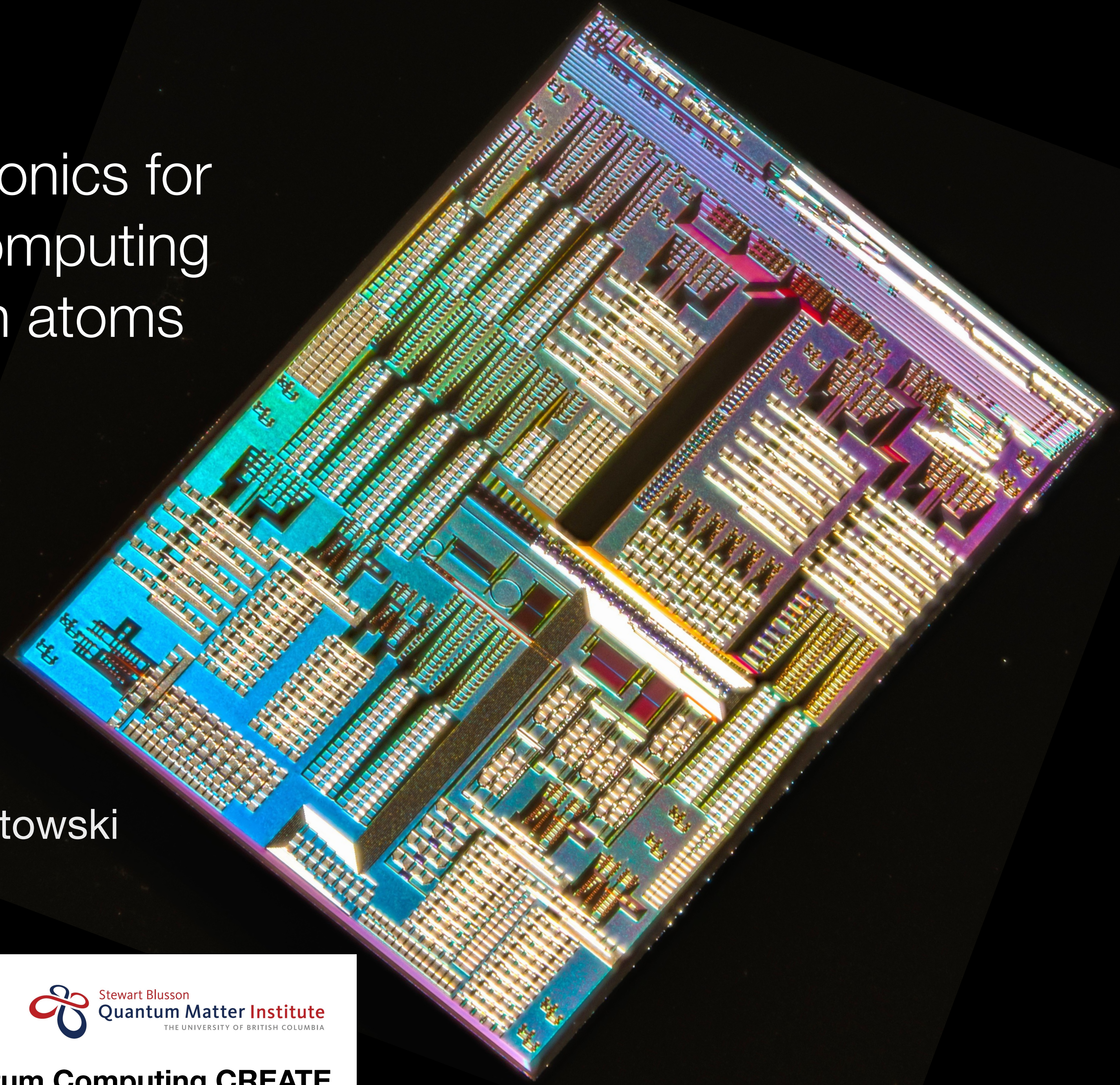
Silicon photonics for quantum computing with spins in atoms

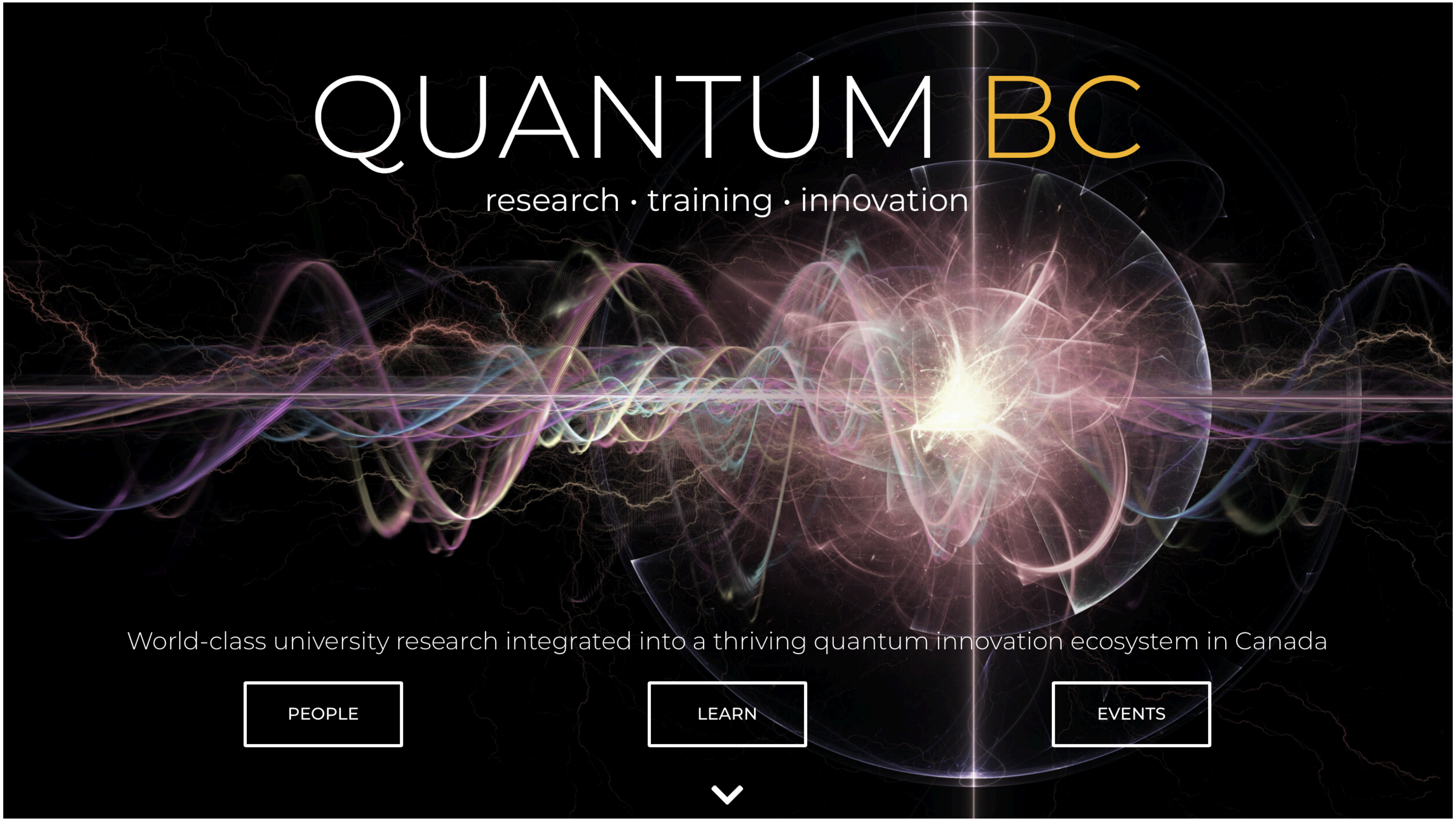


Dr. Lukas Chrostowski
July 2020

UBC
NSERC CRSNG
Stewart Blusson Quantum Matter Institute
THE UNIVERSITY OF BRITISH COLUMBIA
SiEPIC and Quantum Computing CREATE

Integrated software and hardware training program

www.quantum-bc.ca



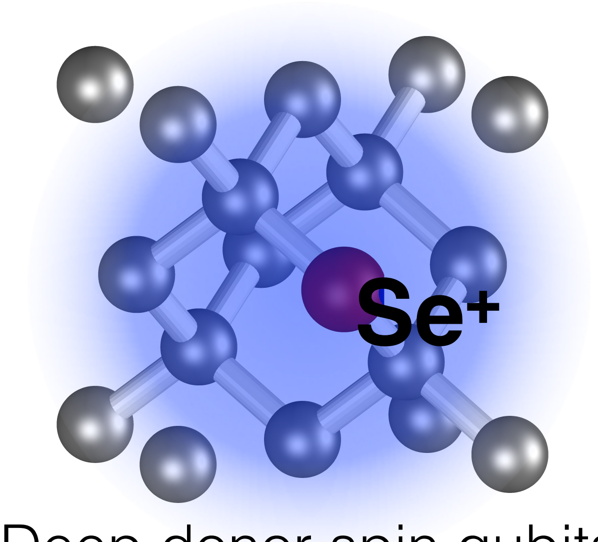
QUANTUM BC

research · training · innovation

World-class university research integrated into a thriving quantum innovation ecosystem in Canada

Faculty: Jeff Young, Robert Raussendorf, Lukas Chrostowski
Students, Postdocs, Researchers: Kashif Awan, Jingda Wu, Xiruo Yan, Donald Witt, Becky Lin, Adam Darcie, Adan Azem, Abdelrahman Afifi, Sebastian Gitt, Matthew Mitchell, Andreas Pfenning, David Roberts
Collaboration with Stephanie Simmons' group at Simon Fraser University.

Silicon Quantum Leap – Deep Donor Spin Qubits, Silicon Photonics, Quantum Computing



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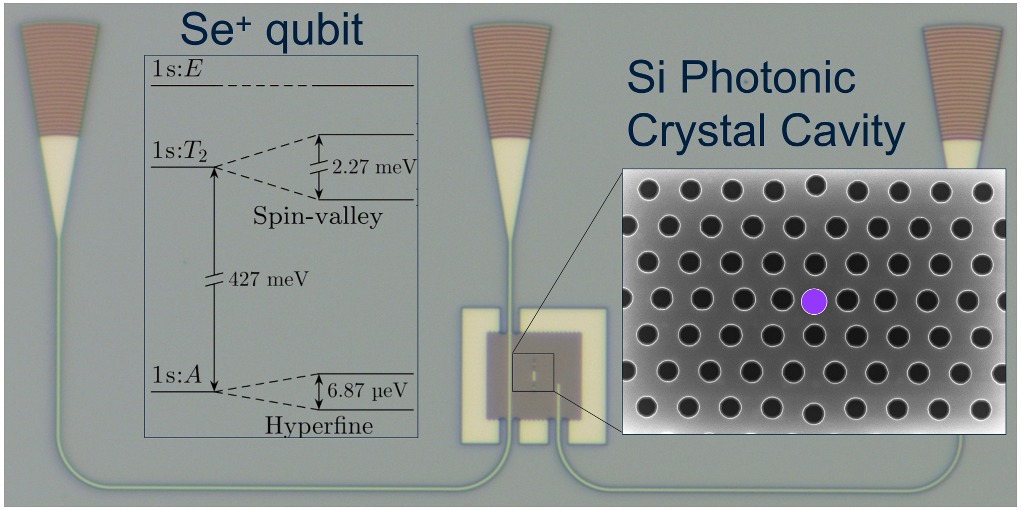


Deep donor spin qubits have amazing properties

Silicon photonic cavity QED for measurement & coupling

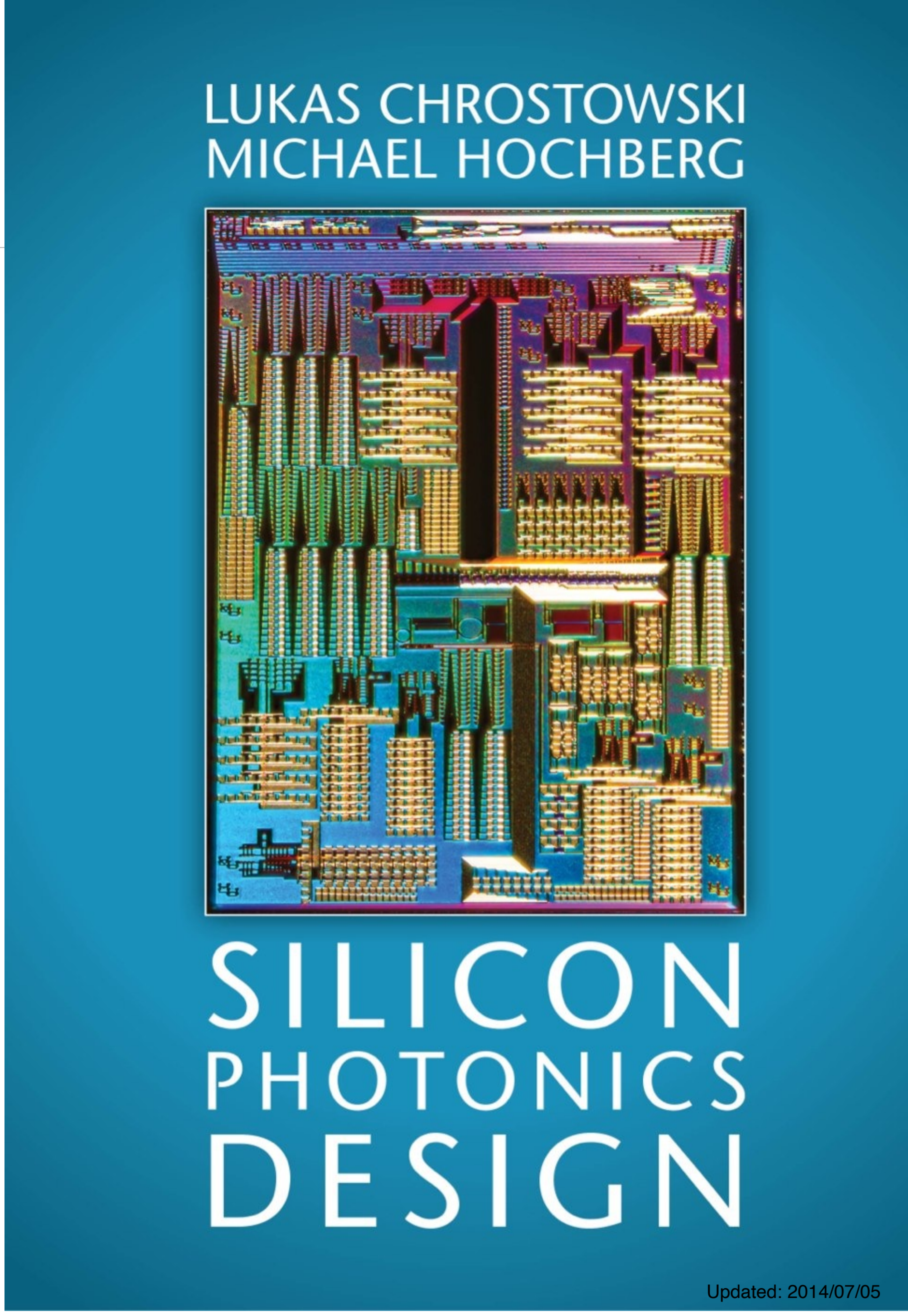
- SFU-UBC Silicon Quantum Leap project, following the proposal published:
  - Kevin J. Morse, et al. (group of Stephanie Simmons) “A photonic platform for donor spin qubits in silicon”, Science Advances, Jul 2017

