Superconducting Nanowire Single Photon Detectors for Optical Communication and Quantum Optics

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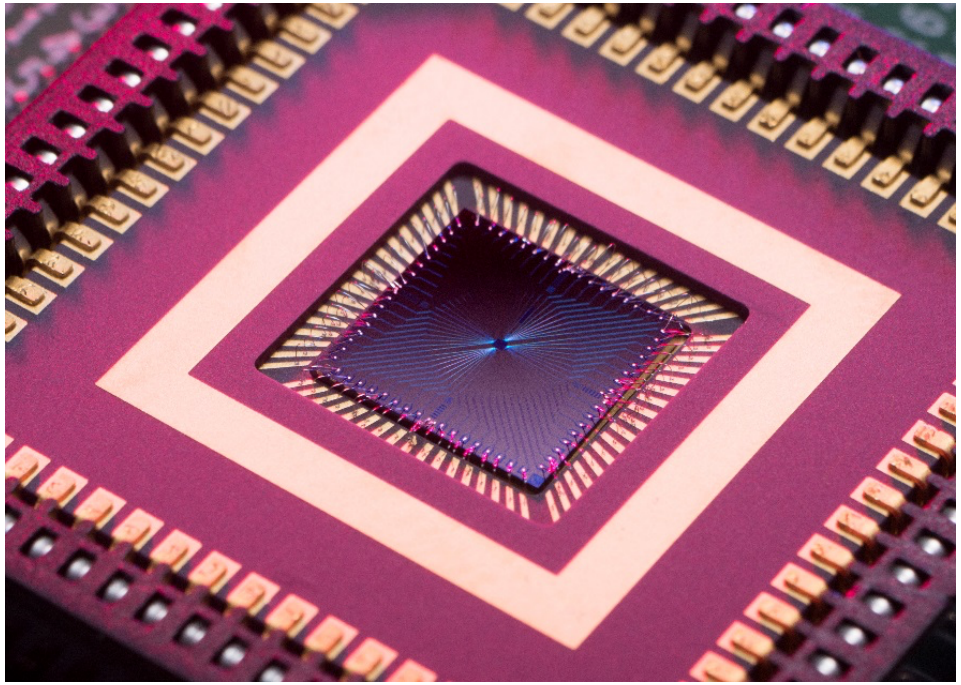

