/bit@1V		10.1fJ/bit@1.5V

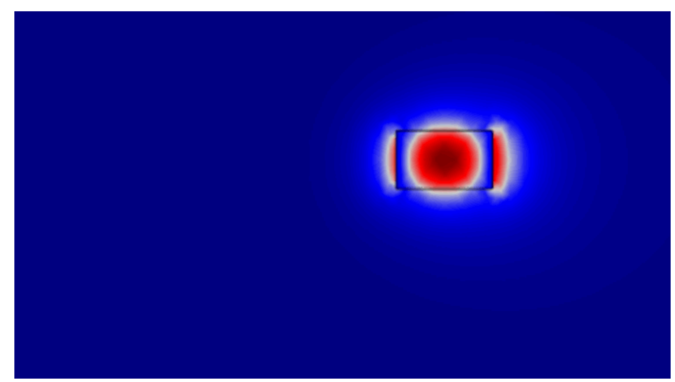
W.A. Zortman, et. al., CLEO 2010 CThJ4

An External Heater Modulator

The idea:
- An <u>efficient</u> heater design
for *any* modulator

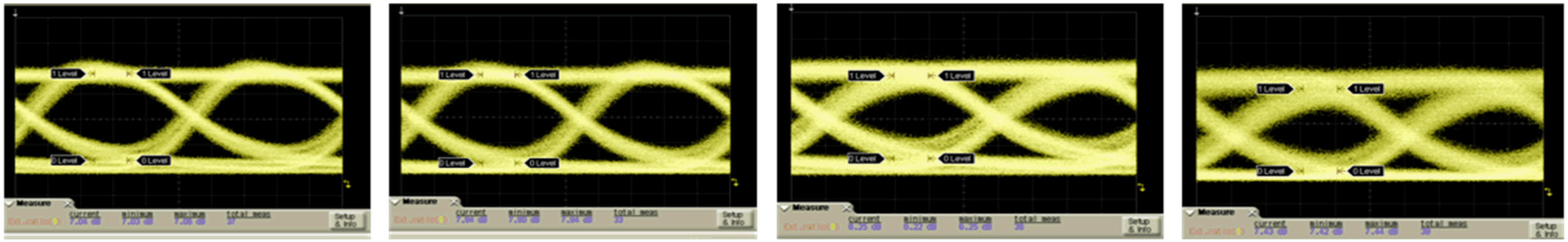


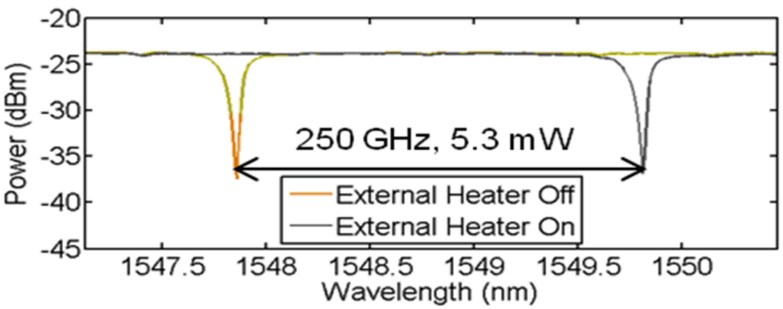


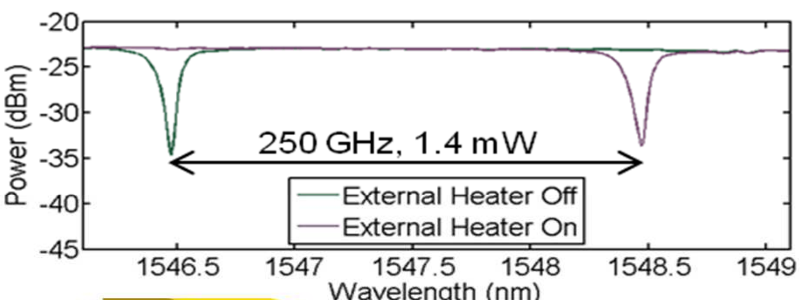


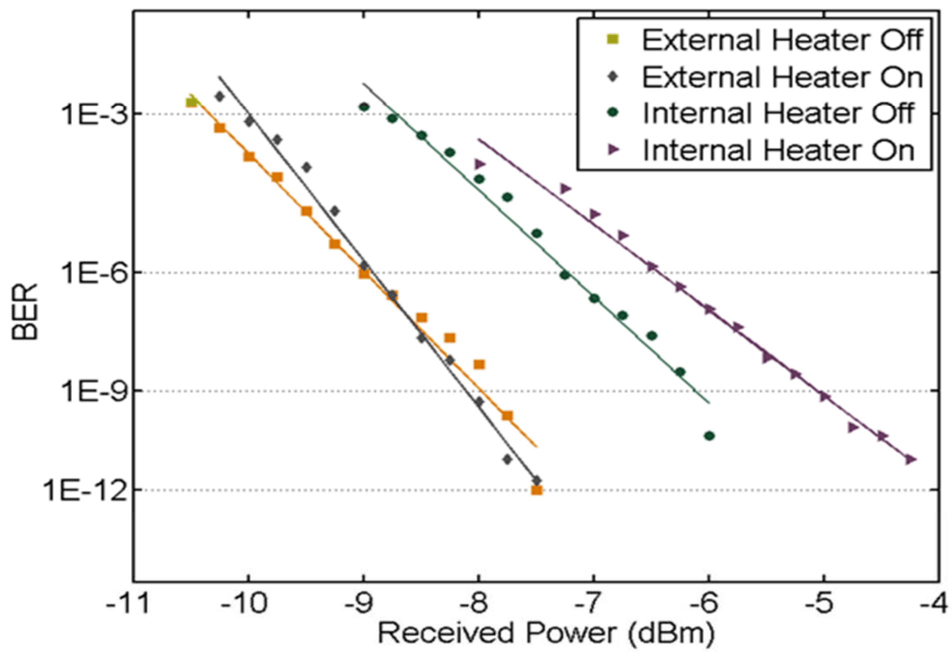
1) Reference

Comparison with Integrated Heater









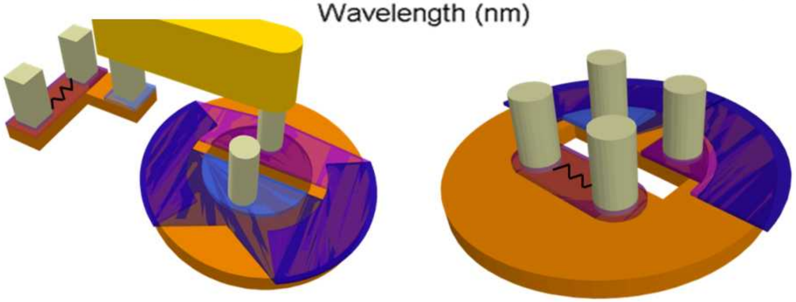
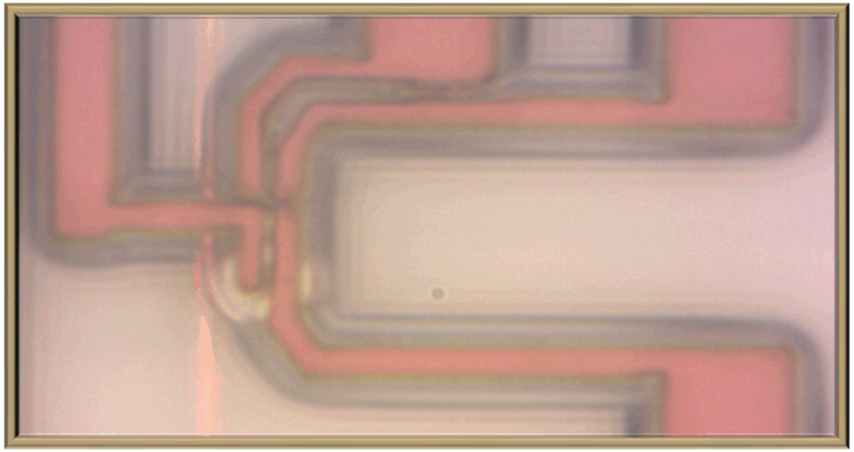
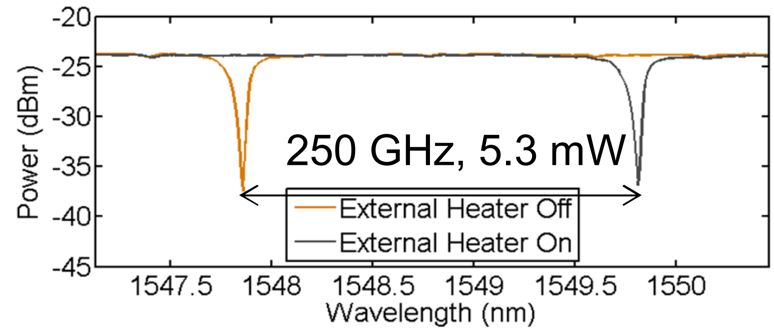


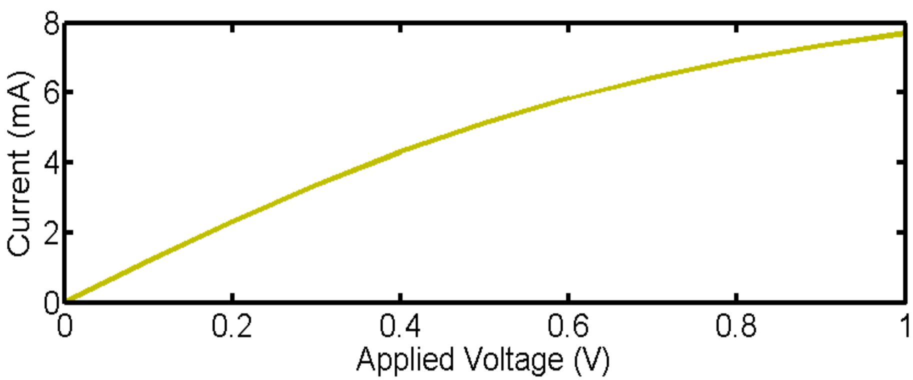
Illustration of the tradeoff between heater efficiency and modulator design