Outline

- Silicon photonics introduction
- SiEPICfab: Canada’s silicon photonics rapid prototyping consortium
  - electron beam lithography (EBL) for fabrication
  - chips, wafers, devices, circuits, novel devices
- Quantum computing - Photonic coupling to spins of atoms in silicon
  - Qubits based on Se+
  - Tuneable Lasers
  - Tuneable Photonic crystals
  - Single Photon Detectors
  - Single Photon Sources

Silicon Photonics – Motivation

- Silicon electronics industry
  - $40+ Billion annual R&D investment*
  - Mature materials, **processing**, **design technologies**
  - Possibility of leveraging this technology for optics/photonics
- Silicon photonics
  - “integrated optics” and “photonic integrated circuits (PICs)” on silicon
  - use silicon for optical waveguides and for optical processing/switching
  - Small size, CMOS compatible
- Both electronics & photonics:
  - electronic and photonic integrated circuits (EPIC) in silicon
- Also need rapid prototyping



Updated: 2014/07/05

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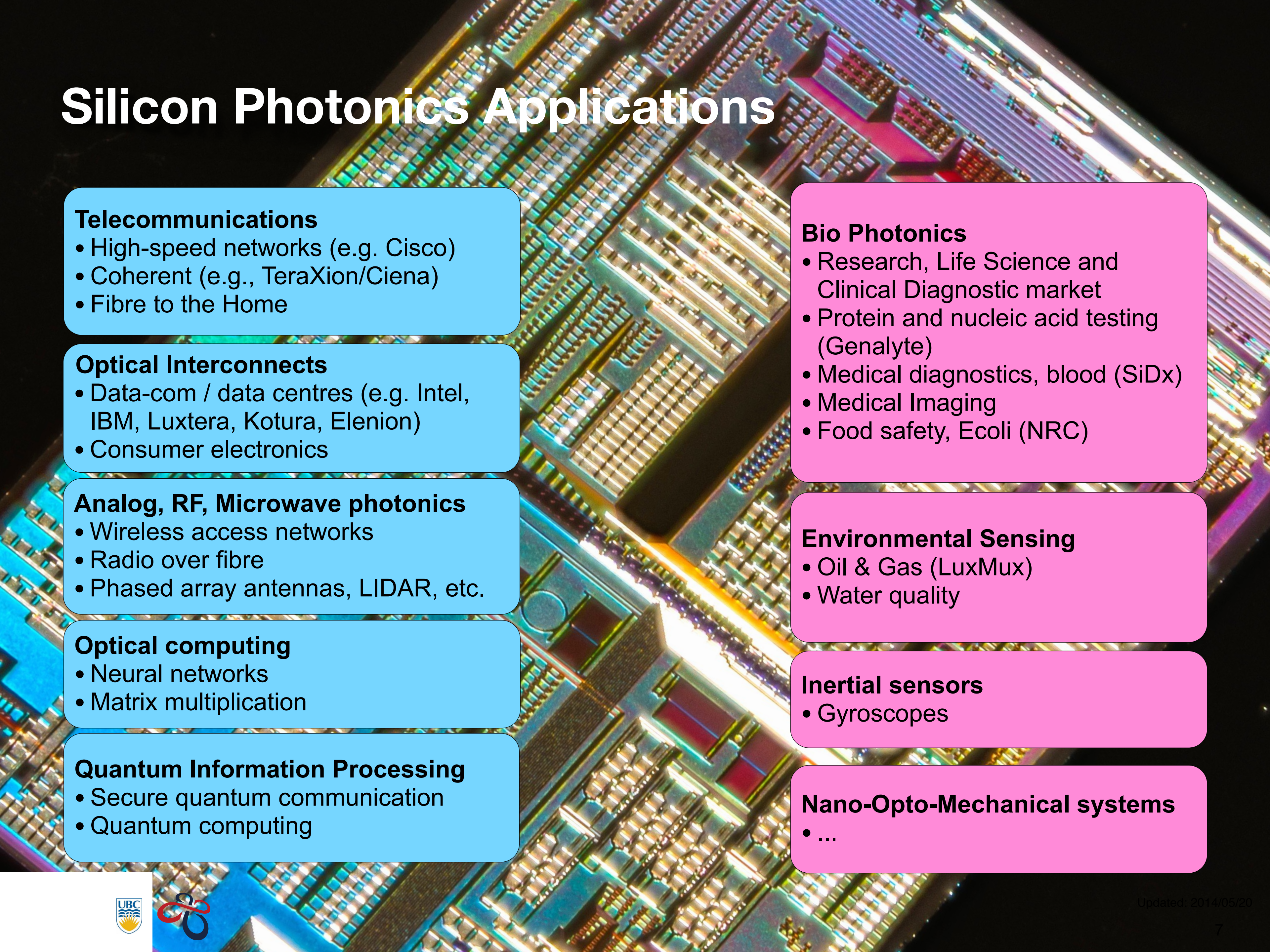
* $53B in 2012. Source: IC Insight, and http://www.electroiq.com/articles/sst/203/02/semiconductor-rand-spending-rises-7percent-despite-weak-market.html

Silicon Photonics Applications



Telecommunications
- High-speed networks (e.g. Cisco)
- Coherent (e.g., TeraXion/Ciena)
- Fibre to the Home

Optical Interconnects
- Data-com / data centres (e.g. Intel, IBM, Luxtera, Kotura, Elenion)
- Consumer electronics

Analog, RF, Microwave photonics
- Wireless access networks
- Radio over fibre
- Phased array antennas, LIDAR, etc.

Optical computing
- Neural networks
- Matrix multiplication

Quantum Information Processing
- Secure quantum communication
- Quantum computing

Bio Photonics
- Research, Life Science and Clinical Diagnostic market
- Protein and nucleic acid testing (Genalyte)
- Medical diagnostics, blood (SiDx)
- Medical Imaging
- Food safety, Ecoli (NRC)

Environmental Sensing
- Oil & Gas (LuxMux)
- Water quality

Inertial sensors
- Gyroscopes

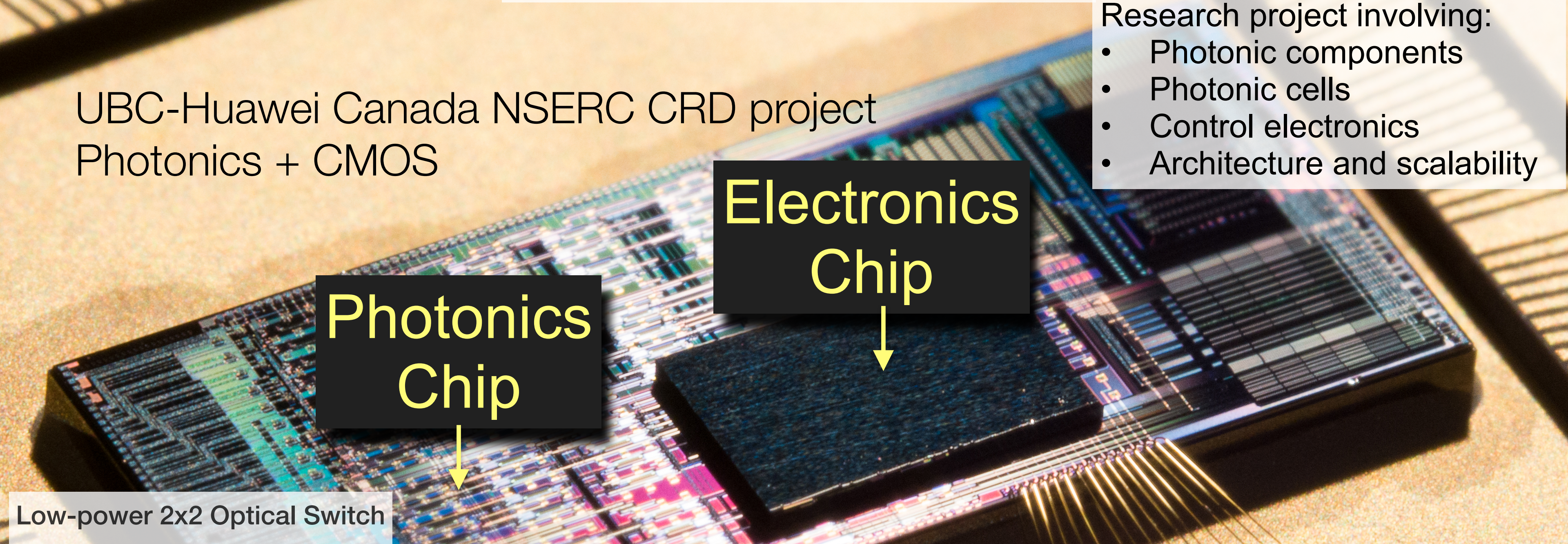
Nano-Opto-Mechanical systems
- ...

Updated: 2014/05/20

Silicon photonics + electronics systems

Professors Chrostowski, Shekhar, Mirabbasi

UBC-Huawei Canada NSERC CRD project
Photonics + CMOS



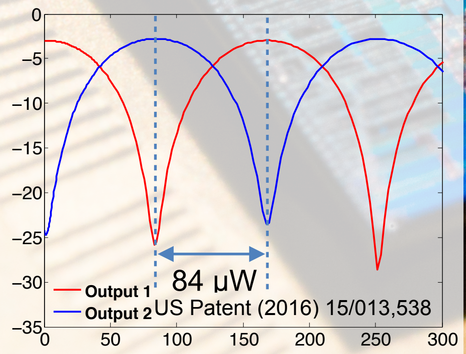
Electronics Chip

Photonics Chip

Optical Switch (2015-2016)
Research project involving:

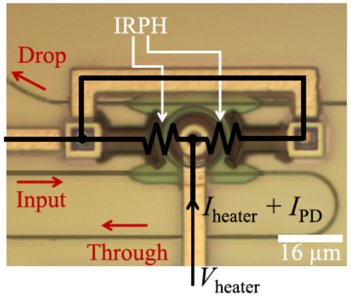
- Photonic components
- Photonic cells
- Control electronics
- Architecture and scalability

Low-power 2x2 Optical Switch

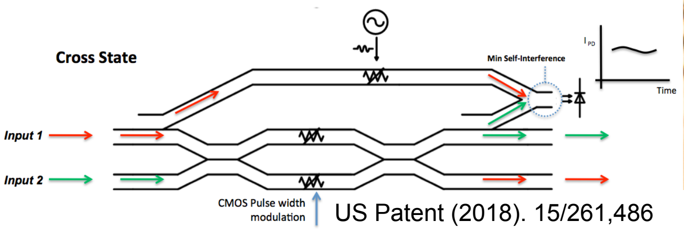


US Patent (2016) 15/013,538

One electrical contact for *both* control and sense



Each switch needs measurements and



US Patent (2018). 15/261,486

Silicon Photonic Foundries (partial list)

- Research foundries, low volume:

CompoundTek

Sandia
National
Laboratories

imec

leti
ceatech

A*STAR
Institute of
Microelectronics

amf
ADVANCED
MICRO
FOUNDRY

VTT

ihp

AIM
photonics
AMERICAN INSTITUTE for MANUFACTURING INTEGRATED PHOTONICS

(300 mm wafers)

- Multi-Project Wafer services:
- High-volume fabs:

ePIXfab

CMC
MICROSYSTEMS

MOSIS

cmp

TOWERJAZZ
The Global Specialty Foundry Leader

GLOBALFOUNDRIES

GF 9WG 90 nm silicon photonics process
(includes CMOS, 300 mm wafers)

ST

- Rapid prototyping using Electron Beam Lithography:

W UNIVERSITY of WASHINGTON

Washington Nanofabrication Facility

ANT APPLIED NANOTOOLS INC.

CORNERSTONE

NSERC
CRSNG

SiEPICfab

UBC

SiEPICfab Consortium

SiEPICfab

- Funding:

NSERC CRSNG

prompt

- Universities:

Lukas Chrostowski

UBC

Stewart Blusson Quantum Matter Institute
THE UNIVERSITY OF BRITISH COLUMBIA

Wei Shi

UNIVERSITÉ LAVAL

Odile Liboiron-Ladouceur

McGill

Andrew Knights

McMaster University

- Foundry & MPW partners:

ANT APPLIED NANOTOOLS INC.

CMC MICROSYSTEMS

- Design tools:

lumerical

GenISys
Advancing the Standard

LUCEDA PHOTONICS

- Applications:

AEPONYX

KEYSIGHT TECHNOLOGIES

HUAWEI

EHVA
Light-Matter Automation

photonic

LUXMUX

ciena
Experience. Outcomes.