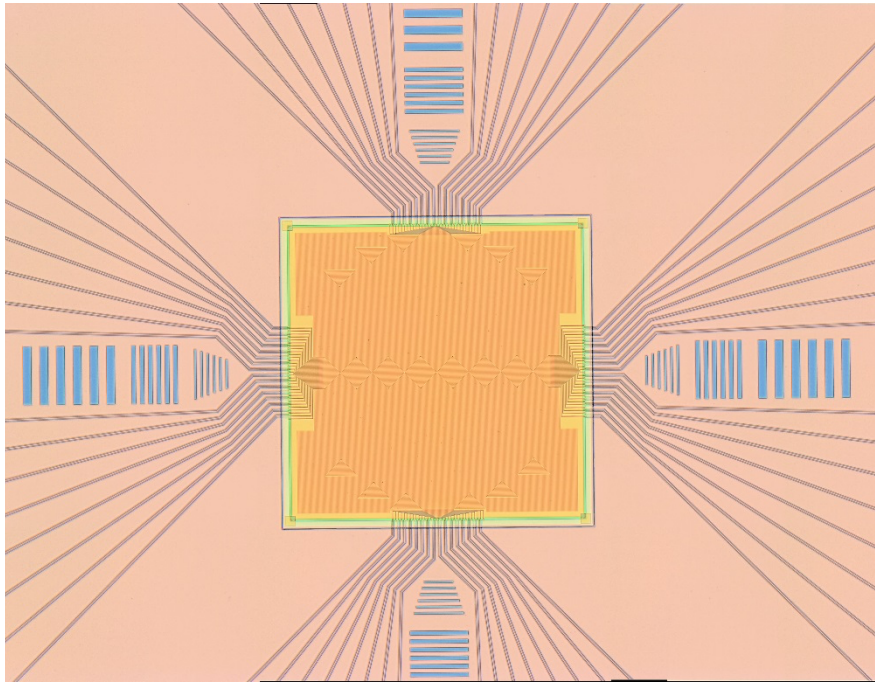

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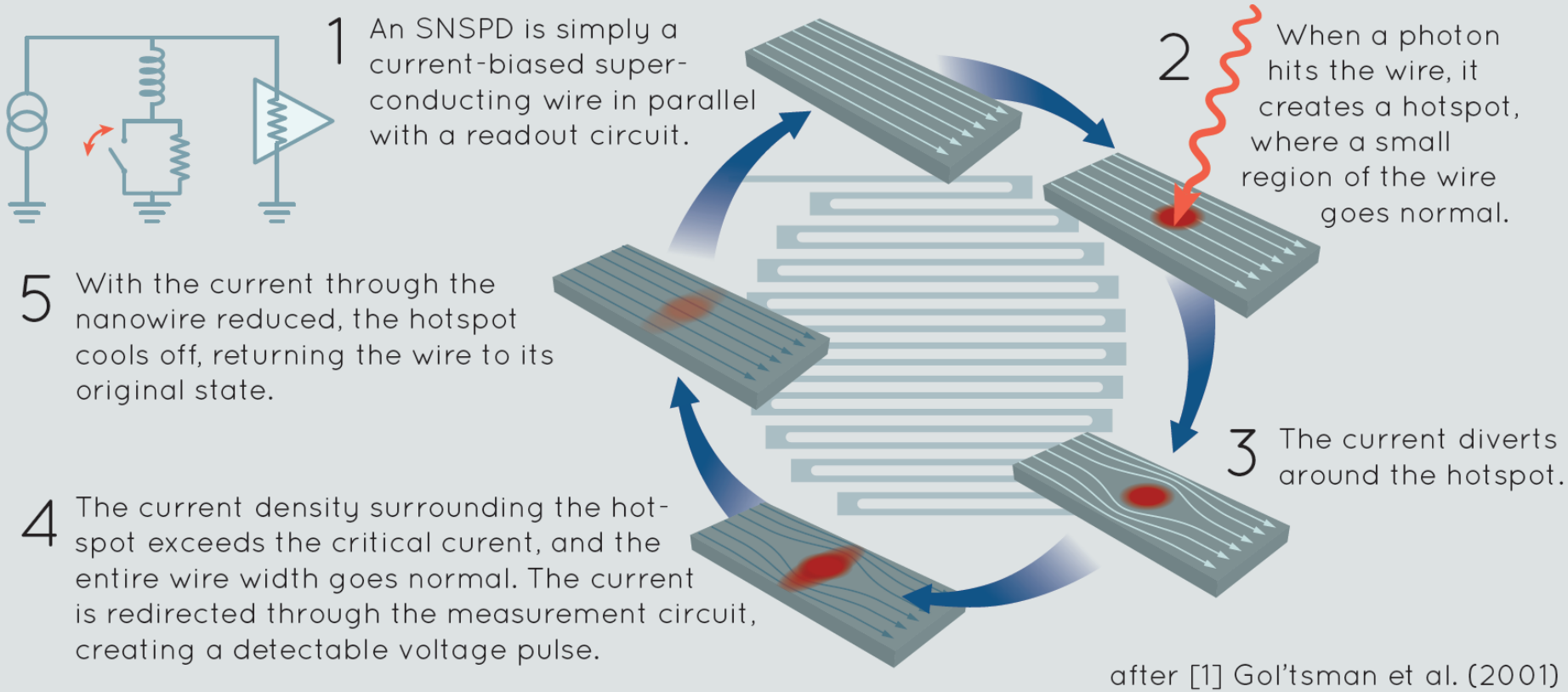
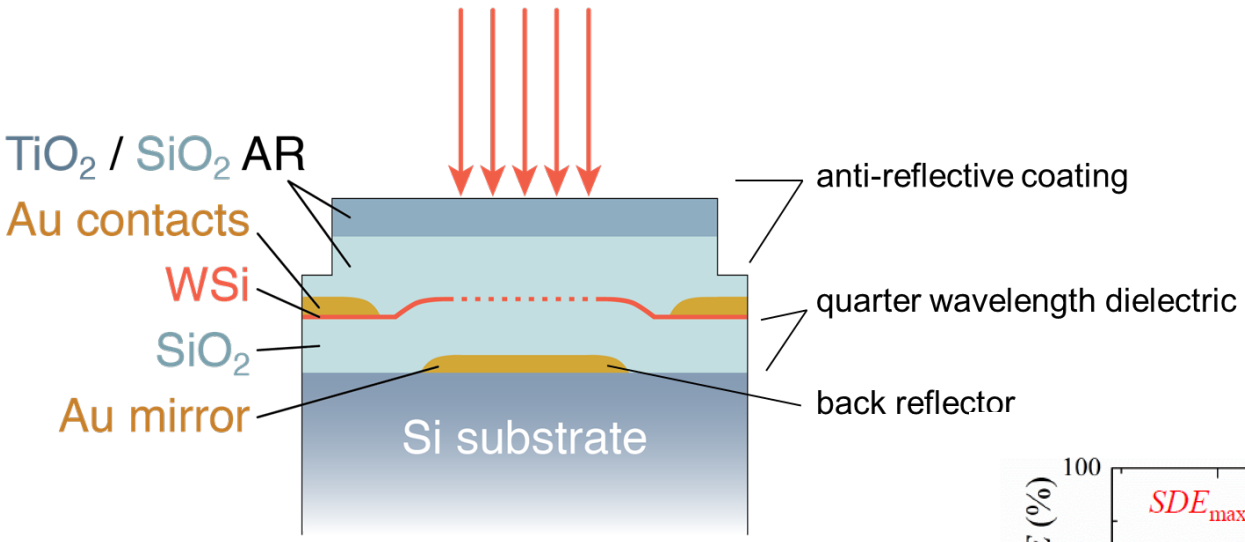
SNSPD Device Concept