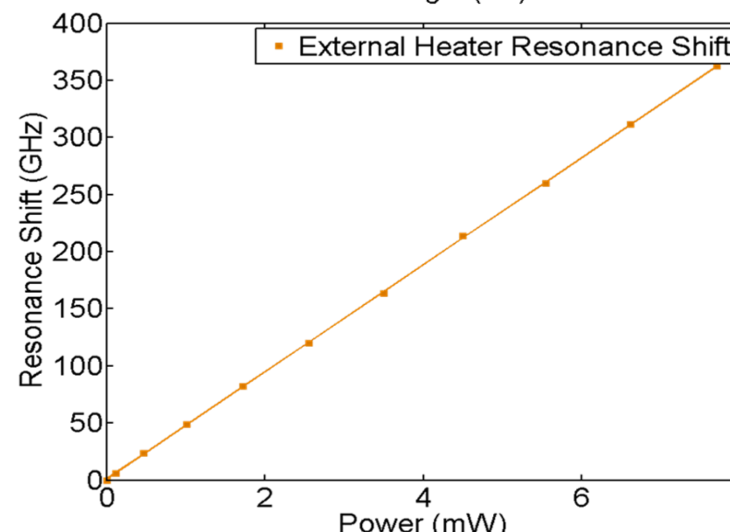
Experimental Results

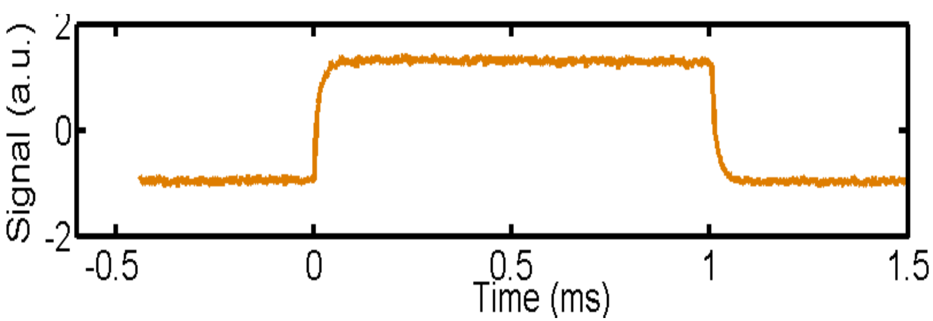
Sandia National Laboratories









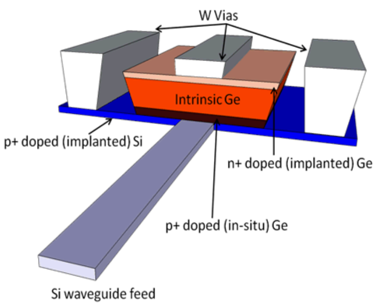


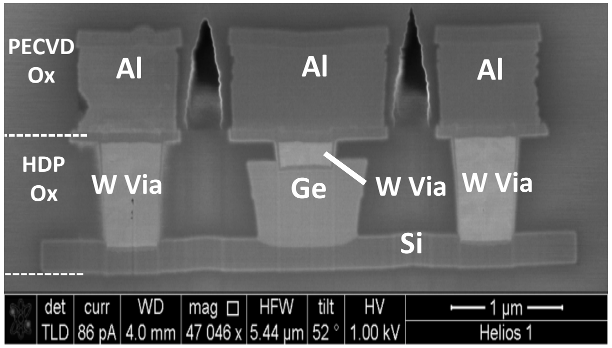
- Fabricated in 230 nm Si on 3μm BOX
- N++ resistive element ~ 100Ω
- Time constant – τ ~ 15 μs
- Resonant shift 21.3 μW/GHz
- Q factor ~ 20000

High Speed Detector

Compact high speed photodiode

Sandia

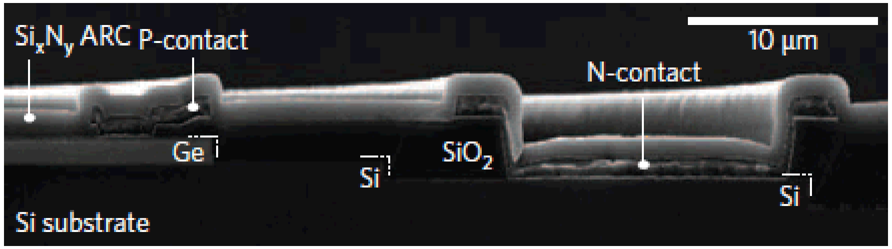




5 December 2011 / Vol. 19, No. 25 / OPTICS EXPRESS 24897

Ge on Si Avalanche Photodiode

Intel, UCSB, UVa

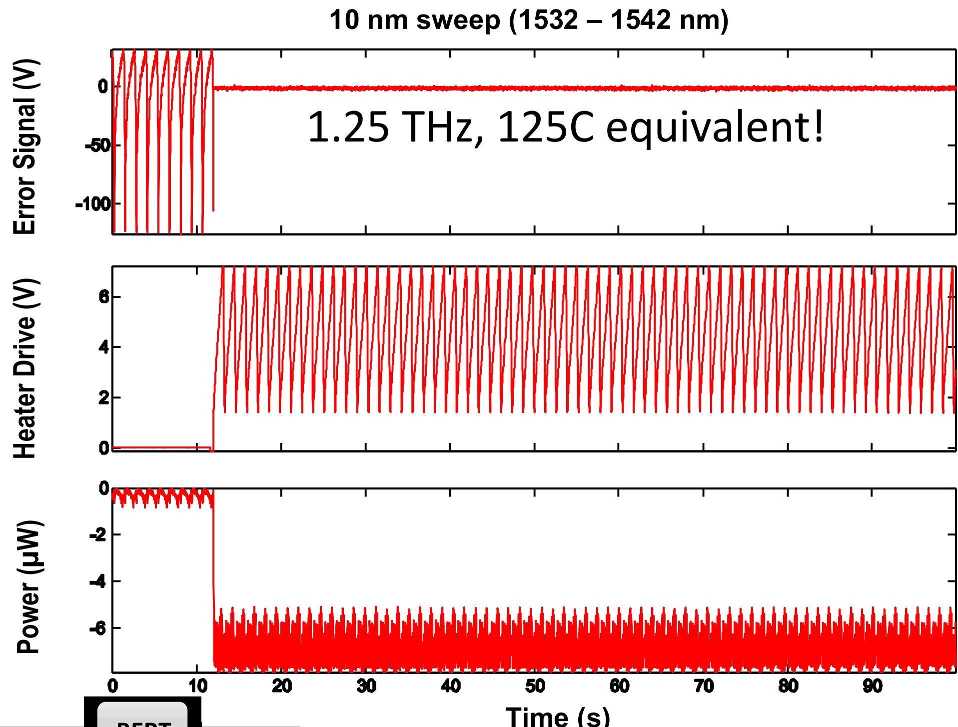


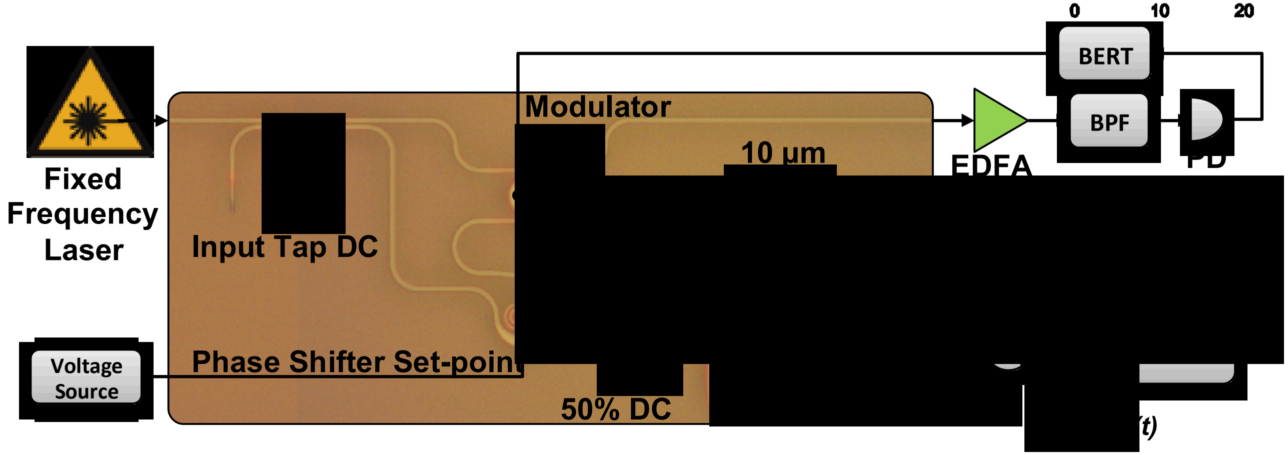
NATURE PHOTONICS | VOL 3 | JANUARY 2009 | www.nature.com/naturephotonics

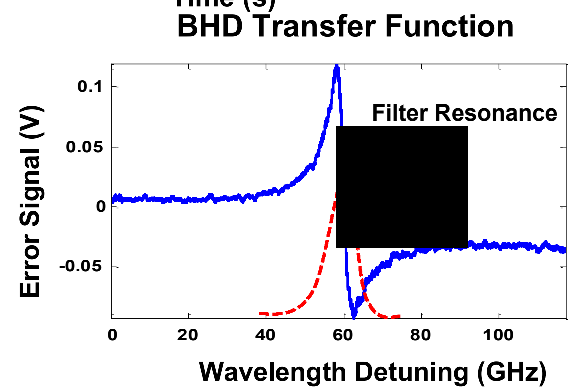
- Integrated waveguide Ge on Si photodetector demonstrated best in class performance.
  - 45 GHz pin with 0.8 A/W demonstrated
- Ge on Si linear mode separate absorption multiplication avalanche photodiode demonstrated 340 GHz gain bandwidth product.
- **Combining new device concepts would enable integrated single photon detection and launch Quantum Si Photonics.**

Modulator Stabilization System

- ***Lock to zero:*** No calibration or reference level needed for locking
- ***Amplitude insensitive:*** Locking point not influenced by optical intensity
- ***Precision locking:*** Resonator is not disturbed
- ***Minimum circuit complexity:*** Power and area consumption of control electronics is minimized



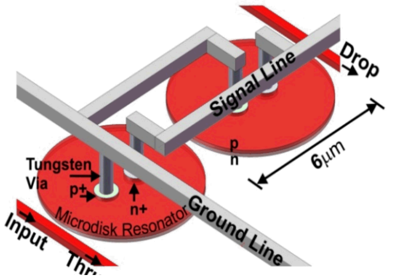


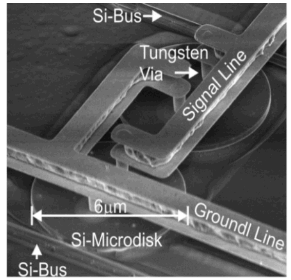


J. A. Cox et. al., Optics Express 2014

Silicon Photonics Platform

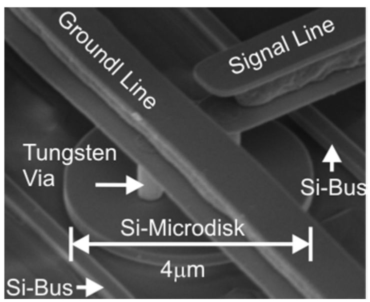
Free-carrier Effect (high-speed)



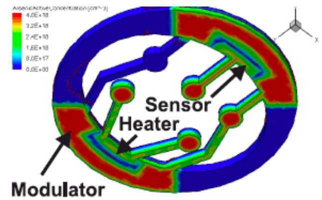


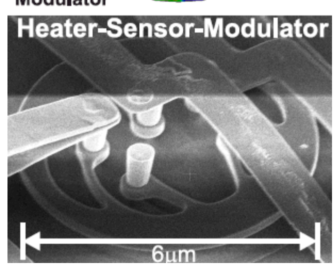
Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s



Resonant Optical Modulator/Filter

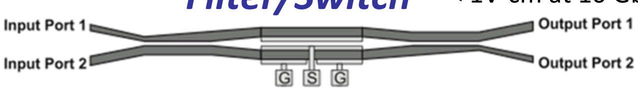




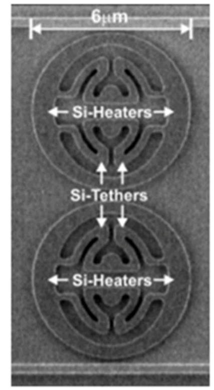
Thermally stabilized modulator

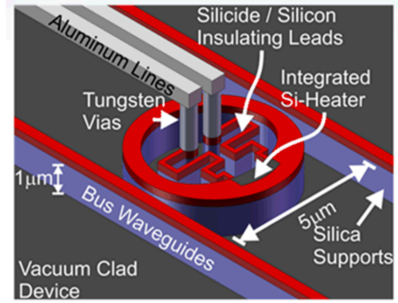
Broadband Mach-Zehnder Filter/Switch

< 1V-cm at 10 Gb/s

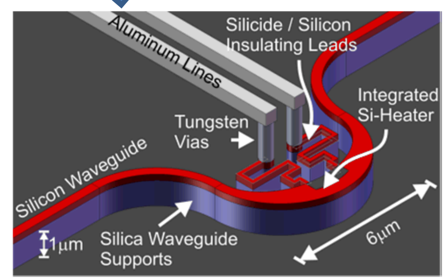


Thermal Optic Effect (wide-band)

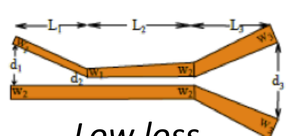




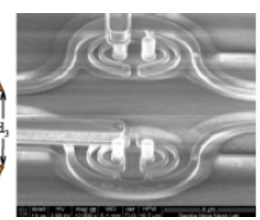
Tunable Resonant Filter



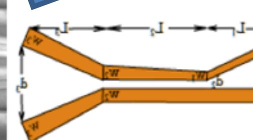
Thermo-optic Phase Shifter



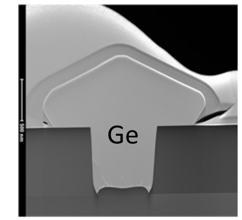
Low loss optical coupler



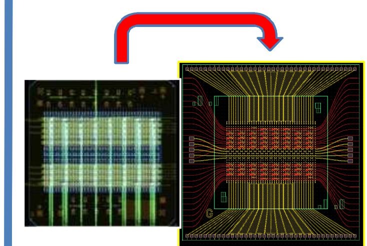
Switch Arrays

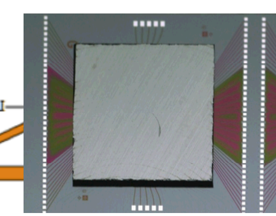


High-speed Ge Detector in Si



Si Photonics-CMOS Integration





Quantum information on-chip

- What is the killer app?
  - CYBER-SECURITY?
    - Authentication in classical com?
    - Infrastructure (FAA, power grid)?
    - Banking and finance? Crypto-currencies?
    - National security? (Quantum computer proof)
- Why on a chip?
  - Implies you will deploy to 10^6 – 10^9 systems?
  - Need economy of scale for chip-manufacturers.