SiEPIC Kits

SiEPICfab – The Canadian Silicon Photonics Foundry Roadmap

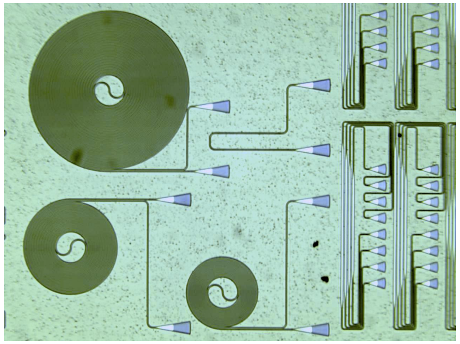
- Fabrication process development (2019-2020):
  - Passives at 1310/1550 nm and mid-IR (2900 nm)
  - Optical IO: grating couplers, edge couplers
  - Heaters
  - Silicon Nitride
  - Bi-Monthly fabrication runs
- Publicly available via Applied Nanotools
- Internal MPW runs:
  - Silicon-based defect-mediated detectors

- On the roadmap:
  - Detectors:
    - 1) superconducting nanowire single photon detectors,
    - 2) Ge,
    - 3) 2D materials integrated with silicon
  - Modulators:
    - 1) pn junction, 2) polymer
  - Photonic wirebond integration
    - Optical fibres
    - III-V InP gain chips and lasers
  - CMOS integration:
    - via wirebond, flip-chip bonding, and fan-out wafer level packaging (FOWLP)
  - Single photon sources and detectors for quantum information processing
  - Complete ecosystem for design, simulation, automated test and packaging

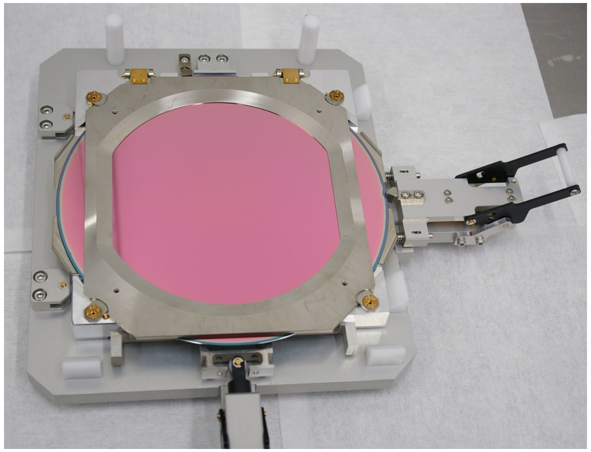
Outline – electron beam lithography (EBL)

- SiEPICfab: electron beam lithography (EBL) for fabrication
  - **chips, wafers**, devices, circuits, novel devices

1 cm^2 chip



200 mm wafer
and holder



EBL tool:
Jeol 8100FS – 200 mm
(only 3 in N. America)

Jewel of the UBC Nanofab: Jeol 8100FS EBL system

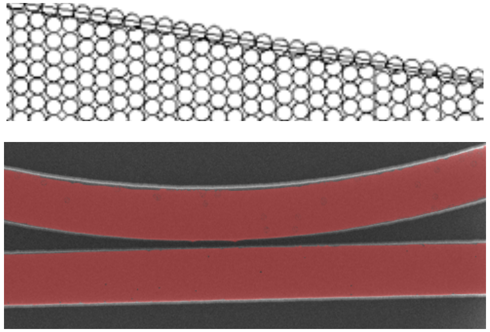
- Acceleration voltage: 100 kV
- stage has a laser positioning resolution of 0.6 nm
- Smallest beam diameter of 2 nm
- maximum scanning speed of 125 MHz
- high-resolution and high-speed modes
- Write-field up to 1 mm x 1 mm
- WF alignment and overlay misalignment +/- 20 nm, at worst case (< 10 nm typ.)
- small pieces to full **wafers up to 200 mm** in diameter

Ref: L. Chrostowski, et al., JSTQE, 2019

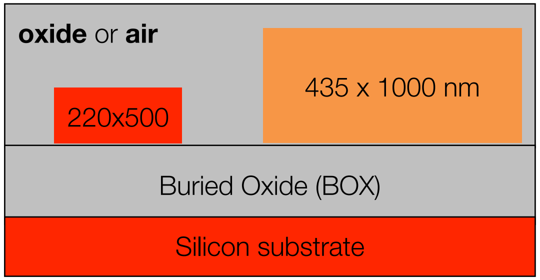
Outline – electron beam lithography (EBL)

- SiEPICfab: electron beam lithography (EBL) for fabrication
  - chips, wafers, **devices**, circuits, novel devices

Waveguides

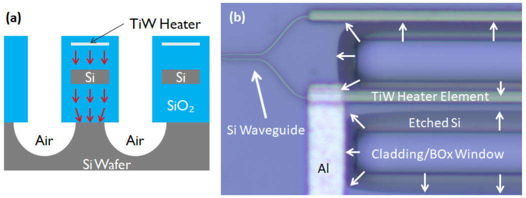


Silicon Silicon Nitride

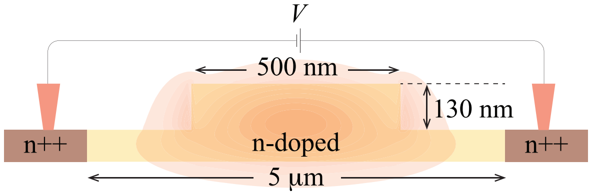


Modulators, Detectors

Thermo-Optic Phase Shifter

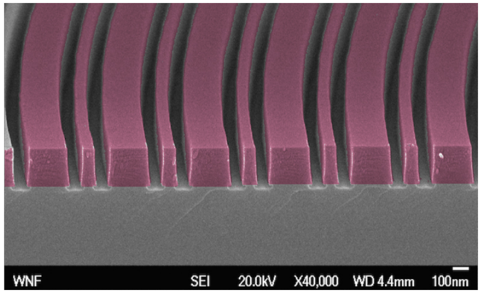


Defect-mediated detectors

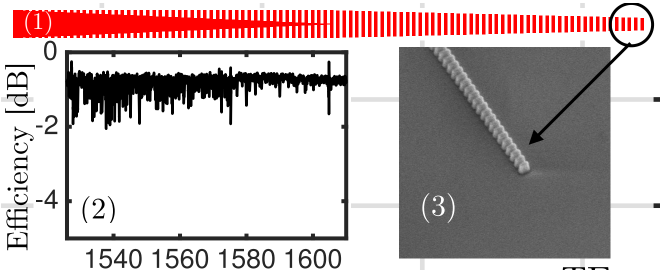


Optical coupling

Grating Coupler



Edge Coupler

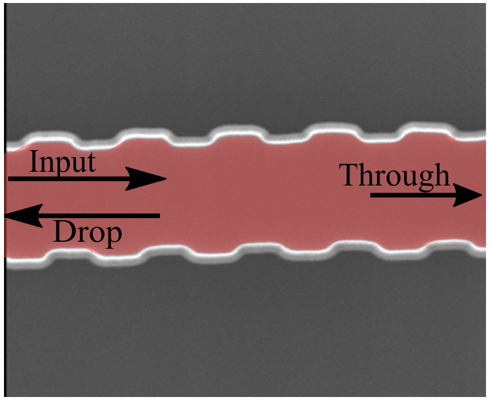


Ref: L. Chrostowski, et al., JSTQE, 2019

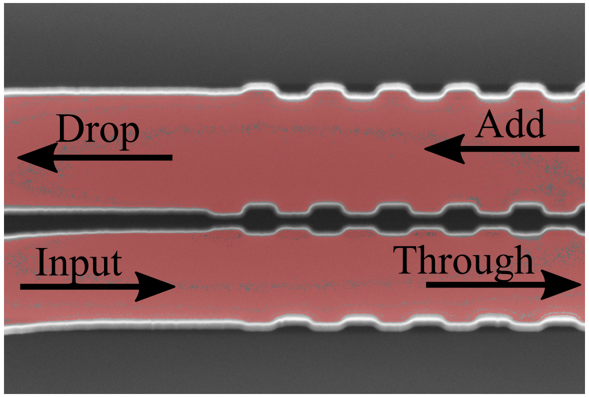
Outline – electron beam lithography (EBL)

- SiEPICfab: electron beam lithography (EBL) for fabrication
  - chips, wafers, **devices, circuits**, novel devices

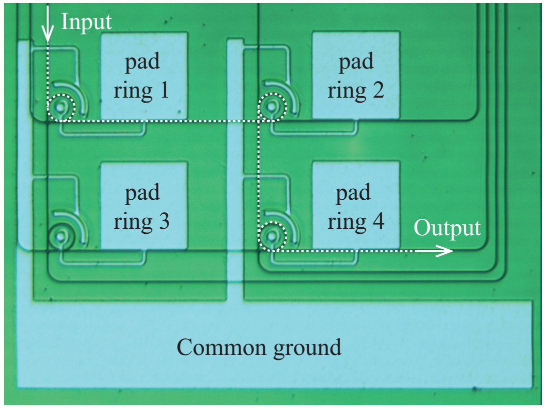
Bragg filter



(Bragg Grating-assisted) Contra-directional coupler filter



NxN ring switches (with feedback loops for control)

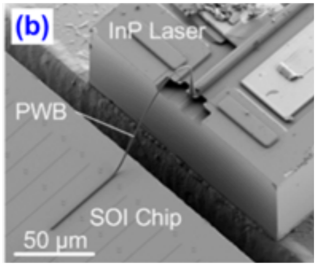


Outline – electron beam lithography (EBL)

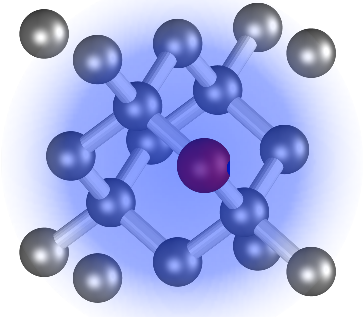
- electron beam lithography (EBL) for fabrication
    - chips, wafers, devices, circuits, **novel materials and devices (R&D)**

Silicon,
Light sources

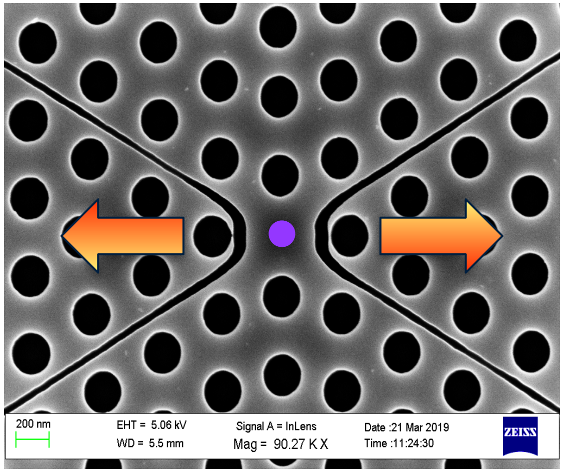
III-V integration
(Photonic Wirebond)



Emission in Silicon

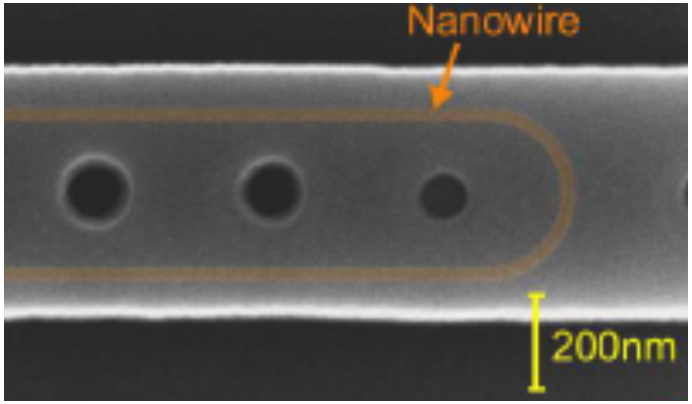


NEMS tunable
Photonic Crystals



Coupling to qubits

Single photon
detectors



Photonics for Quantum Computing

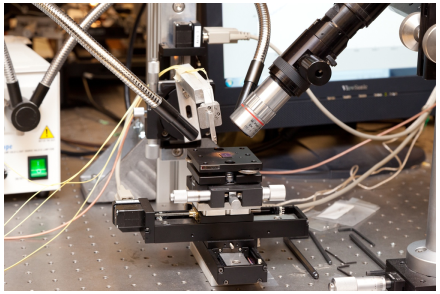
Ref: L. Chrostowski, et al., JSTQE, 2019

Outline – Test, Packaging – Electrical, Optical

- Test, Packaging – Electrical, Optical

Automated Test

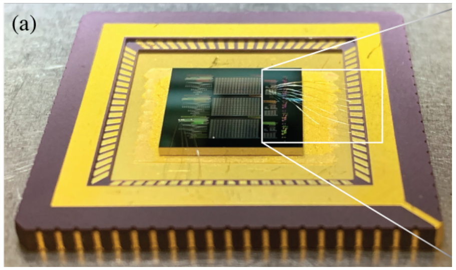
Chips
(Maple Leaf Photonics LLC)



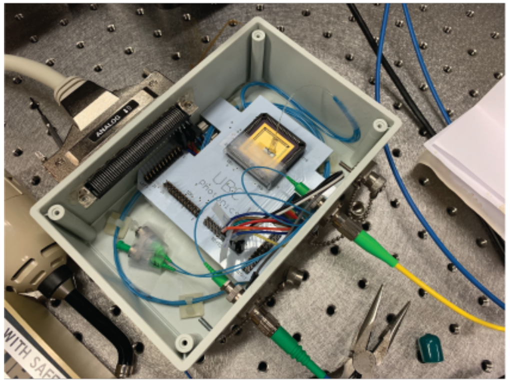
Wafers
(EHVA; Wei Shi, Laval)

Electrical Packaging

Carrier,
Wire-bonding

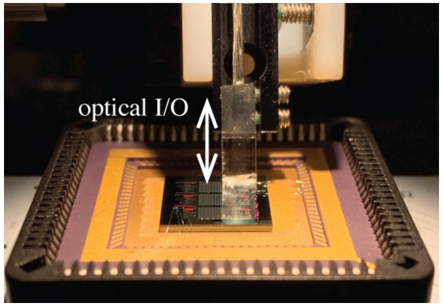


12 to 88 channel electrical stimulus

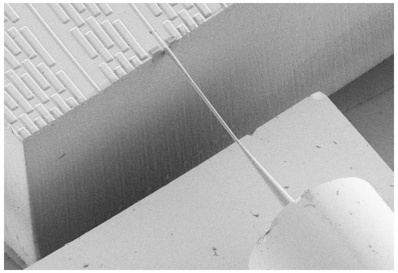


Optical Packaging

Glued fibre arrays

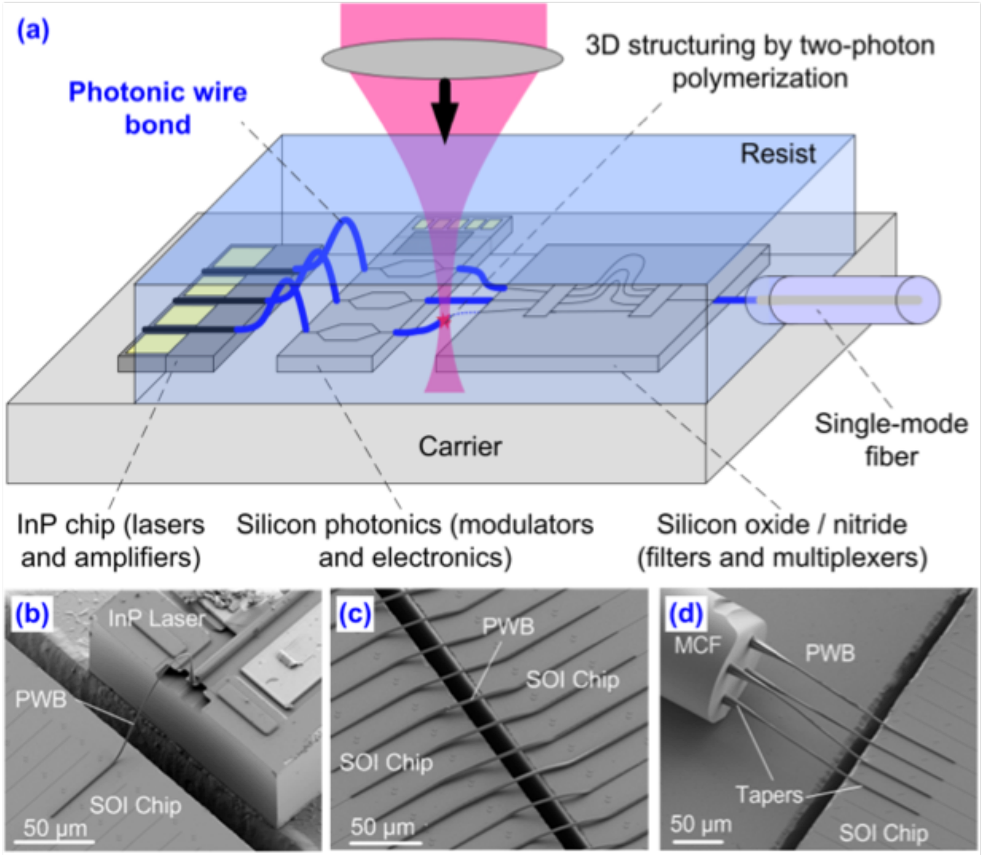


Photonic Wirebonds
Optical Fibre



Technology Status – Photonic Wirebonds

- Lab Demonstration:
  - Photonic wirebonds (PWB) using 3D printer (Nanoscribe):
    - fibre-SiP, laser-SiP, SiP-SiP
    - Loss loss, < 1 dB
    - High power handling
  - Research activity since 2012 by C. Koos at KIT
- Purchased by UBC in 2019
  - Delivery: July 20, 2020