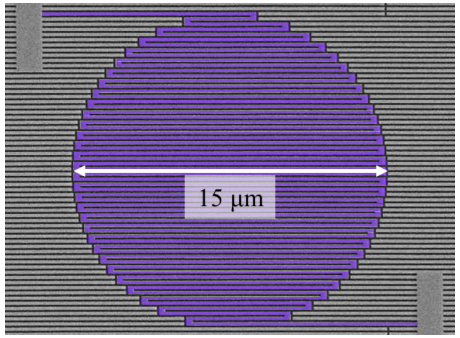


after [1] Gol'tsman et al. (2001)

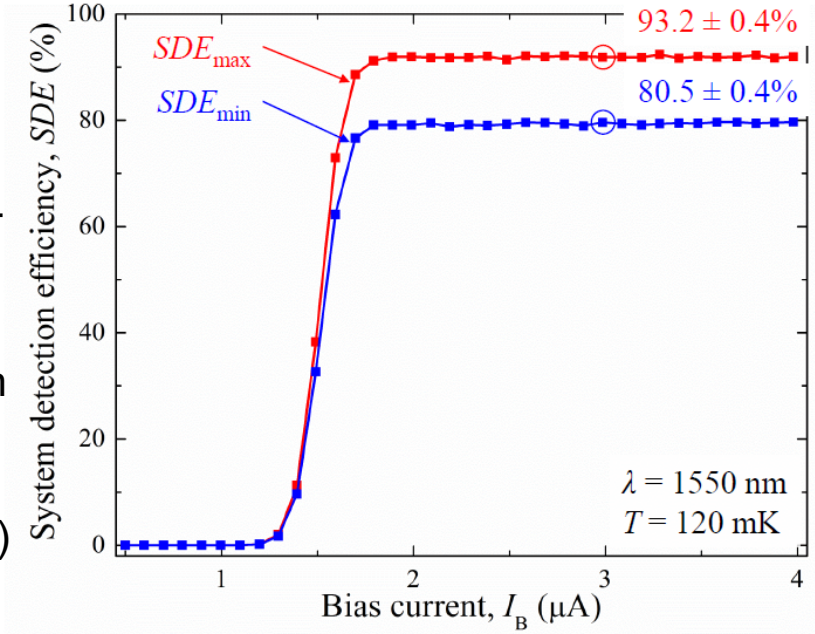
- Highest performing detector available for time-correlated single photon counting, UV to mid-IR
- Requires 1 – 4 Kelvin cryogenic cooling
- Commercial single-pixel SNSPDs have been widely adopted by the quantum optics community