Quantum Photonics

- Beam splitters and interferometers are key components.
- Polarization components.
- Hot or Cold?
- Si Photonics leverages mature telecom/datacom
  - Choice of wavelengths: 850, 1310 or 1550 nm
  - Some would like 850 nm, Si out of the question for waveguide but detector.
  - 2300 nm allows for Si and potential GeSn laser integration. Need new detector GeSn tech.
    - Lasing in direct-bandgap GeSn alloy grown on Si
    - **S. Wirths, R. Geiger, N. von den Driesch, G. Mussler, T. Stoica, S. Mantl, Z. Ikonic, M. Luysberg, S. Chiussi, J. M. Hartmann, H. Sigg, J. Faist, D. Buca & D. Grützmacher**
    - *Nature Photonics* **9**, 88–92 (2015) doi:10.1038/nphoton.2014.321

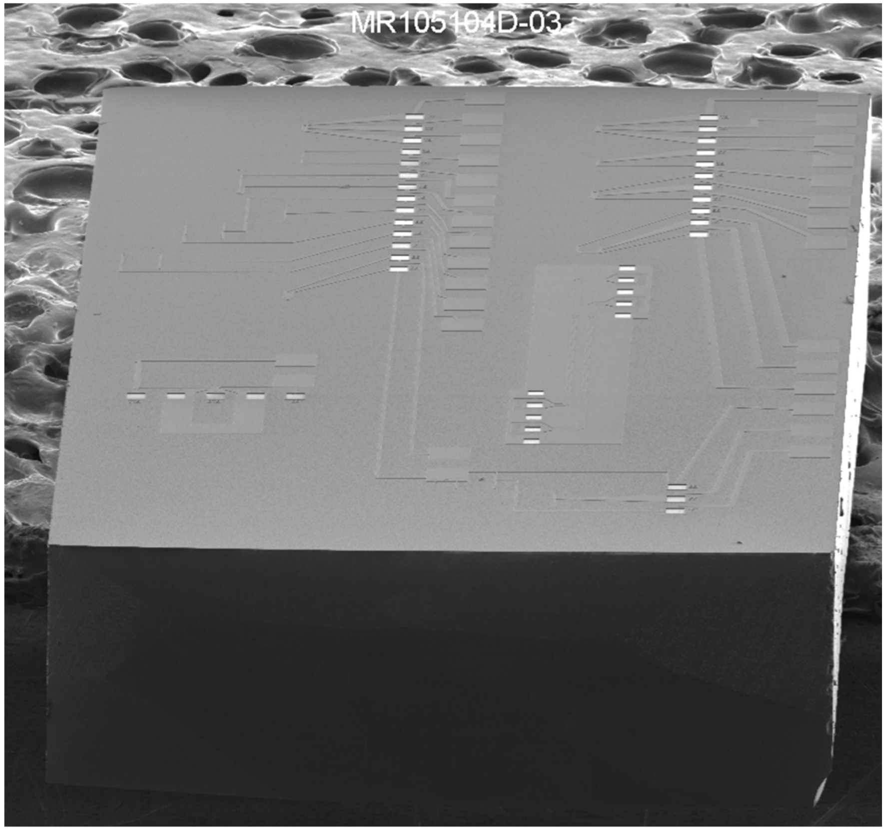
Chip-scale Quantum Photonics

- Program goal: Demonstrate chip-scale QKD.
- QKD is demonstration application using Si Photonics Platform.
- Expand Si Photonics Platform with new building blocks for quantum optics.
  - Polarization elements.
  - Single photon detectors.
  - Low loss coupling and on-chip signal routing.

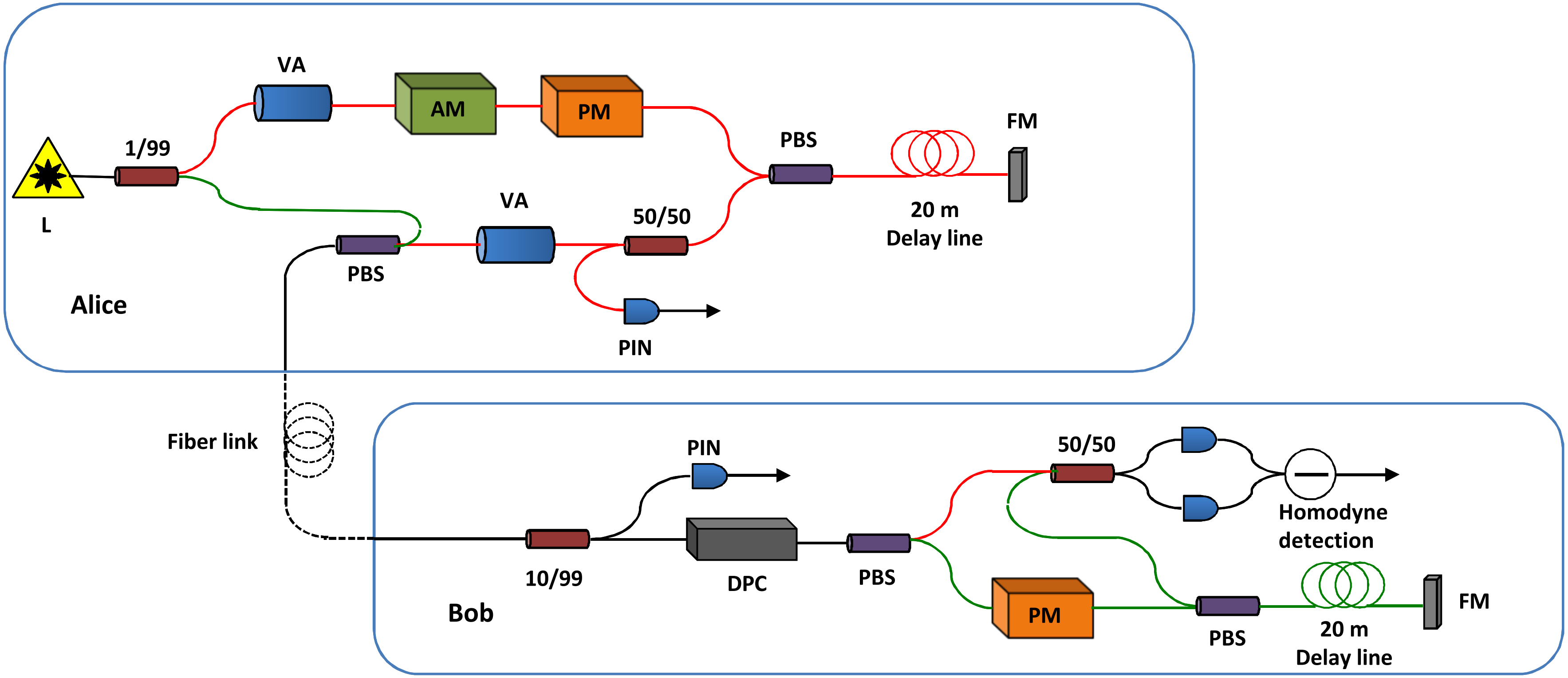
Outline

- CV-QKD chip-scale fiber link.
- DV-QKD chip-scale free-space link.
- Integrated Single Photon Detector development.

CV-QKD Transceiver



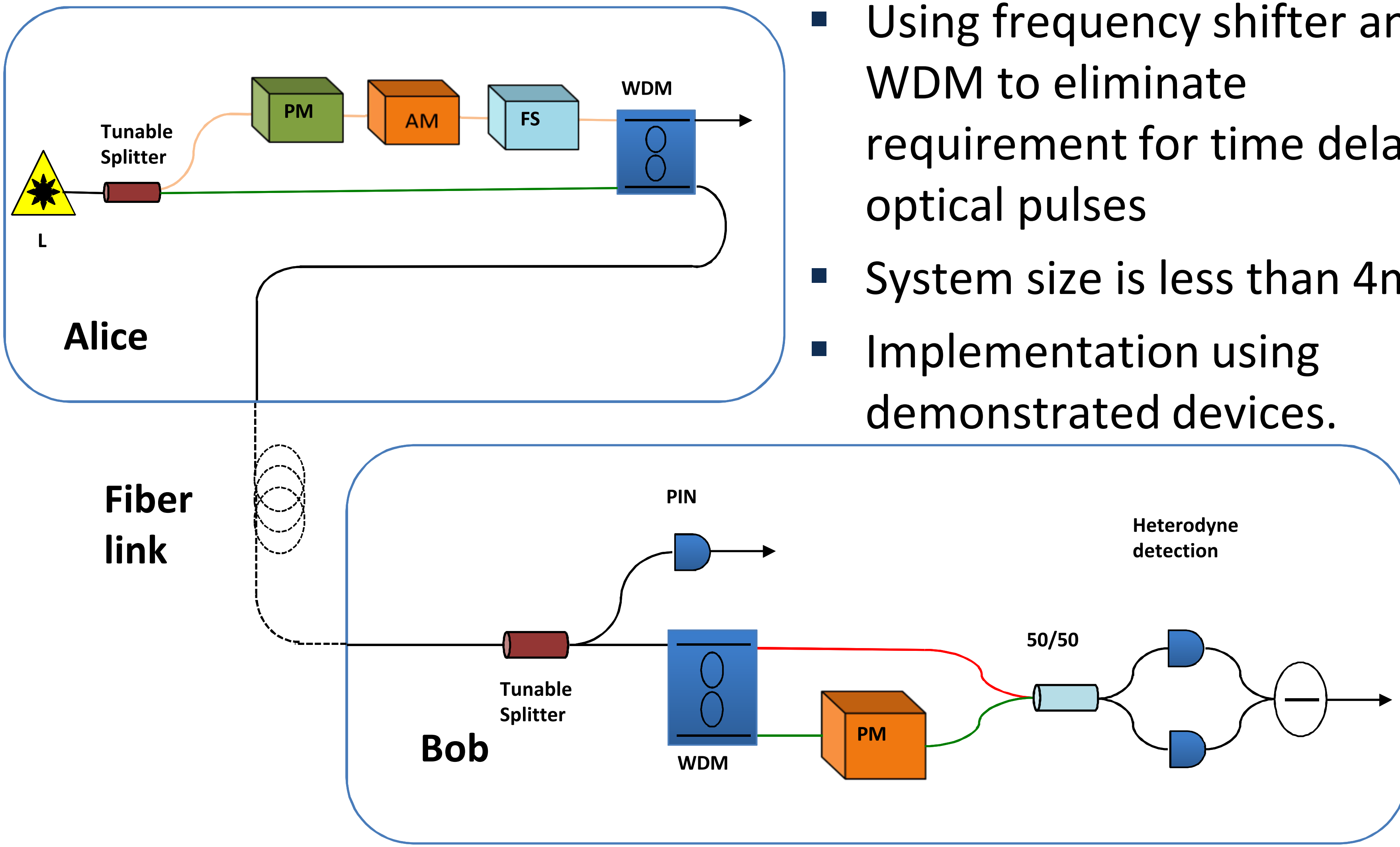
Bench-top CV-QKD link



Current State of the Art CVQKD link using coherent state source

P. Jouguet, S. Kunz-Jacques, A. Leverrier, P. Grangier, and E. Diamanti. Experimental demonstration of long-distance continuous-variable quantum key distribution. Nature Photonics, 7(5):378–381, 2013.