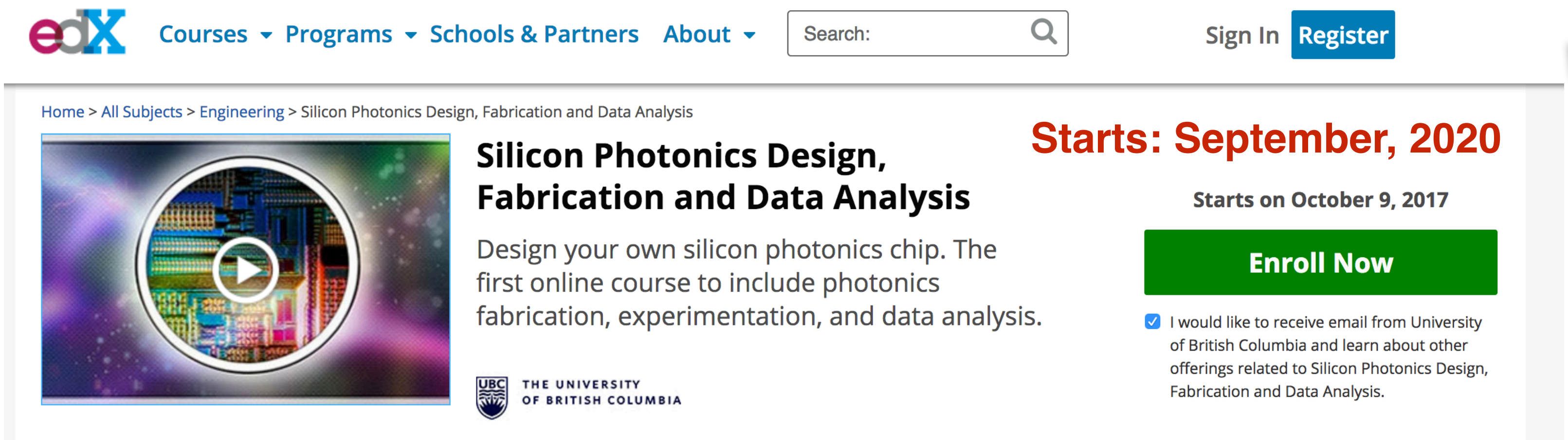
- http://www.vanguard-photonics.com

•[1] Lindenmann, N.; Balthasar, G.; Hillerkuss, D.; Schmogrow, R.; Jordan, M.; Leuthold, J.; Freude, W.; Koos, C.: 'Photonic wire bonding: a novel concept for chip-scale interconnects'; *Opt. Express 20, 17667-17677, (2012)*
•[2] Lindenmann, N.; Dottermusch, S.; Goedecke, M.-L.; Hoose, T.; Billah, M.-R.; Onanuga, T.-P; Hofmann, A.; Freude, W.; Koos, C.: 'Connecting silicon photonic circuits to multicore fibers by photonic wire bonding'; *Journal of Lightwave Technology 33, 755 – 760 (2015)*
•[3] Billah, M. R.; Hoose, T.; Onanuga, T.; Lindenmann, N.; Dietrich, P.; Wingert, T.; Goedecke, M. L.; Hoffmann, A.; Troppenz, U.; Sigmund, A.; Möhrle, M.; Freude, W.; Koos, C.: 'Multi-chip integration of lasers and silicon photonics by photonic wire bonding', *Conf. on Lasers and Electro-Optics (CLEO'15), San Jose (CA), USA, May 10–15, 2015. Paper STu2F.*

SiEPIC Successes – Research Training

Includes fabrication provided by SiEPICfab, Applied Nanotools and University of Washington

- offers annual workshops & courses:
  - SiEPIC-Passives (since 2008), SiEPIC-Actives (since 2012), CMOS, Systems…
  - total 20 SiEPIC workshops so far.
- has trained:
  - over 318 students; from 34 universities (total of 67 groups); from 21 companies or gov't labs
- led to new industrial products (Ciena/Teraxion coherent transceiver), and inspired new start-ups.
- led to many publications
- offers the first online course (Phot1x Silicon Photonics Design, Fabrication and Data Analysis) that includes **fabrication of student designs**; it is offered on the edX platform
  - has been taken by > 1000 students to date (2015-2019)



Home > All Subjects > Engineering > Silicon Photonics Design, Fabrication and Data Analysis

Silicon Photonics Design, Fabrication and Data Analysis

Design your own silicon photonics chip. The first online course to include photonics fabrication, experimentation, and data analysis.

THE UNIVERSITY OF BRITISH COLUMBIA

Starts: September, 2020

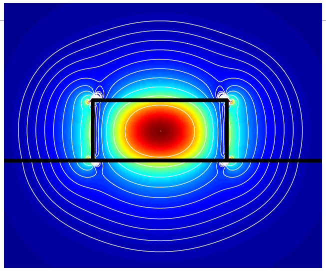
Starts on October 9, 2017

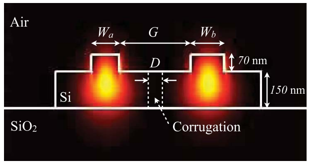
☑ I would like to receive email from University of British Columbia and learn about other offerings related to Silicon Photonics Design, Fabrication and Data Analysis.

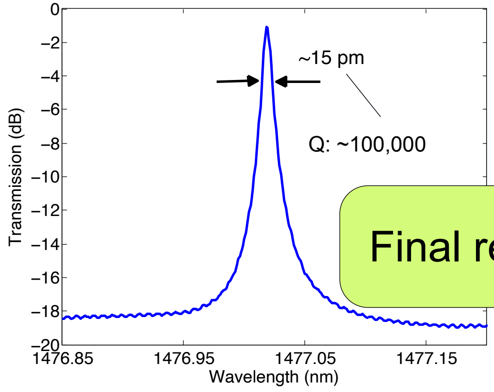
edX Silicon Photonics Phot1x

7 week online course

2 weeks optical modelling: devices, circuits







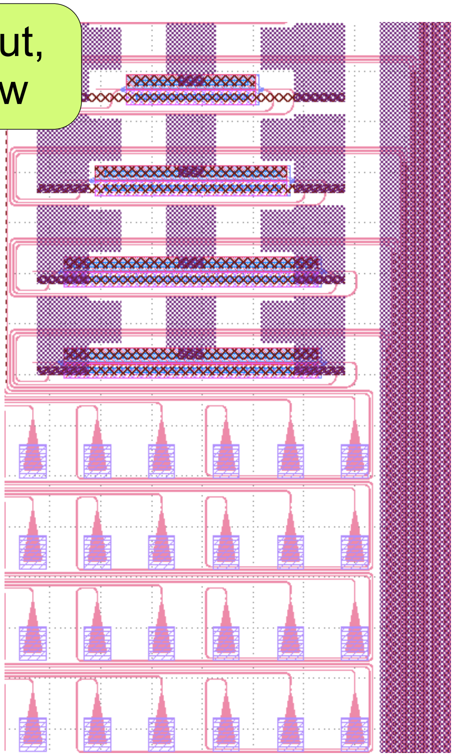
Final report

Design & Modelling

Prepare:

- Proposal
- Design doc

2 weeks layout, design review



Mask Layout

Submit:

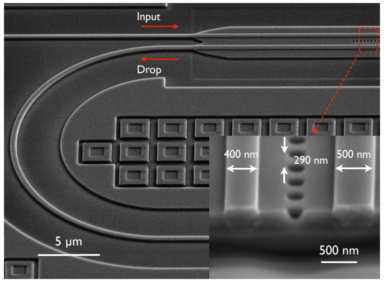
- Draft GDS
- Final GDS

Fabrication (ANT, UW)

~2 weeks waiting for fab & test

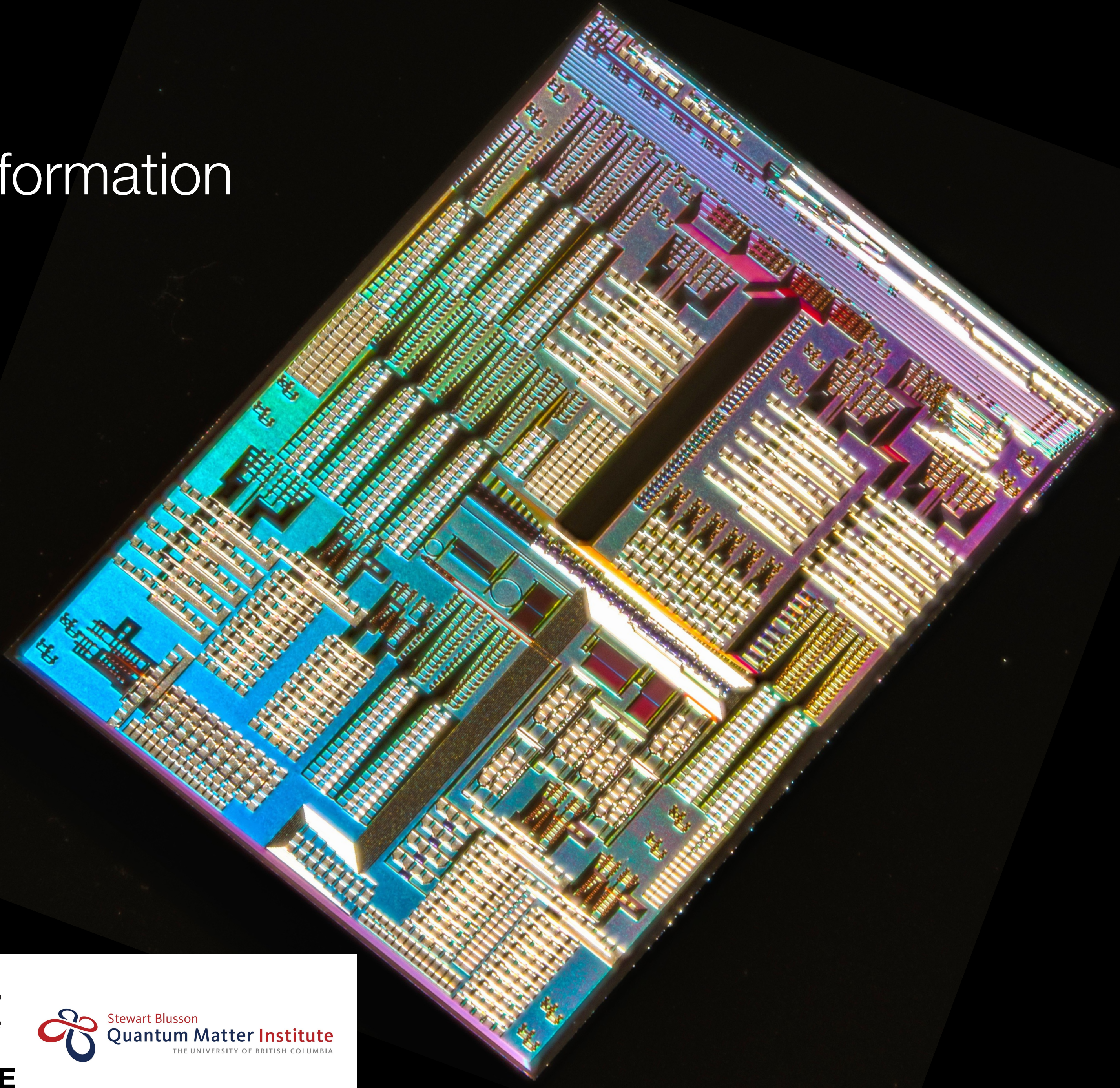
Test & Packaging

- Test report



Updated: 2014/05/20

Quantum Information Processing with Silicon Photonics



UBC

NSERC CRSNG

Si-EPIC CREATE

Stewart Blusson Quantum Matter Institute
THE UNIVERSITY OF BRITISH COLUMBIA

Joshua W. Silverstone, Damien Bonneau, Jeremy L. O’Brien, Mark G. Thompson, “Silicon Quantum Photonics,” IEEE JSTQE, 2016

Linear Optical Quantum Computing (LOQC) Approach

- Required:
  - single photon sources (heralded vs. on-demand), with pump removal filters
  - linear optical network (arbitrary N x N unitary matrix operation)
  - single photon detectors
  - electronics: control, stabilization