WSi SNSPD Architecture





- WSi SNSPDs developed in 2012 by JPL and NIST
- Now fully commercialized
- System detection efficiency up to 93% @ 1550 nm
- Sub-Hertz intrinsic dark counts
- Maximum count rates of 20 Mcps (3 dB saturation)
- 80 ps FWHM timing jitter

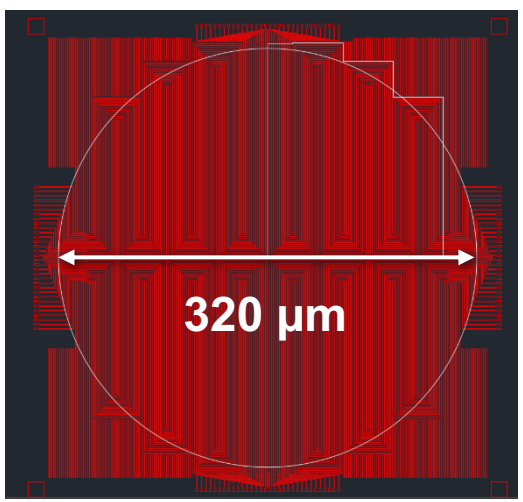


System detection efficiency for single pixel device

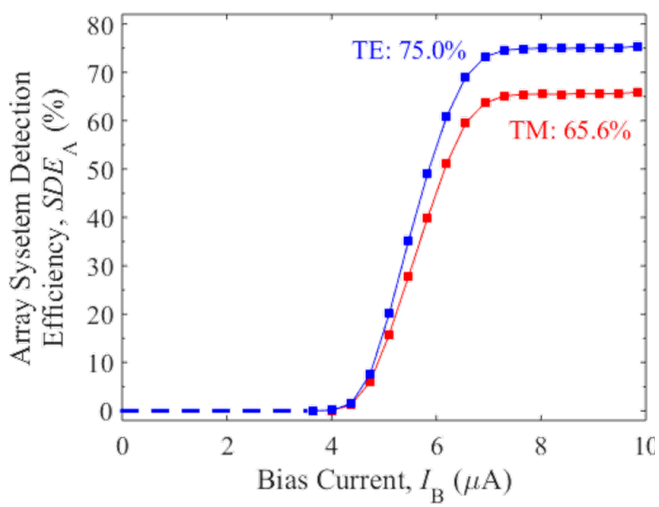
Marsili et al, *Nature Photonics* **7**, 210 (2013)

64-Pixel SNSPD Arrays for Optical Communication

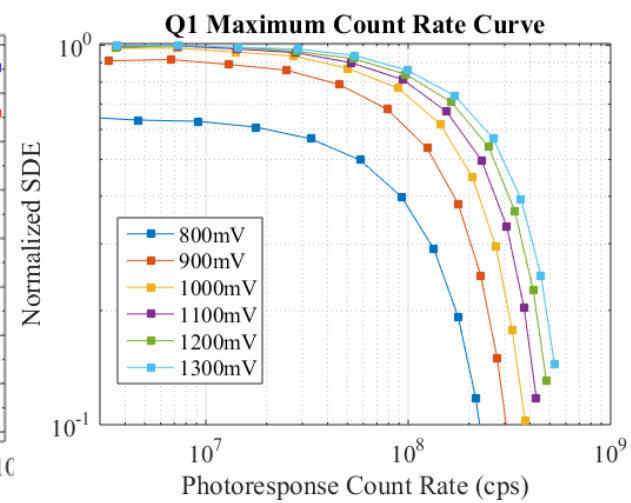
- JPL has recently developed 64-pixel SNSPD arrays for the ground terminal of its Deep Space Optical Communication (DSOC) project, to demonstrate laser communication to 2.7 AU
- SNSPD array planned for the DSOC ground terminal at Palomar Observatory
- 320 μm diameter active area, free space coupling, 64 independent SNSPD sensor elements
- 1.2 Gcps maximum count rate, 75% system detection efficiency, 80 ps timing jitter
- High pixel count fiber-coupled SNSPD arrays are a straightforward variation
- Also relevant for photon number resolution, ultra-high-rate quantum communication, and space-to-ground quantum communication systems