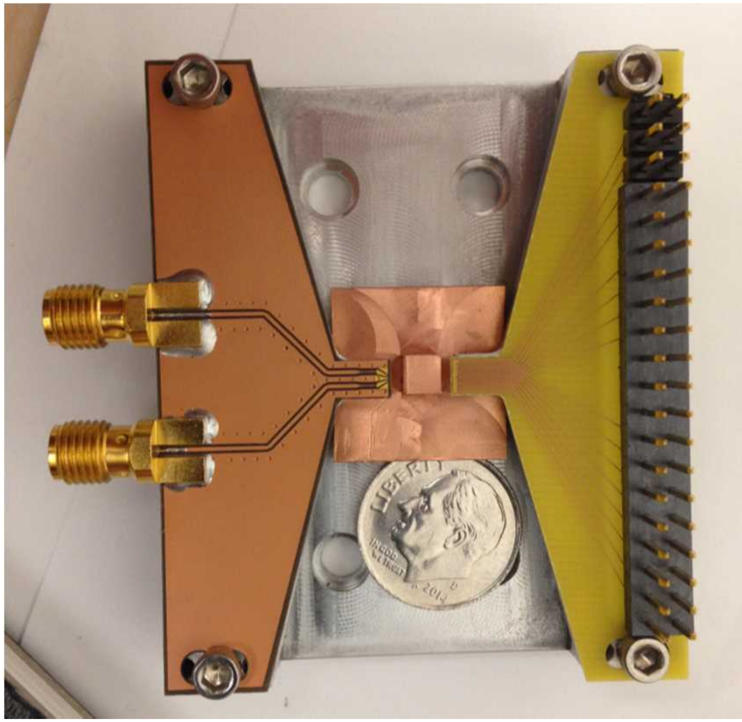
On-Chip CV-QKD System



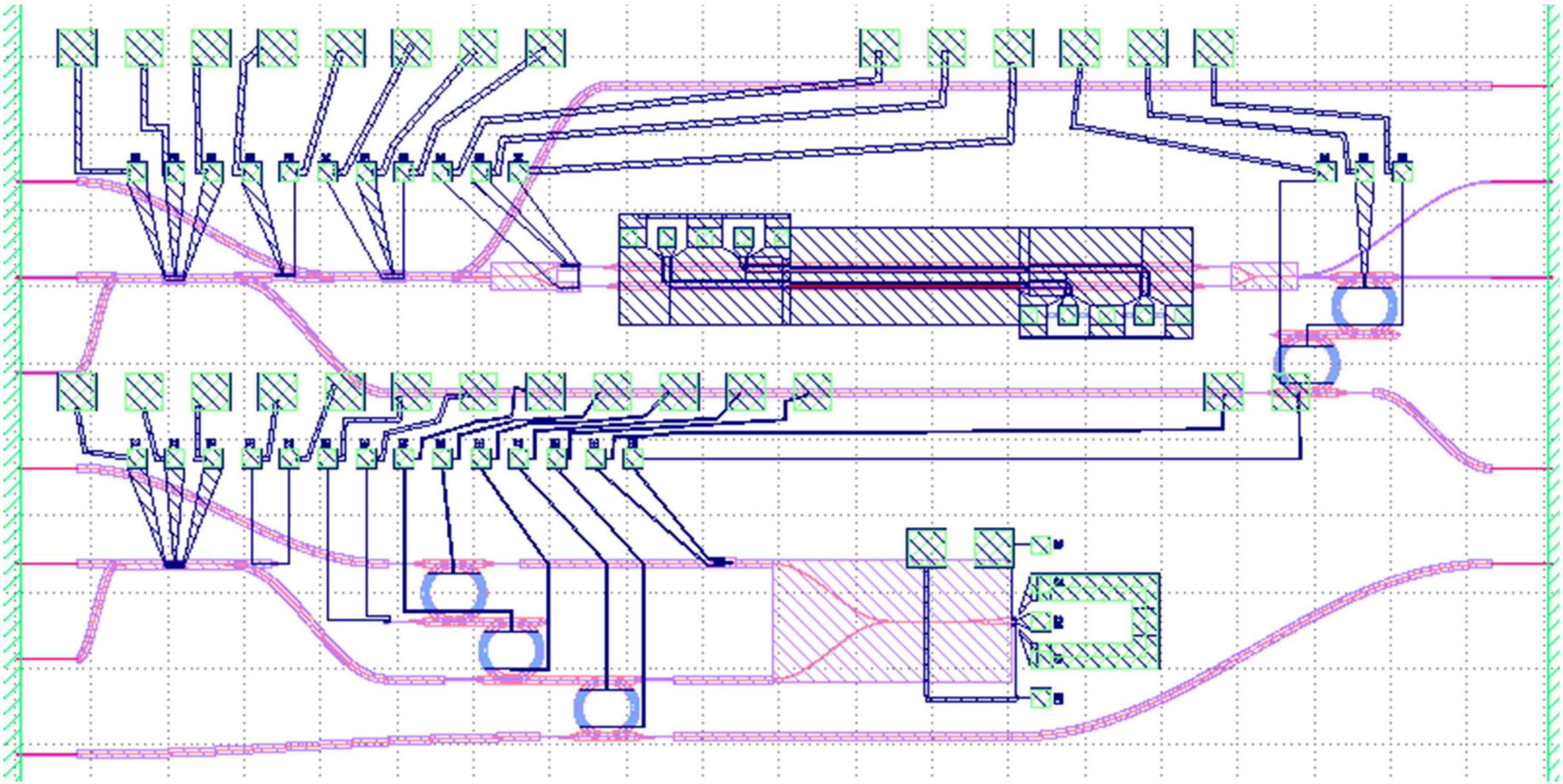
- Using frequency shifter and WDM to eliminate requirement for time delayed optical pulses
- System size is less than $4mm^2$
- Implementation using demonstrated devices.

Chip-scale CV-QKD Transceiver

- Modified from Granger-Diamanti bench-top design due to difficulty in long delays on chip.
- Uses well-characterized existing devices within Sandia's Si Photonics platform.
- Can use coherent states or squeezed states.
- Need to develop simple package for protocol testing.