Startups: Xanadu, PsiQuantum

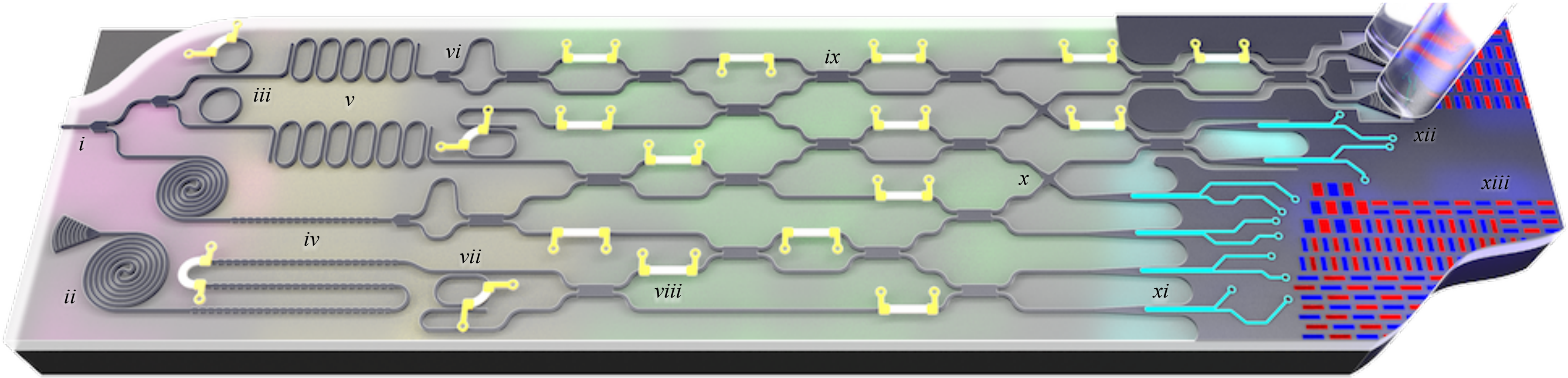


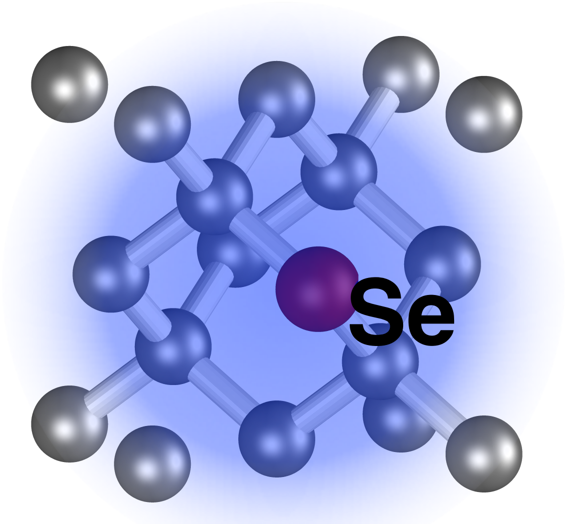
Fig. 1. Mock-up of a quantum photonic device, showing how various components might fit together, and what those components might look like. Regions of the chip are color coded (color online). From left to right: photon sources (magenta), pump-removal filters (yellow), passive and active optics (green), single-photon detectors (cyan), and control and feedback electronics (blue). Labels indicate: ***i.*** pump input and splitter, ***ii.*** spiralled waveguide photon-pair source, ***iii.*** ring resonator photon-pair source, ***iv.*** Bragg reflector pump removal filter, ***v.*** coupled-resonator optical waveguide (CROW) pump removal filter, ***vi.*** asymmetric Mach-Zehnder interferometer (MZI) wavelength-division multiplexer (WDM), ***vii.*** ring resonator WDM, ***viii.*** thermal phase tuner, ***ix.*** multi-mode interference waveguide coupler (MMI), ***x.*** waveguide crossing, ***xi.*** superconducting nanowire single-photon detector (SNSPD), ***xii.*** grating-based fibre-to-chip coupler, and ***xiii.*** control and logic electronics.

Qubits for quantum computing

Approach	*Lifetime (coherence, dephasing)*	*Scalability*
Superconducting	***Microseconds***	***53 Google*** ***2000 D-Wave***
Ion traps	***Minutes***	***Very limited*** ***14 Innsbruck***
Photonics (flying qubits)	***ps to ns***	***Silicon photonics – possibly millions***
cQED – NV diamond	***seconds (spin)***	***Challenging***
Se^+ spins in silicon	***seconds (spin)***	***Silicon photonics***

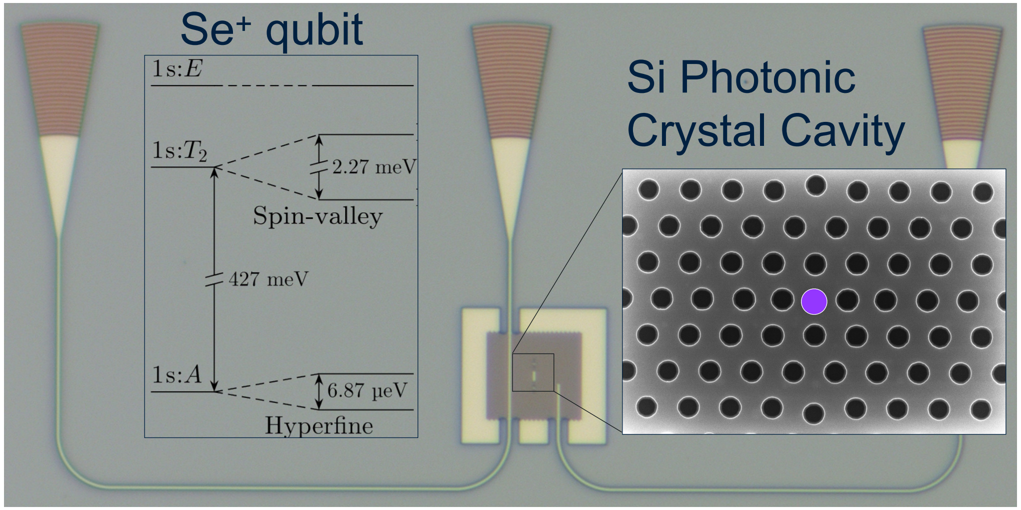
- Other important parameters: identical qubits, high fidelity operations, high temperature, and no interface issues.
- Appears that Se+ with silicon photonics meets all requirements simultaneously.

Silicon Quantum Leap – Deep Donor Spin Qubits, Silicon Photonics, Quantum Computing



Deep donor spin qubits have amazing properties

+

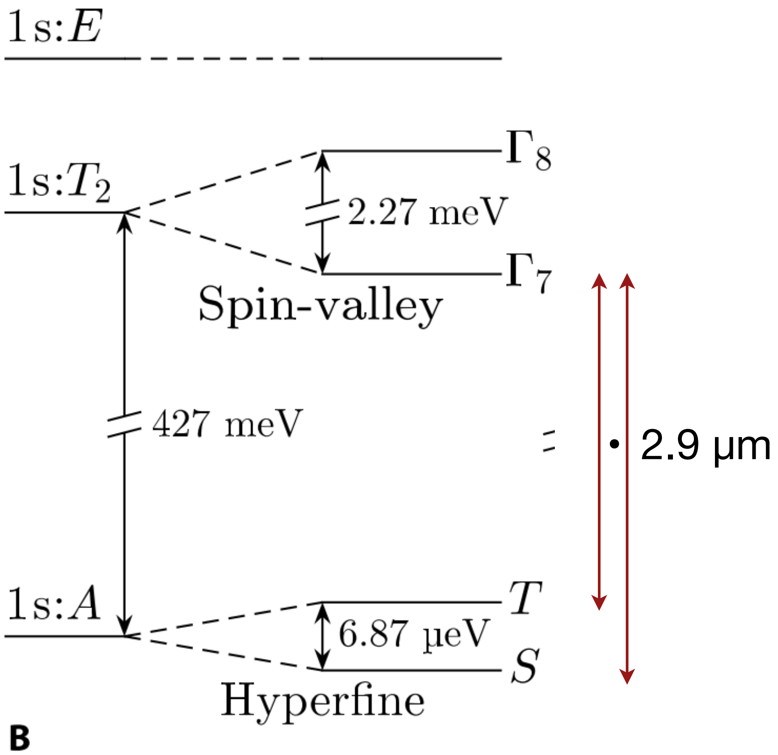


Silicon photonic cavity QED for measurement & coupling

- SFU-UBC Silicon Quantum Leap project, following the proposal published:
  - Kevin J. Morse, et al. (group of Stephanie Simmons) “A photonic platform for donor spin qubits in silicon”, Science Advances, Jul 2017; more since then.

Se+ deep donor spin qubits

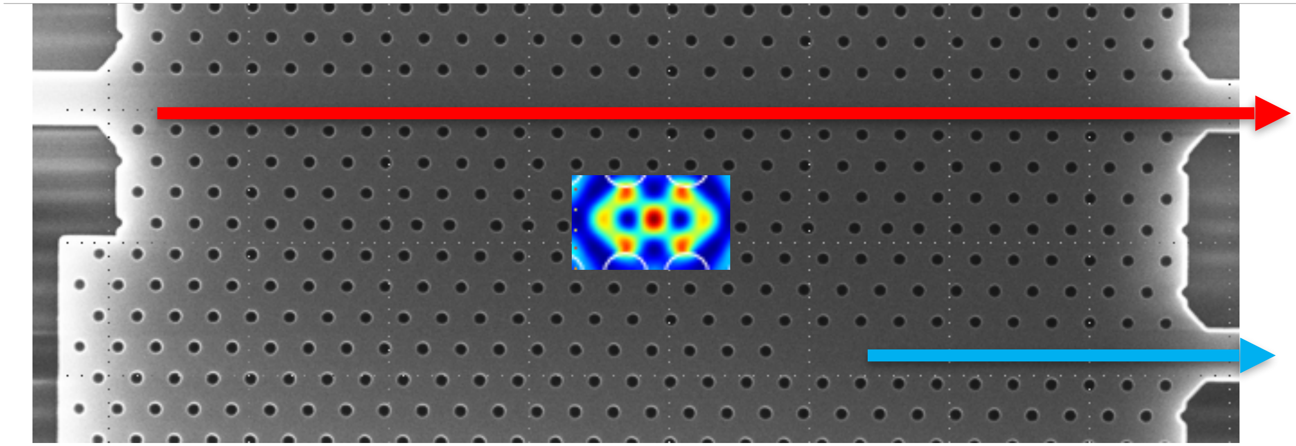
- Long lived S0⇔T0 qubit
  - T1>6 min (T=1.6K); 4 hours in 2019 [2]
  - T2 = 2.14 ± 0.04 s (T=1.5K) [1]
- Microwave pulses (GHz frequencies) to manipulate individual qubits, between the S, T levels, where:
  - S state is |0>
  - T state is |1>
- Large binding energy, enables electric dipole allowed optical transitions (2.9 µm)
  - for spin qubit read-out, ~ 2 D [2]
  - for qubit to qubit interactions



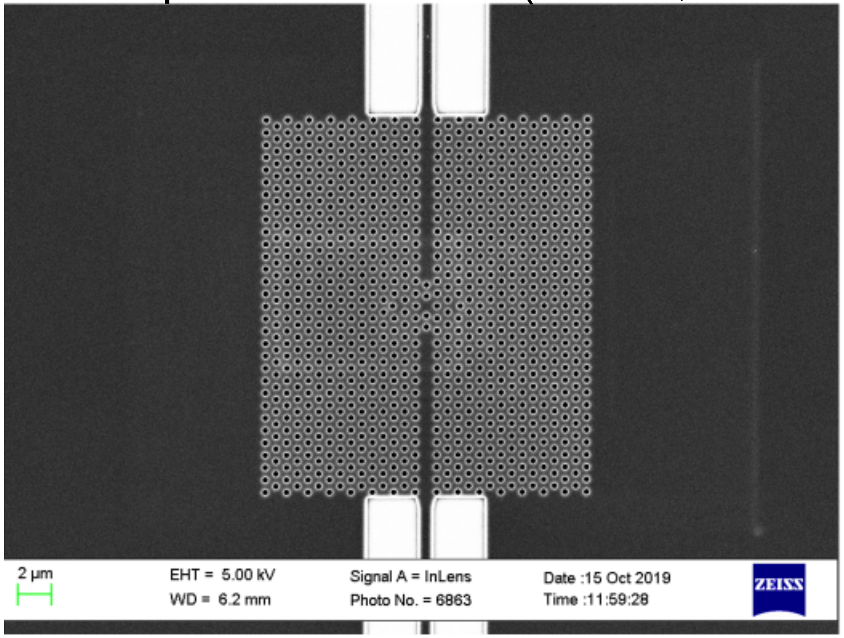
[1] K. Saeedi, et al., “Room-temperature quantum bit storage exceeding 39 minutes using ionized donors in silicon-28”, Science 342:6160, 2013
[2] A. Deabreu, Phys Rev Applied, 2019

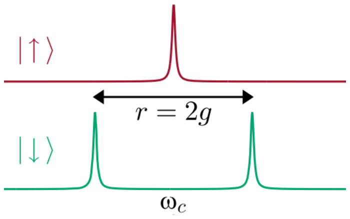
Planar Micro-Cavity circuits

GC-coupled PC cavities (NIR) 220 nm SOI



GC-coupled PC cavities (mid-IR, 2900 nm) on 500 nm SOI





Achievable:

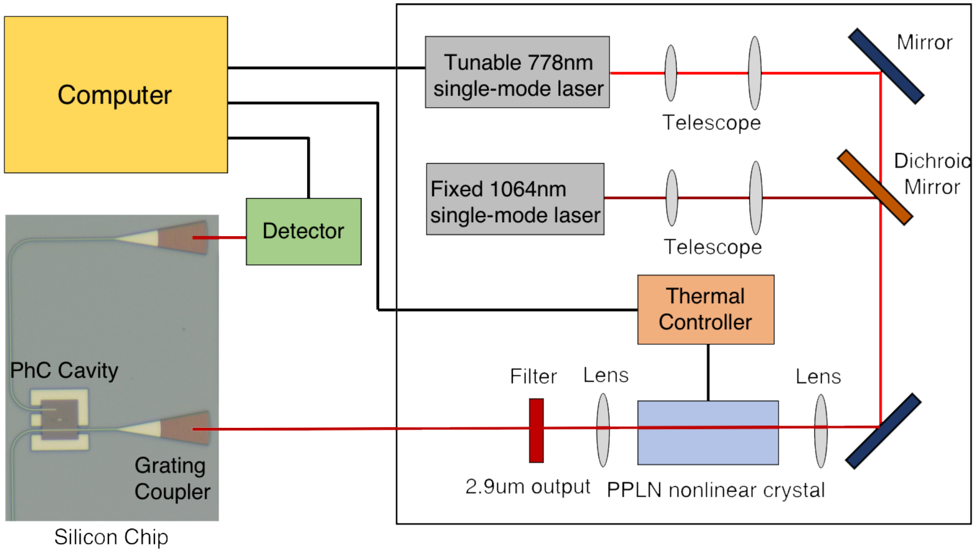
Q > 10^6
$V_{mode} < (\lambda/n)^3$

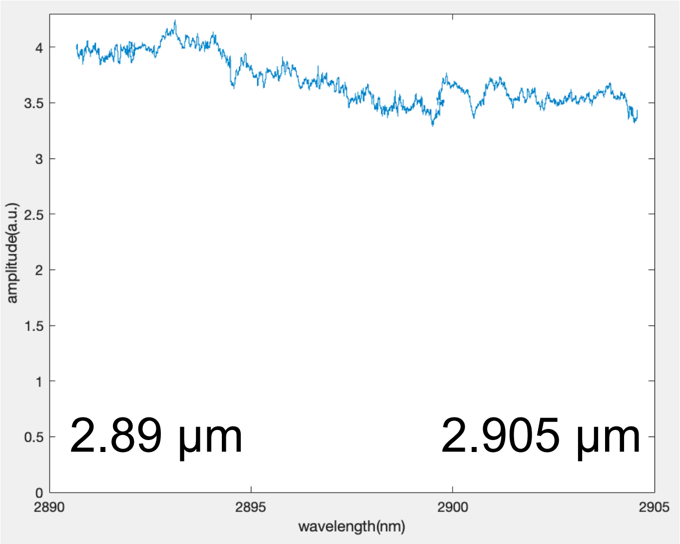
For strong coupling, need

- Q of 35,000 for
- ~ 3 GHz splitting with 1.96 Debye in Se+

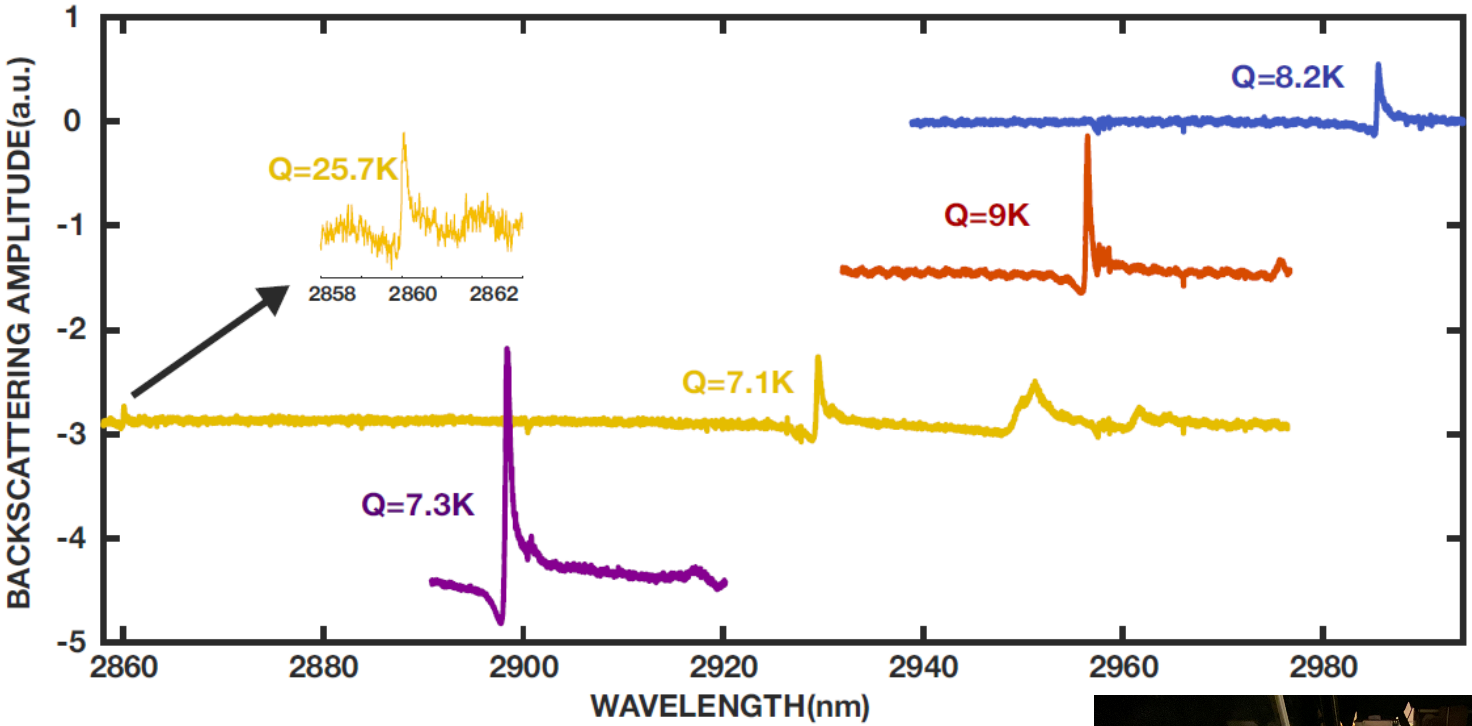
Tuneable Lasers at 2.9 µm

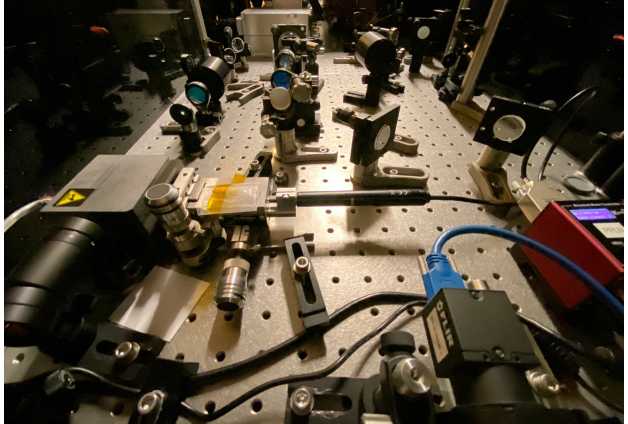
- >15 mW free-space output (with half of the max 1064 nm pump power)
- 3 min scan for 100 nm at 750 MHz resolution (allows for ~70k quality factor)
- 5 MHz resolution capable
- Fiber-coupled





Mid IR L3 cavities



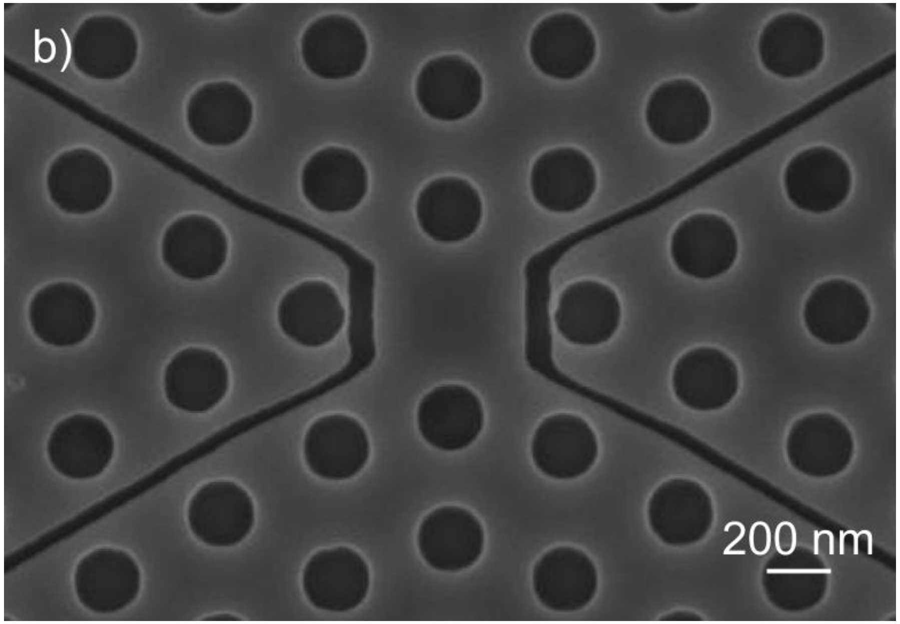


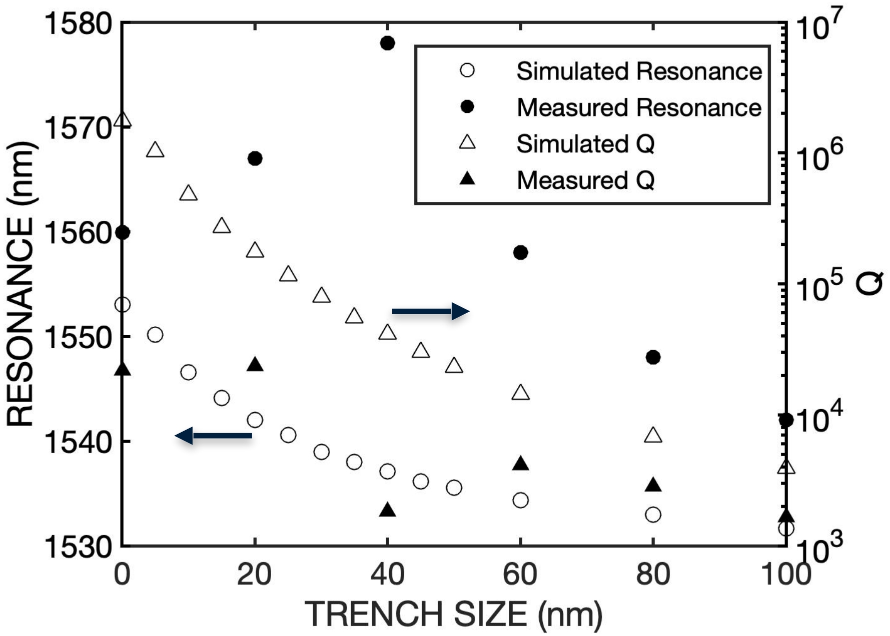
Photonic Crystals – resonance frequency matching

- Key challenge
    - Atomic transition has a ~100 MHz linewidth
    - Silicon photonic manufacturing variations (+/- few nm in height, width) of ~1 THz
- Problem: Need 10,000 better manufacturing!
    - Can imagine some post-processing trimming techniques. Scalable?
- More realistic, need tuning mechanisms
    - Objective: in order to match the sharp atomic transition for each donor in the cavity, it is crucial to develop resonance tuning methods for the PhC cavities to compensate for fabrication imperfections without sacrificing the Q
    - Possible Approaches:
        - Typical silicon photonics tuning & stabilization approaches:
            - thermo-optic (10 GHz/K) – won't work; Si bandgap doesn't change near 4 K
            - carrier injection / depletion (weak effect) – would introduce optical absorption
        - Nano-opto-mechanical systems (NEMS, MEMS)
            - Cavity opto-mechanics research around the world, e.g., Paul Barclay, Calgary.

Split cavity: static structures @ 1550 nm

- H0 Cavity. Engineered cuts to minimize Q reduction
- Fabricated test structures with different gaps to mimic tuning
  - Tuning: excellent
  - Quality factor: needs more fabrication process development





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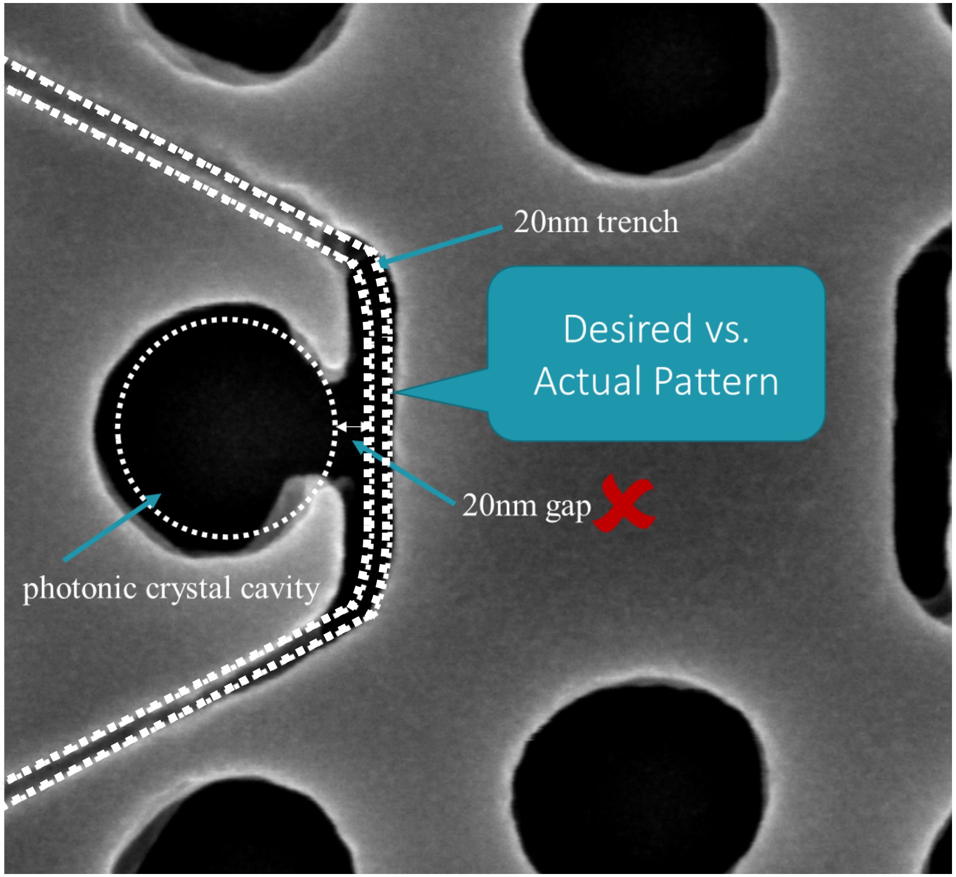
Fabrication challenges

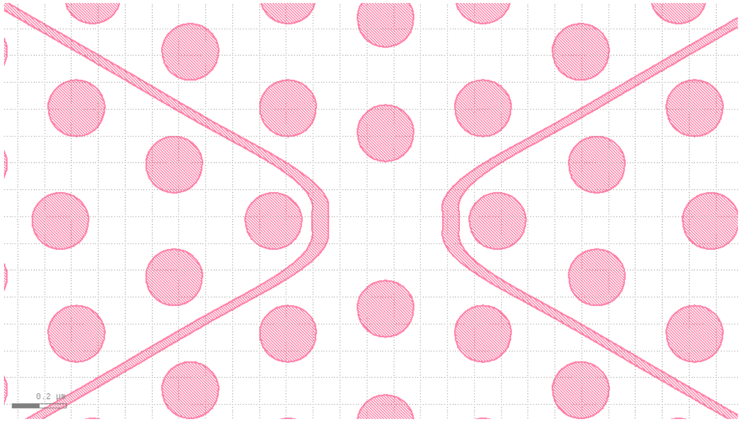
- JEOL 8100 + ZEP520A
  - Accelerating Voltage: 100 keV
  - Shot Pitch: 2 nm
  - Resist Thickness: 500 nm
- Challenges
  - Attempting to resolve a 20 nm gap between a photonic crystal cavity and trench (NEMS + Photonic circuit)
  - PEC initially did not yield any intuitive results.
- Limitations:
  - Cannot reduce resist thickness due to etch requirements
  - Anything near 20 nm does not resolve