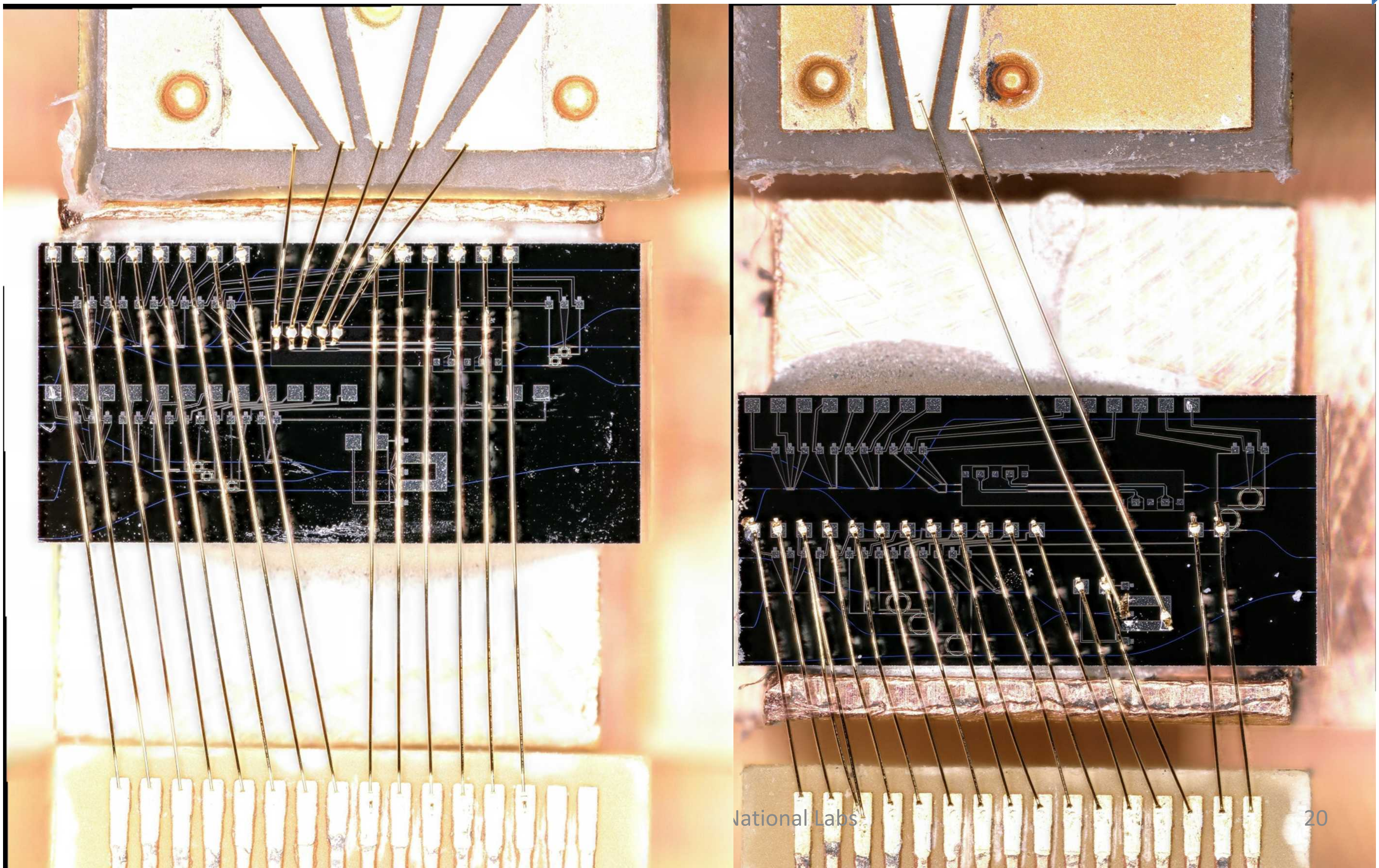


CV-TX/RX Layout

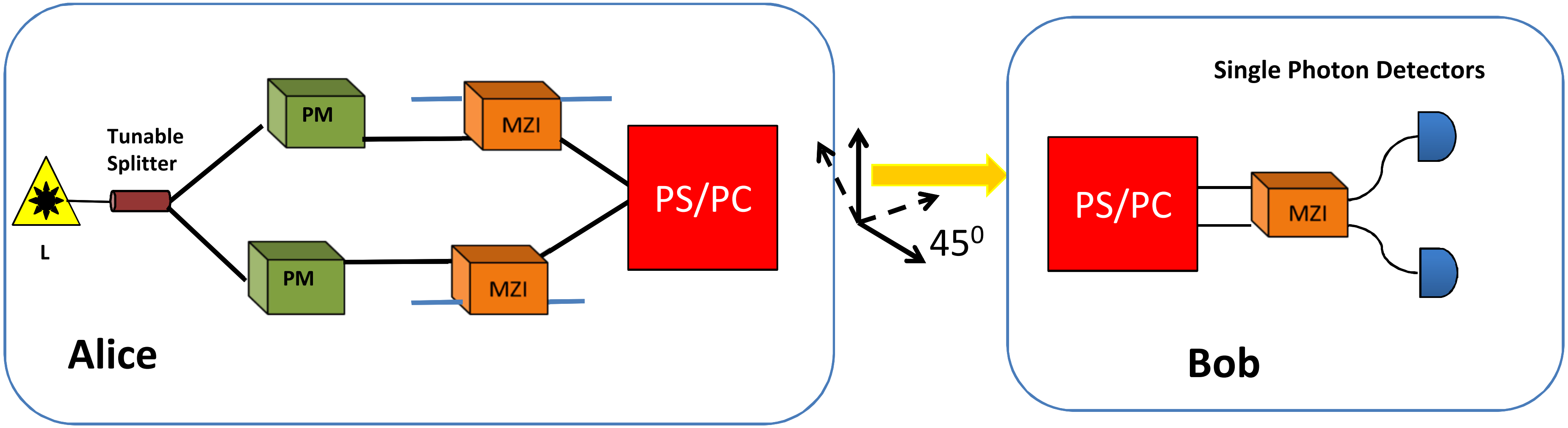


CV-QKD Tx/Rx

Skip ahead



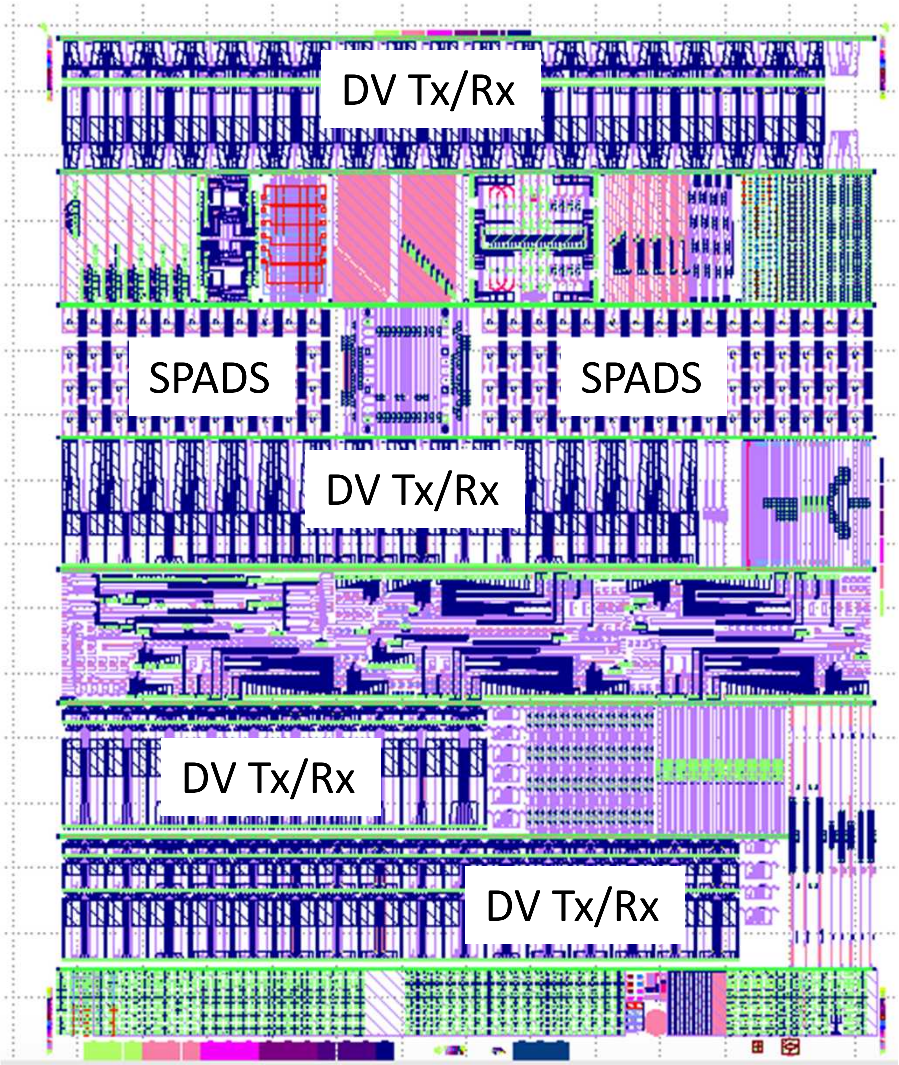
On-Chip Free-Space DV-QKD

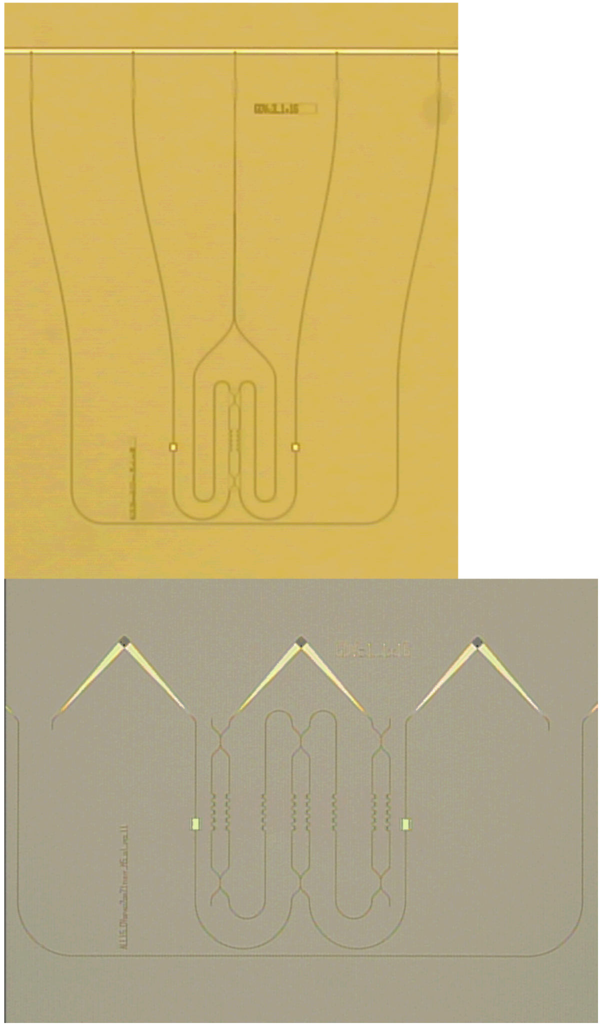


Note, Rx can also be symmetric 2x2 MZI **Free-space Link**

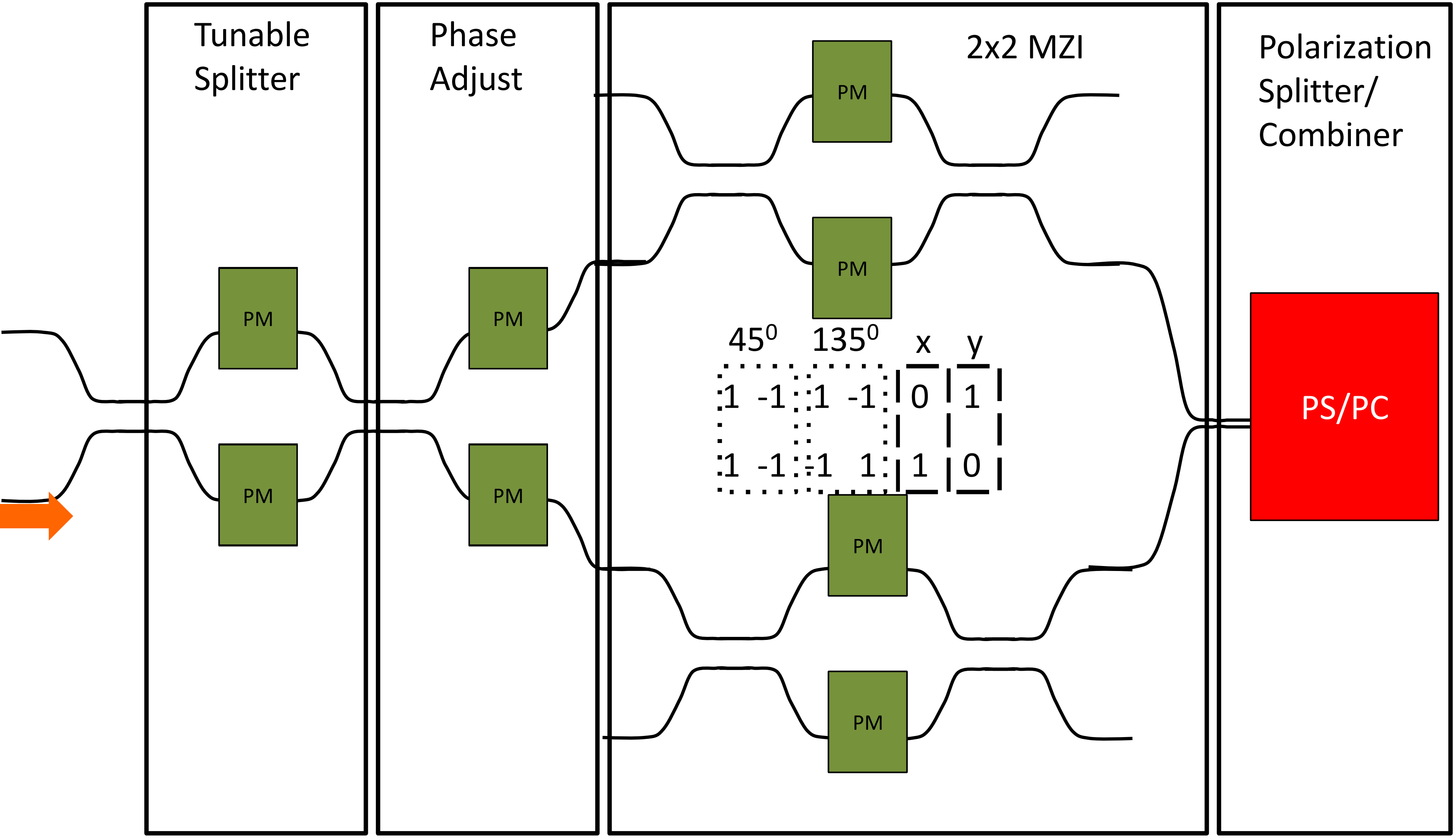
- Free-space BB84 uses Polarization of single photons.
- Need new polarization splitter/combiners in Si Photonics Platform.
- Single Photon detection is required.