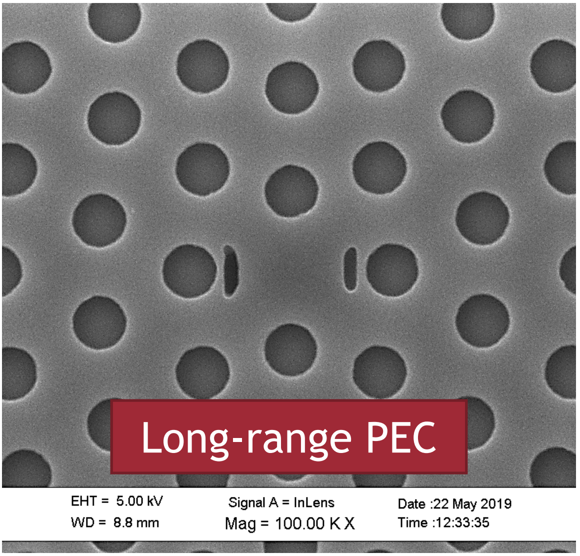


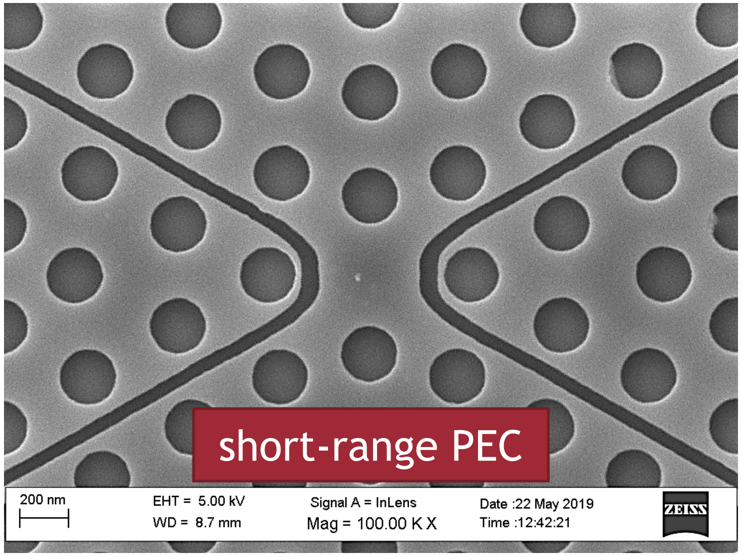
Device design carried out by Xiruo Yan and Jingda Wu

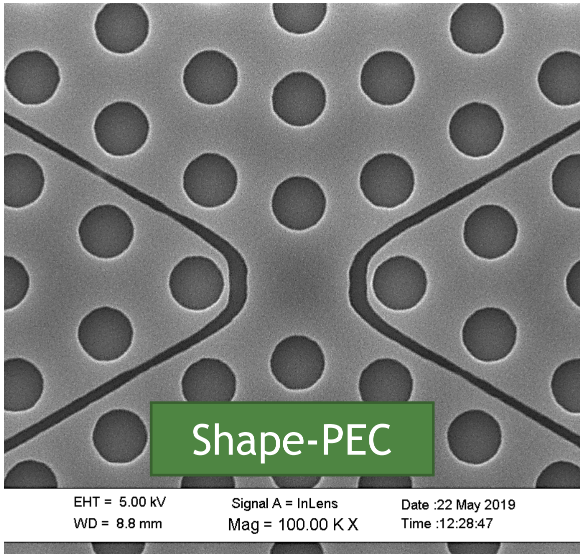
Fabrication improvement: Shape PEC

- Improving Process Window via Contrast Enhancement using Shape Proximity Error Correction (PEC)
- By Kashif Masud Awan, Gerald Lopez (University of Pennsylvania), GenISys

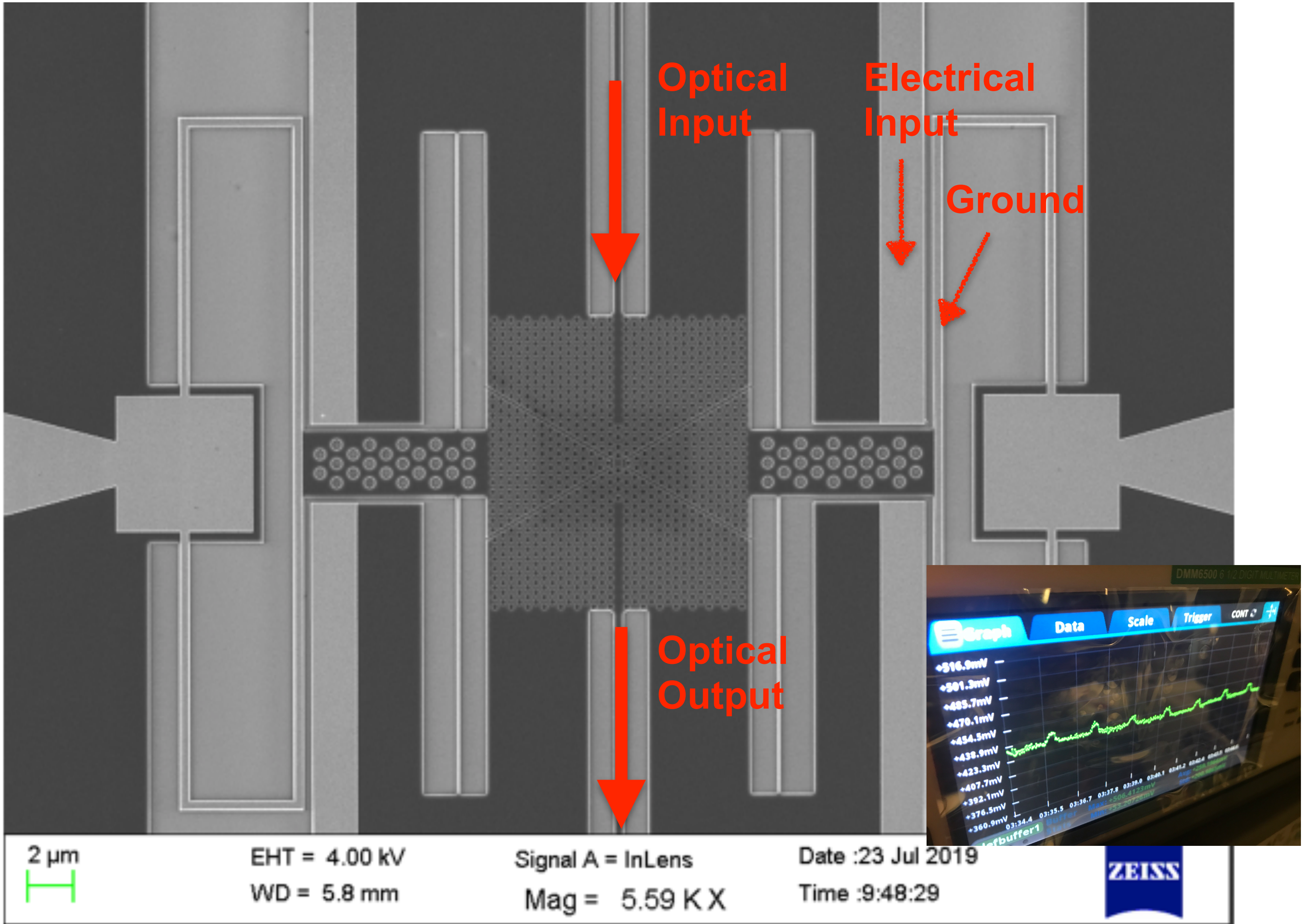






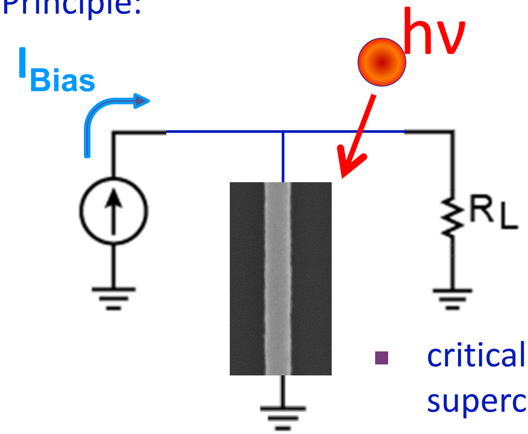


Fabricated MEMS device

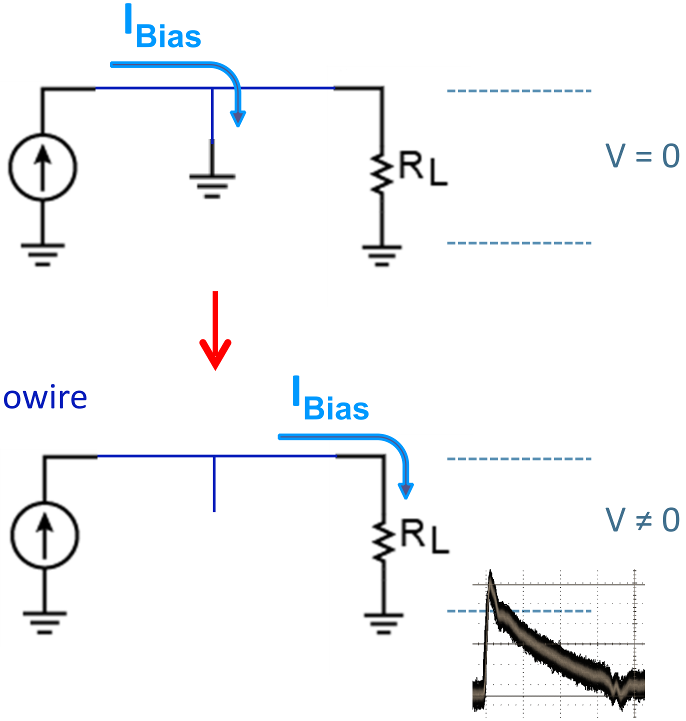


Superconducting Nanowire Single Photon Detectors

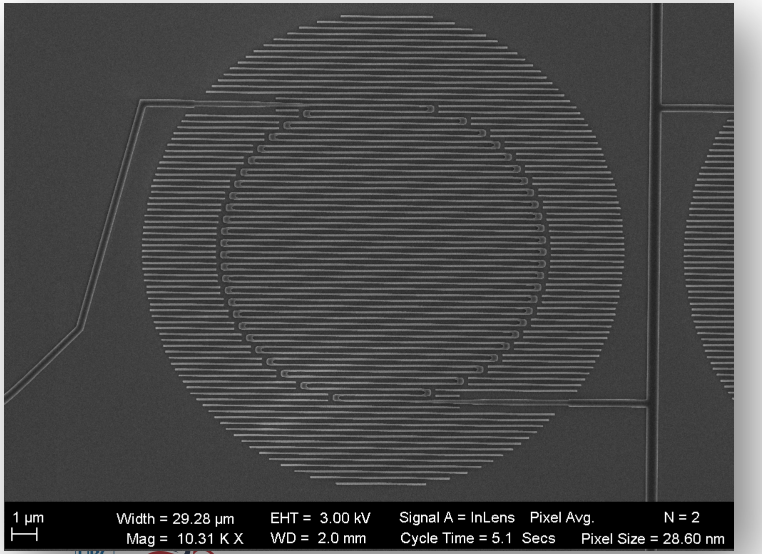
Working Principle:



- critically-biased superconducting nanowire



Typical Meandering Implementation:



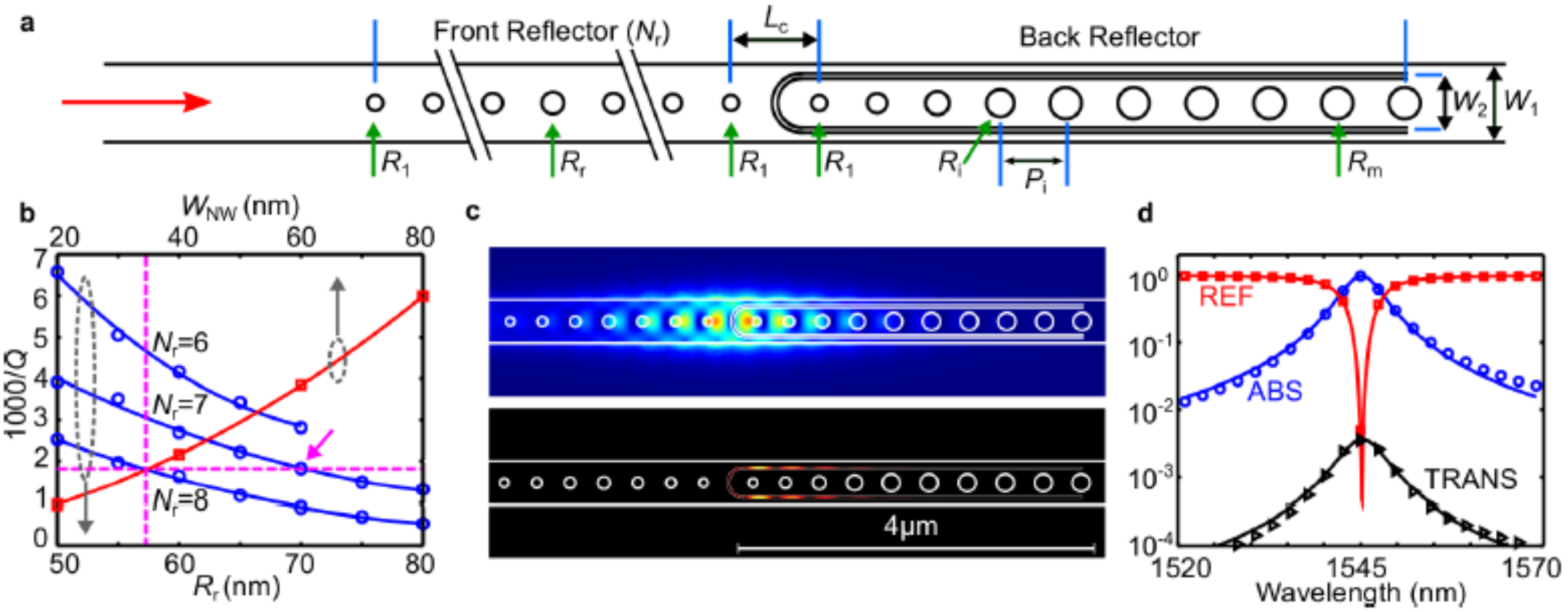
- NbN, NbTiN, Nb
- Few nm Thick
- About 100nm Wide