DV-Tx/Rx





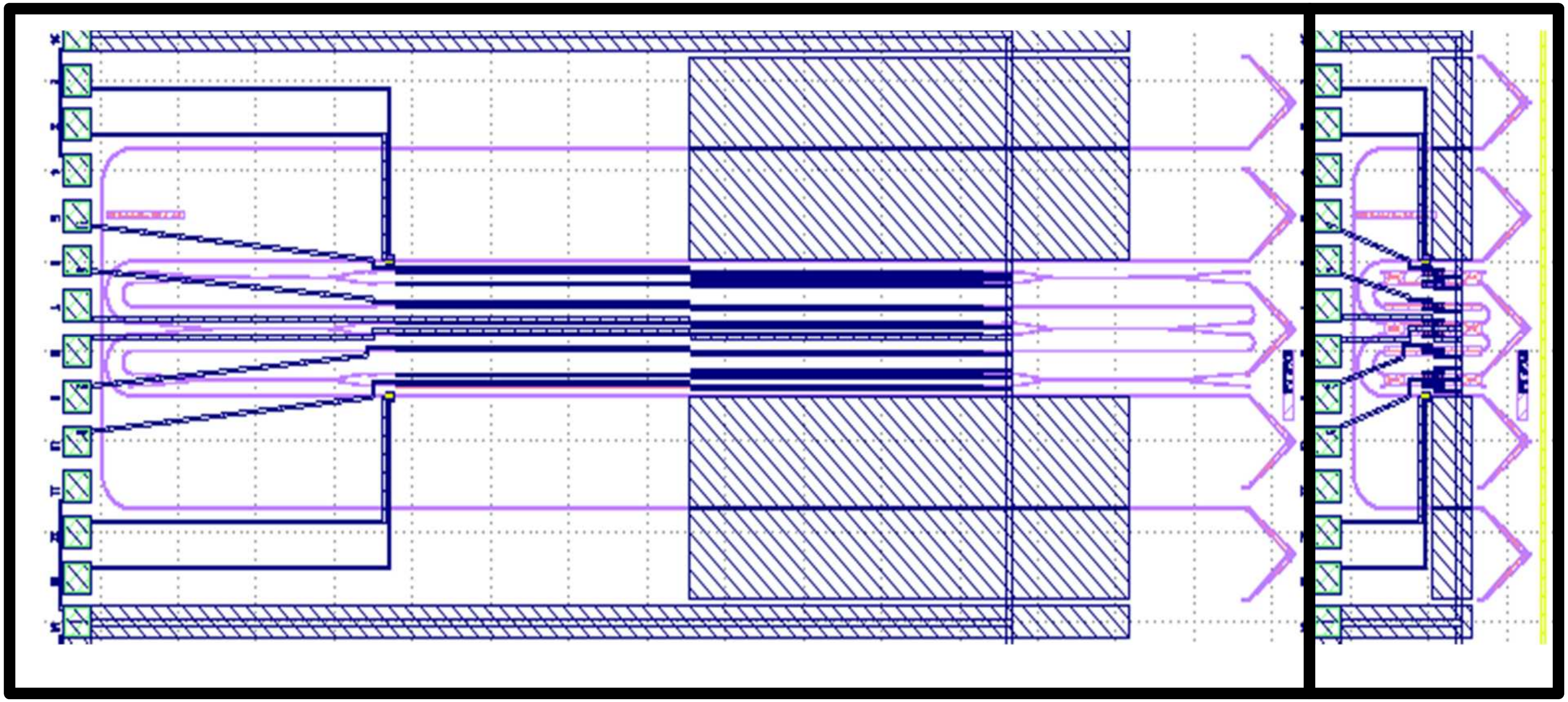
Chip-scale DV-Alice



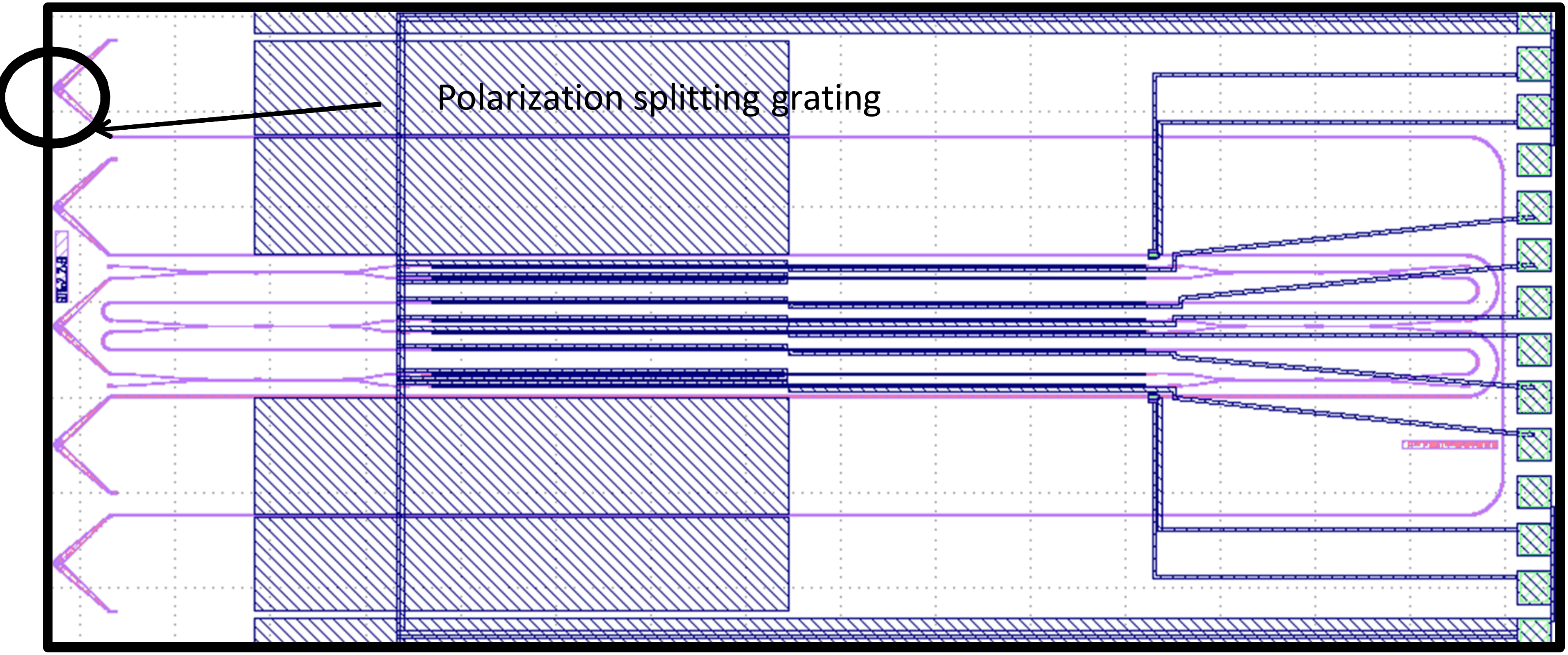
Free-space DV Tx/Rx

Alice

Bob

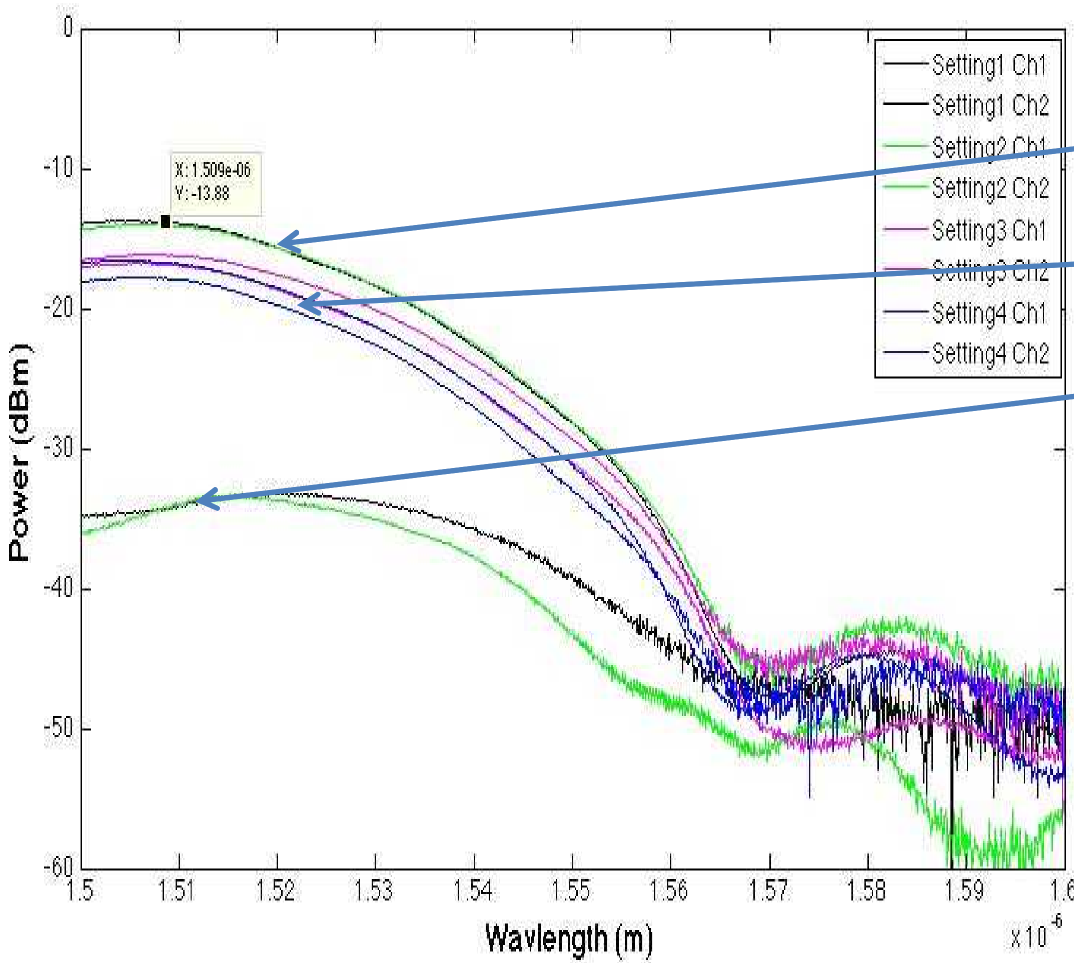


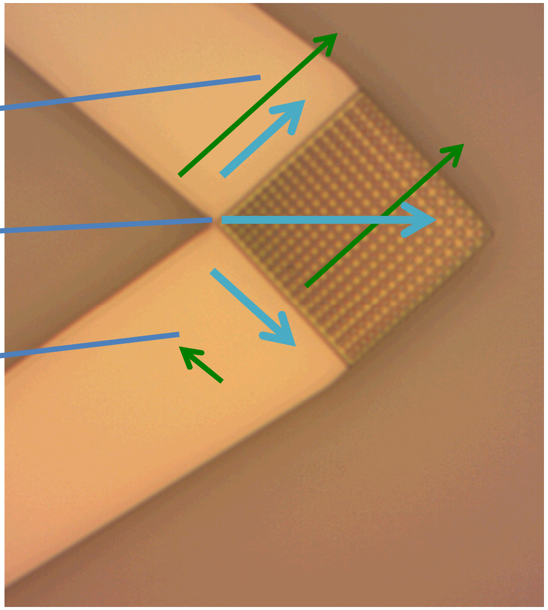
Free-space DV Tx/Rx: Alice



Waveguide polarization gratings

New polarization components developed for Free-space DV QKD with BB84



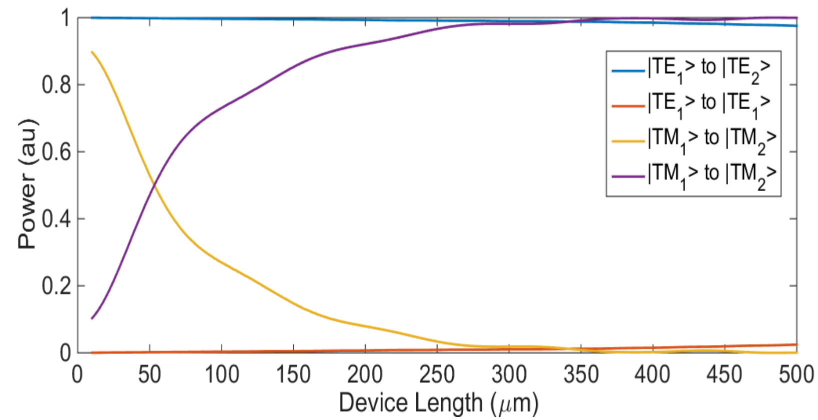


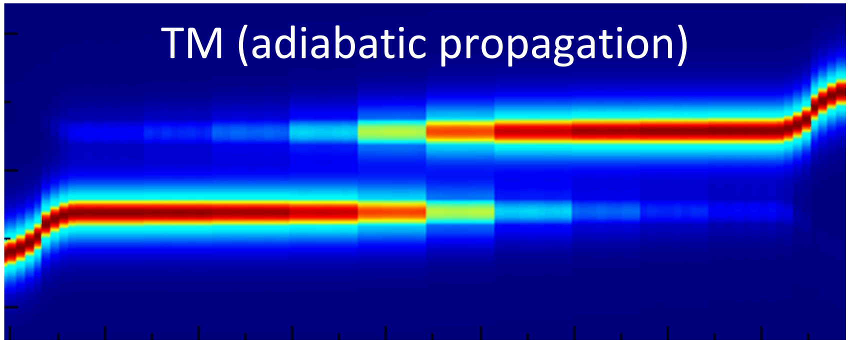
3dB split for blue polarization

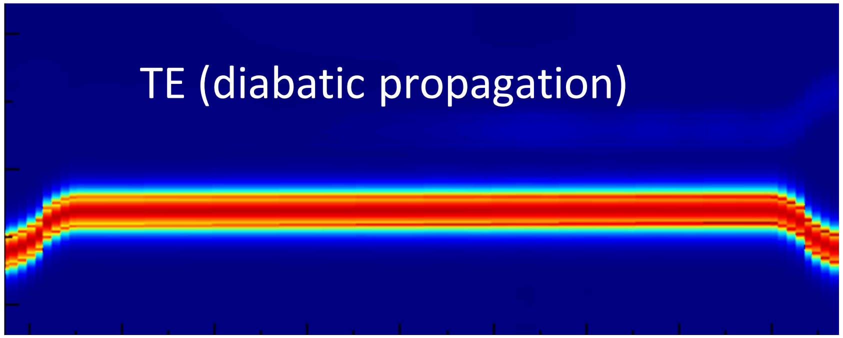
Wide-Band Polarization Beam Splitter

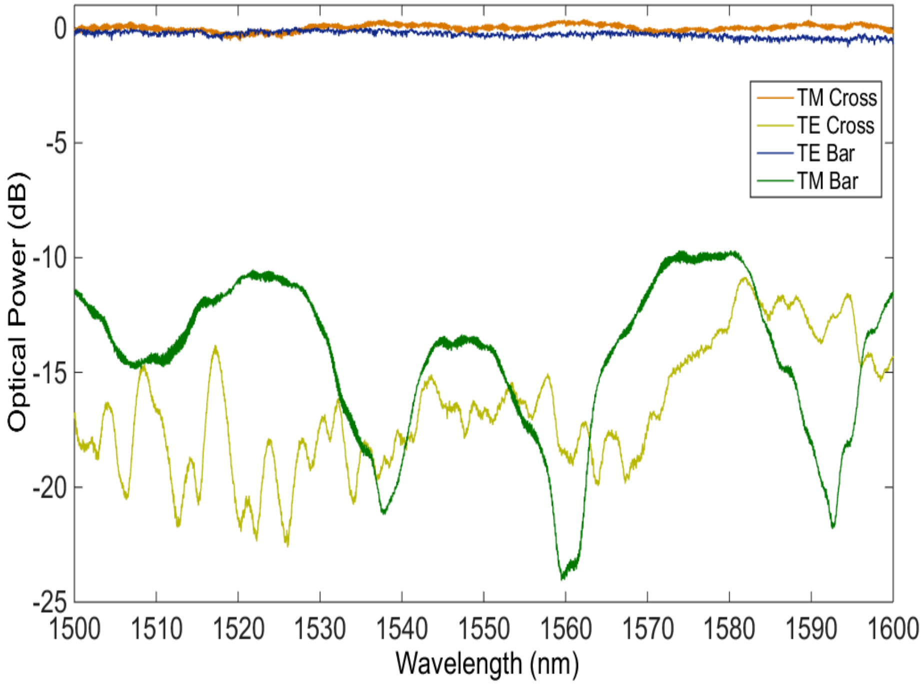
Sandia National Laboratories

- Developed a PBS based on adiabatic (TM) and diabatic (TE) mode evolution
  - ***Not*** a directional coupler
- 10 dB PER across 100 nm bandwidth
- PER can be improved by adding ‘clean-up’ PBS









Future for Quantum Photonics

- Demonstrate Quantum Photonics Circuits.
  - QKD on-chip both discrete variable and continuous variable.
  - Key learning for future quantum photonics.
- Add New functionality specifically for Quantum Photonics.
  - NbN superconducting films.
  - AlN for electro-optic modulators.
  - WSi is completely CMOS compatible.
  - GeSn Laser (Source at 2300 nm)

Ge in Modern CMOS

Germanium old semiconductor technology.

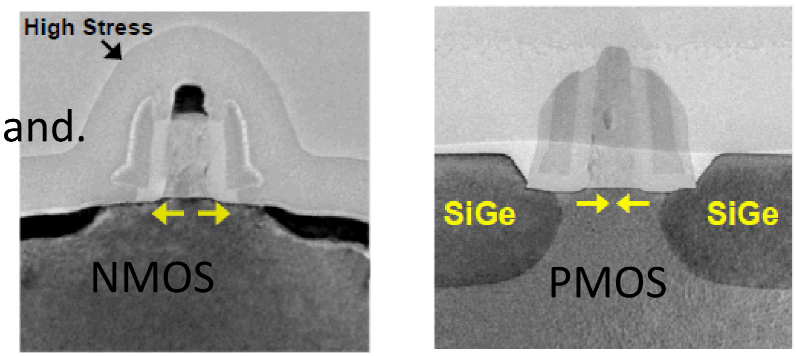
- Indirect Bandgap at 0.66 eV.
- Direct Bandgap at 0.8 eV (1550 nm) in telecom band.
- Not efficient optical emitter.

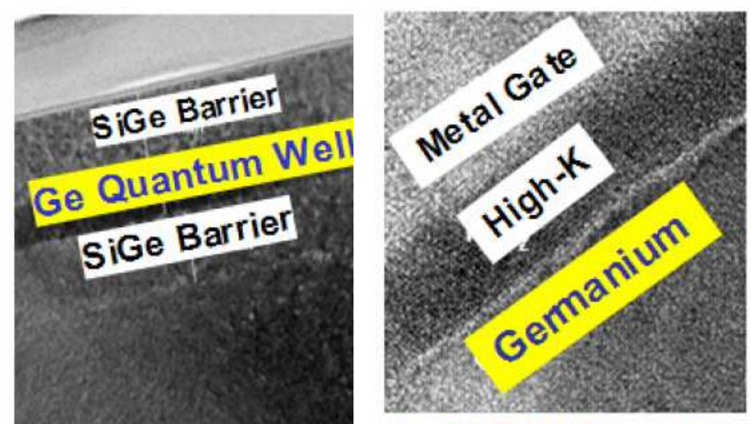
Selective epitaxial growth of Ge on Si has enabled advanced strain engineering in modern CMOS.
Fully CMOS Compatible.
High electron and hole mobilities.

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

Strain engineering in CMOS

Intel 45nm



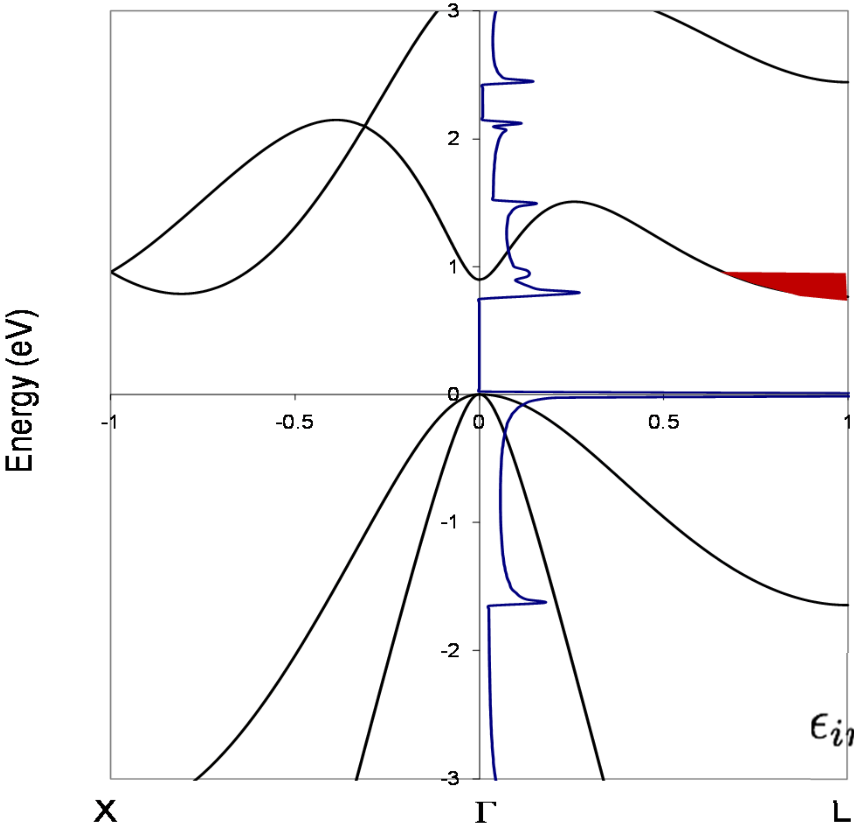


Ge Quantum-well Ge MISFET Transistor

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

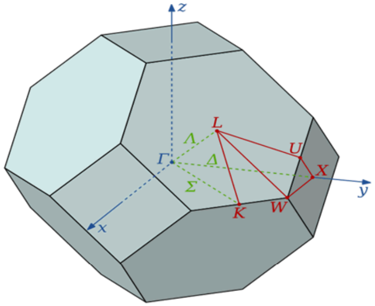
Optical Properties of Doped Ge

Tight binding band-structure



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

Optical Properties of Heavily Doped Semiconductor



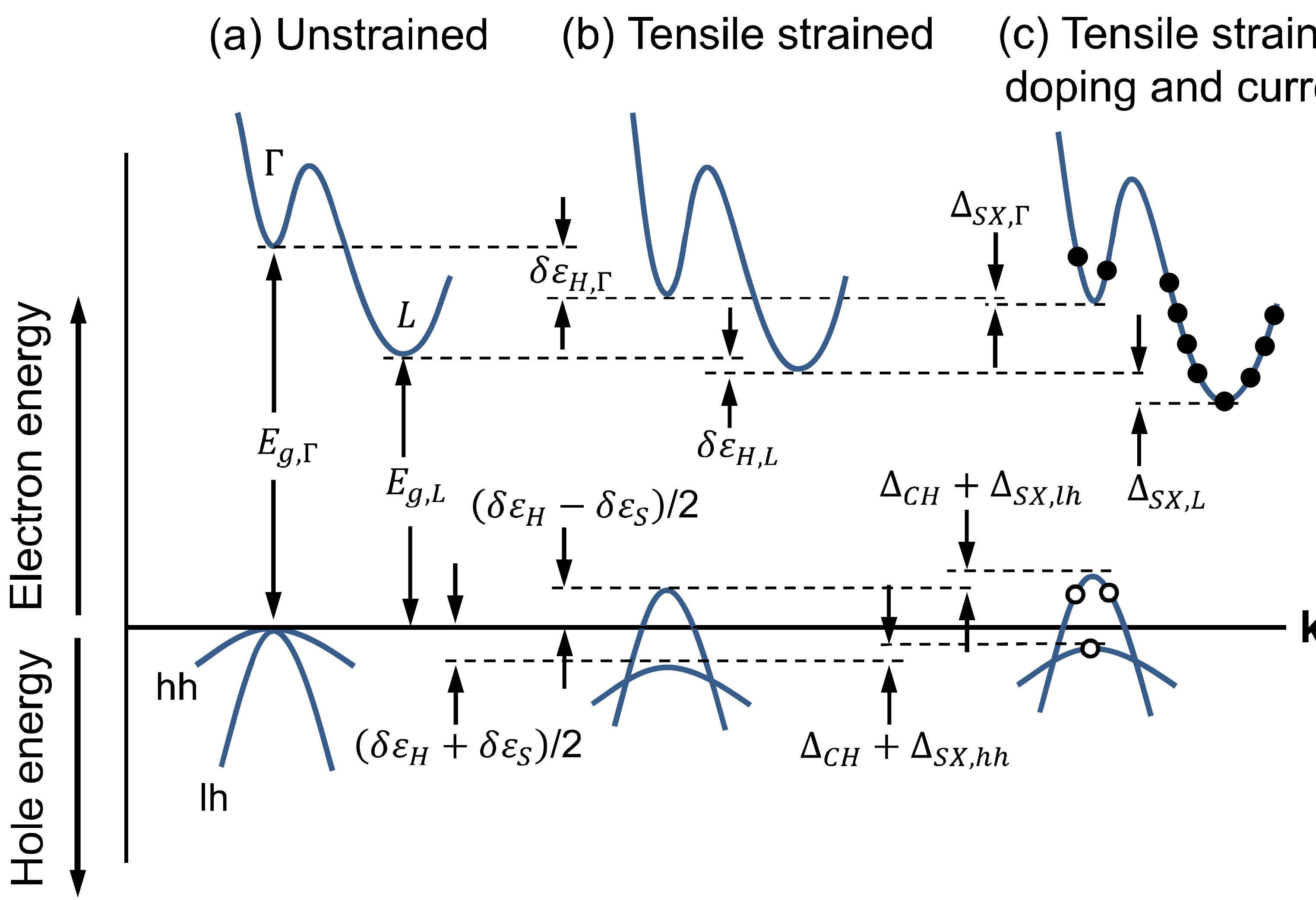
J. Jung, T. G . Pederson, JAP,113,114904,(2013)