Courtesy: Jeff Young

Mohsen K. Akhlaghi Ellen Schelew and J.F. Young,
Nature Communications, 6:2041-1723 (2015)

Superconducting Nanowire Single Photon Detectors

- Design:
  - resonant detector leads to 100% absorption
  - minimized length of wire for high-speed, low jitter, low dark count



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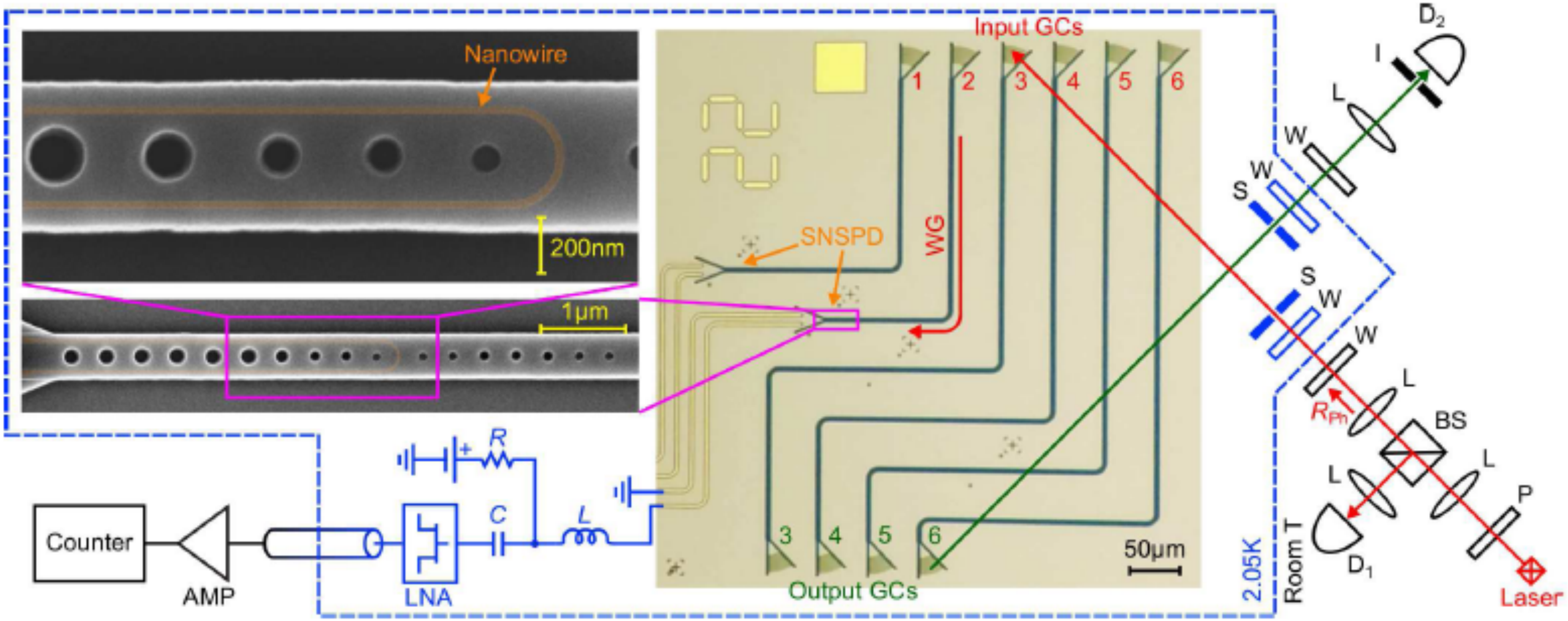
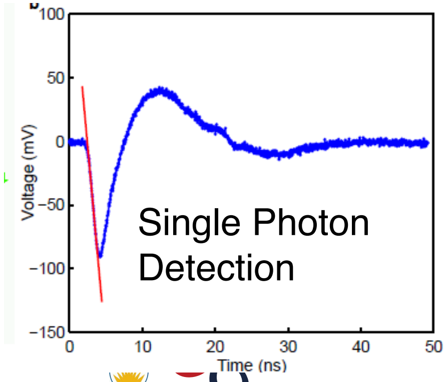
Superconducting Nanowire Single Photon Detectors



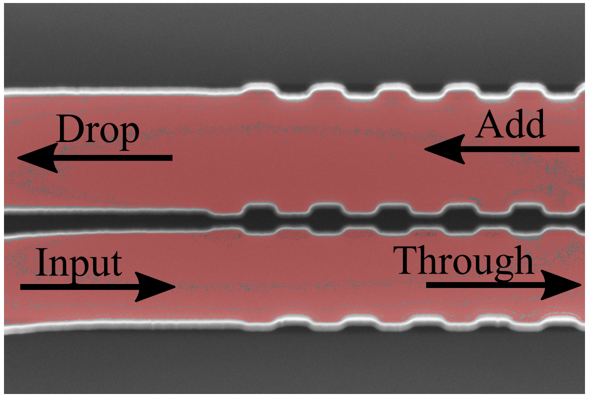


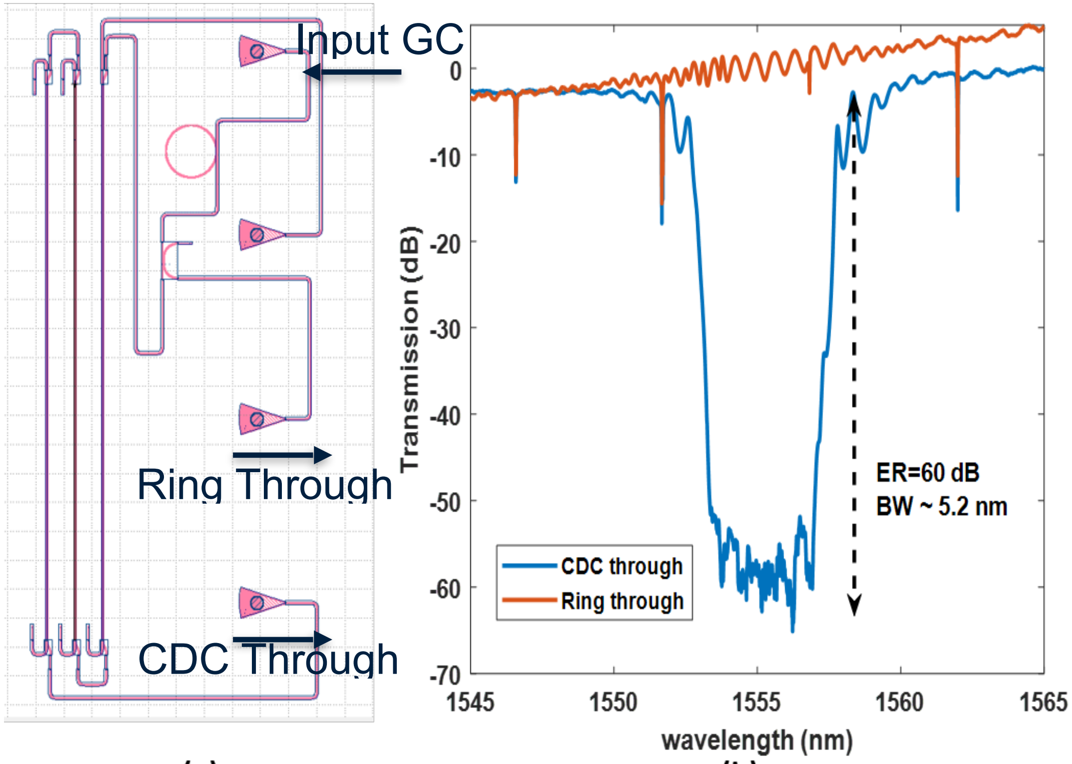
- 200 nm SOI, with 8 nm of NiTiN superconducting film [T_c=7.2K, J_c(T=0)=7.6 x 10^6 A/cm^2]
- 8.5 µm long, 35 nm wide NiTiN nanowire “perfect absorber”
- 96% Q.E.; Dark rate < 0.1 Hz; < 7 ns reset time.

Single Photon Sources: Ring + Pump reject filter

- Ring Resonator for spontaneous four-wave mixing (SFWM) photon pairs
- Optical pump reject filter
  - Cascaded contra-directional grating-assisted coupler
  - Pump is filtered and removed from chip

(Bragg Grating-assisted) Contra-directional coupler filter



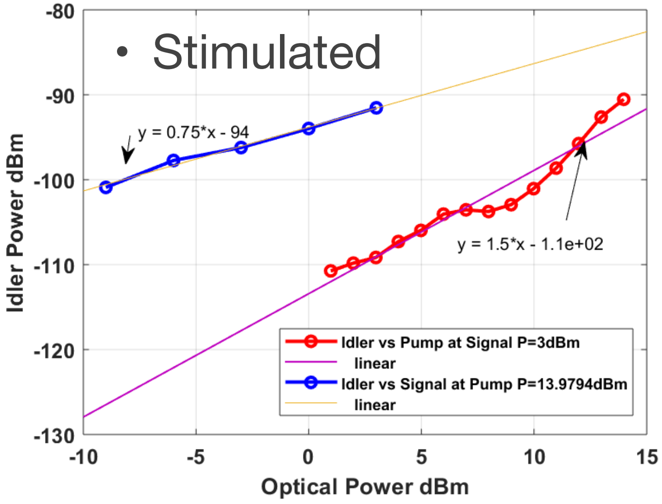


(a) (b)

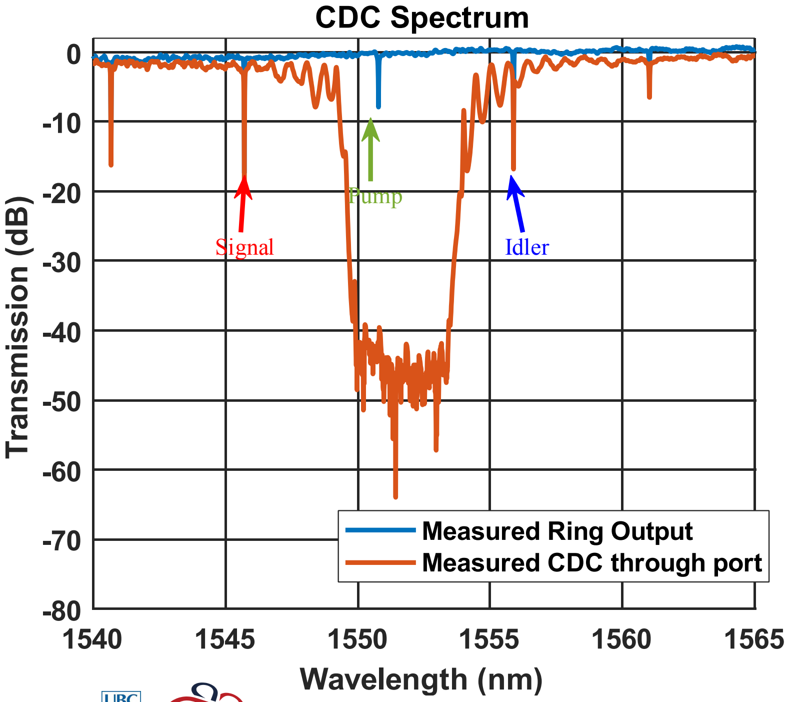
Lukas Chrostowski, 2020

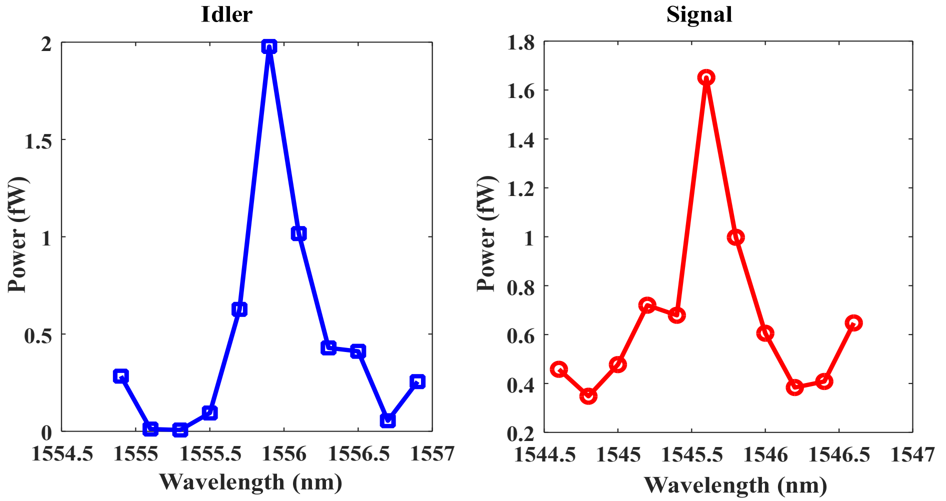
Single Photon Sources: Ring + Pump reject filter

- Stimulated four-wave mixing (SFWM)
- Spontaneous four-wave mixing (SFWM)
- To do:
  - Improve filtering
  - Quantify photon pair quality



- Stimulated





- Spontaneous

Conclusion: Silicon Photonic-based Quantum Computing

- Two approaches:
  - Flying qubits – photons – Linear Optical Quantum Computing
  - Coupling photons to spin qubits – Cavity Quantum Electrodynamics (cQED)
- What will be required to build a silicon photonic-based quantum computer?
  - **low loss optical components and interfaces are critical (photonic wirebonds)**
  - automated probe stations, vacuum/cryogenic
  - **single photon detectors - operate at 4K**
  - **single photon sources - on-demand versus heralded (spontaneous)**
  - **optical tuning techniques – phase shifters for interferometers, resonance tuning**
  - electronics interfacing to 4K photonics
  - cQED using Se+:
    - **high-Q cavities, with small mode volumes, at mid-IR**
    - lasers for mid-IR characterization and operation
    - Se ion implantation, selective, controllable
- Present challenge: achieving strong coupling of photon to Se+ spin

Keep in touch – workshops & courses

- Silicon photonics workshops announced on social media:
  - LinkedIn Group: SiEPIC - Silicon Electronic Photonic Integrated Circuits
    - https://www.linkedin.com/groups/6560209/
  - Facebook Page: Silicon Photonics Design and Fabrication workshops
    - https://www.facebook.com/siphotonics
  - Mailing list, MailChimp: http://eepurl.com/3LkX1
  - SiEPIC Web page
    - www.siepic.ubc.ca
- edX course, edx.org, search for silicon photonics
  - Includes design tools, fabrication, and automated test
  - Next: September, 2020
- Quantum computing program
  - www.quantum-bc.ca