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

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

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

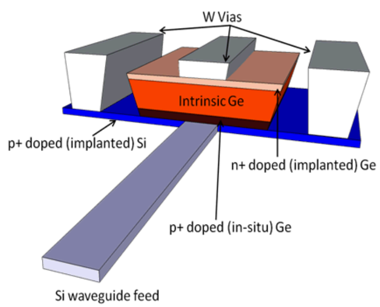
Indirect Bandgap in Strained Ge

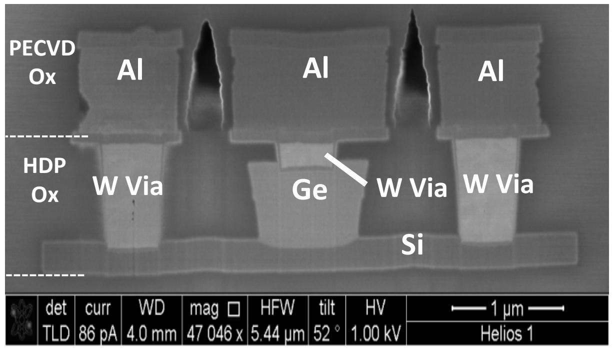


Ge on Si Detector Development

Compact high speed photodiode

Sandia

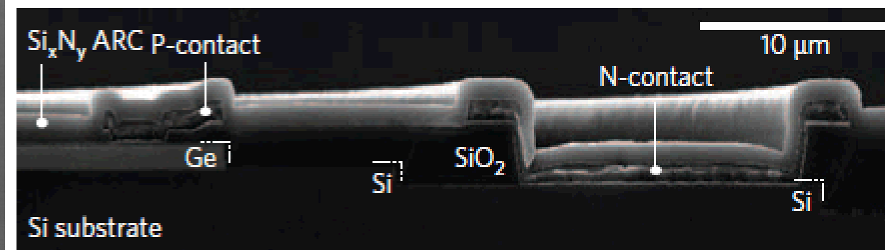




5 December 2011 / Vol. 19, No. 25 / OPTICS EXPRESS 24897

Ge on Si Avalanche Photodiode

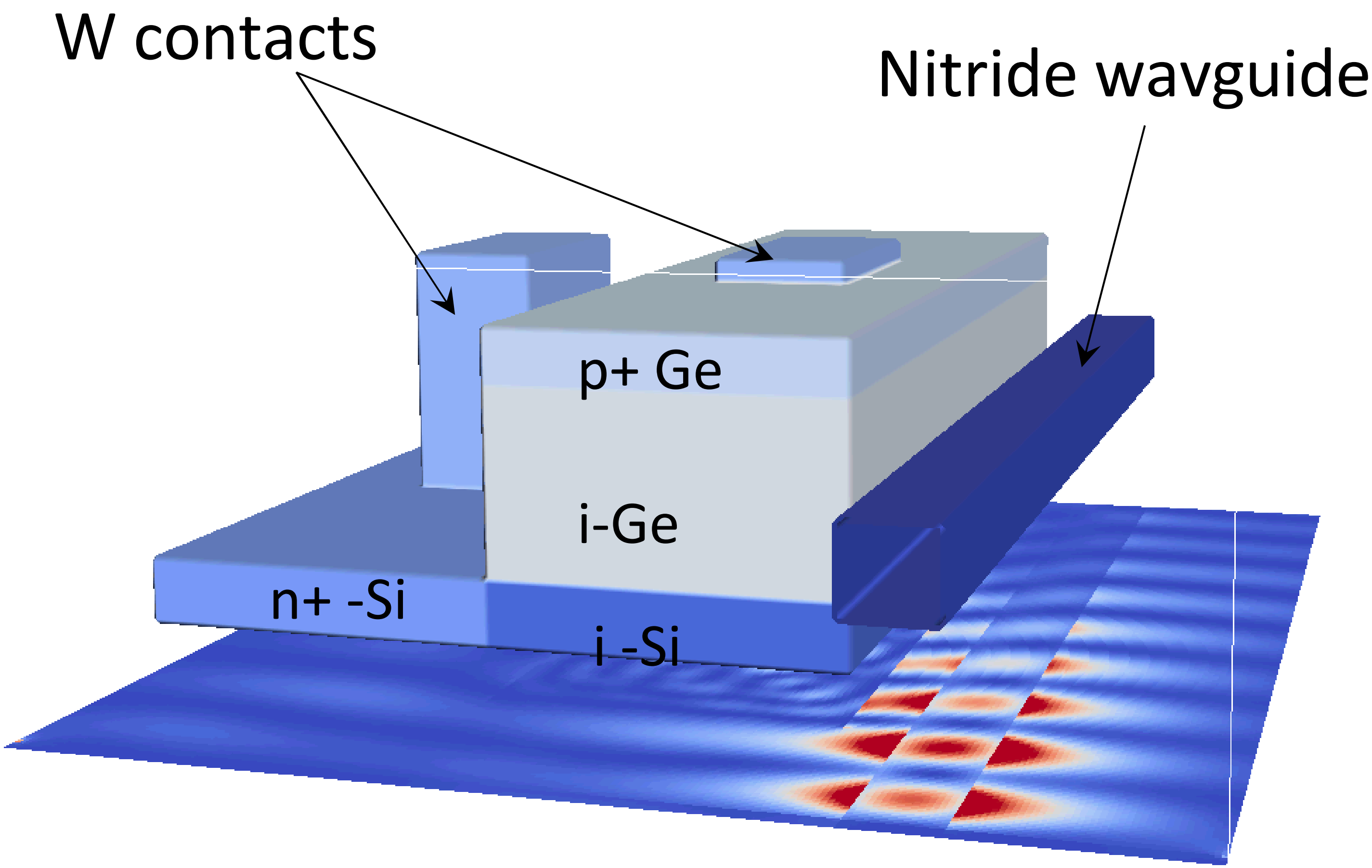
Intel, UCSB, UVa



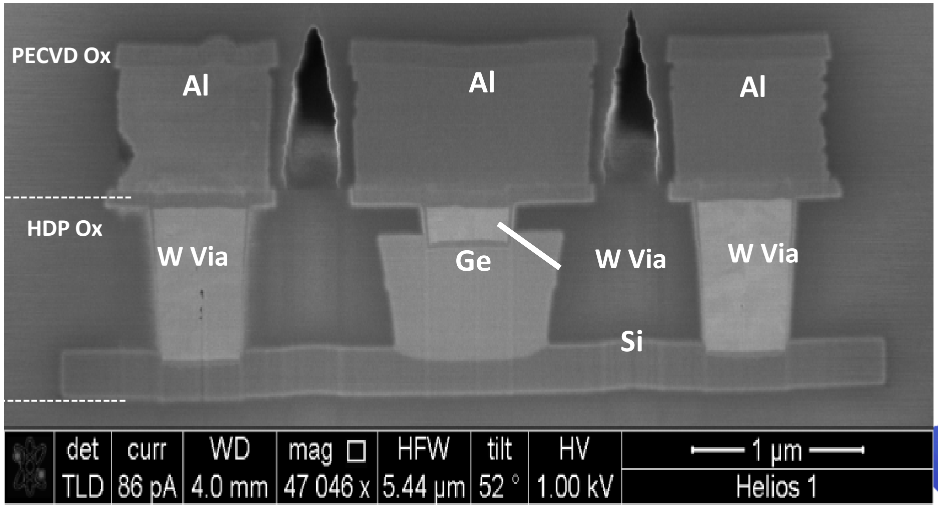
NATURE PHOTONICS | VOL 3 | JANUARY 2009 | www.nature.com/naturephotonics

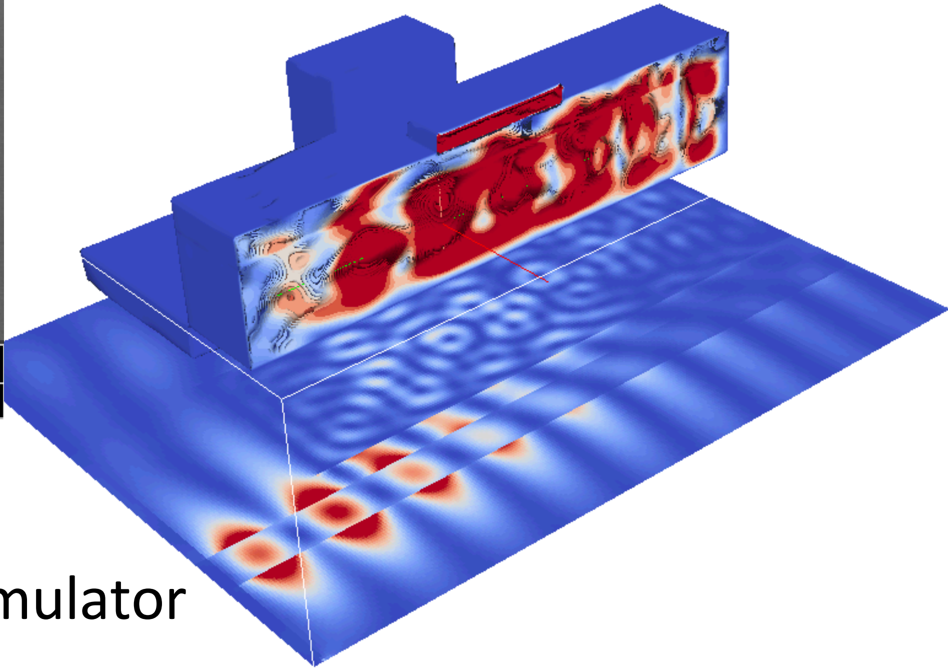
- Integrated waveguide Ge on Si photodetector demonstrated best in class performance.
- Ge on Si linear mode separate absorption multiplication avalanche photodiode demonstrated 340 GHz gain bandwidth product.
- **Combining new device concepts would enable integrated single photon detection and launch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

Waveguide Coupled SPAD



Ge Photodetector Development





Input Generation rate into Device simulator
Synopsis drift-diffusion.
APD simulations currently underway.

C. T. DeRose, D. C. Trotter, W. A. Zortman, A. Starbuck, M. Fisher, M. R. Watts, and P. S. Davids, "Ultra compact 45GHz CMOS compatible Ge waveguide photodiode with low dark current," *Optics Express*, vol. 12, no. 25, p. 24897, 2011.