CAD Design of SNSPD focal plane array



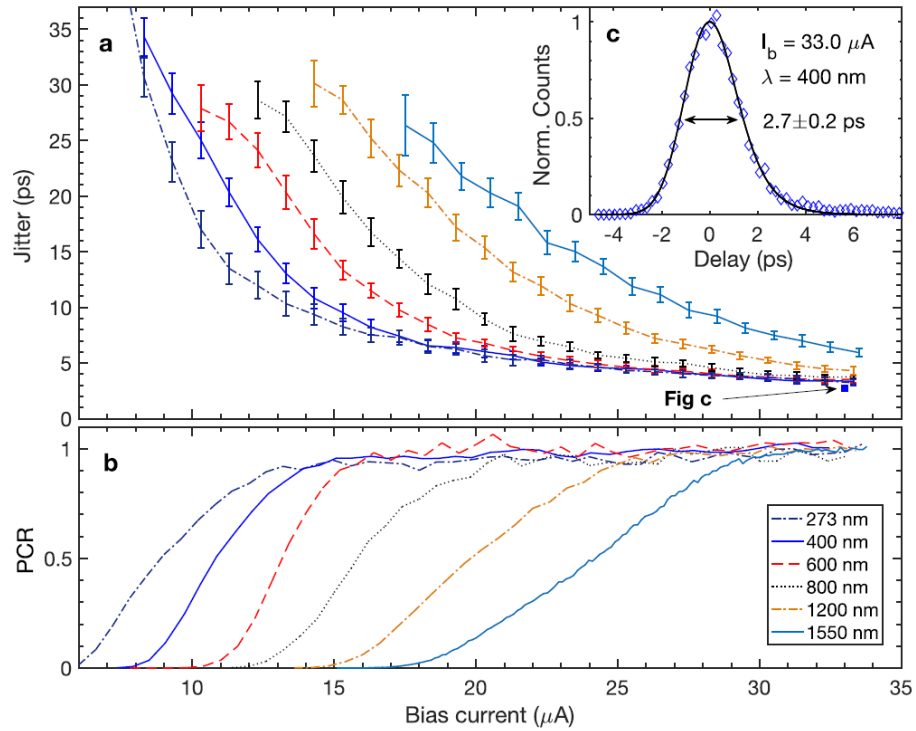
Free-space coupled system detection efficiency of 64-pixel array

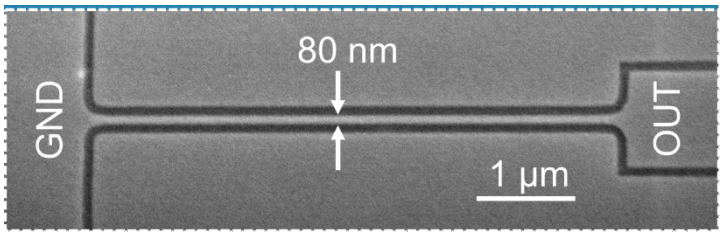


Maximum count rate measured on one 16-channel quadrant of array

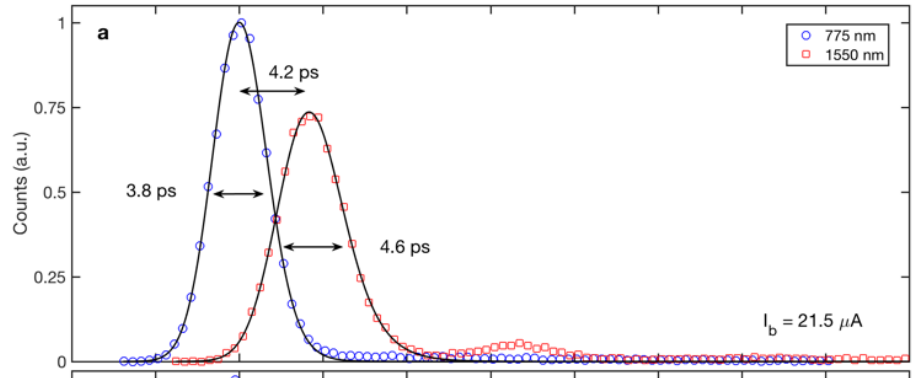
Ultra-high time resolution in SNSPDs

- Collaborative research project between MIT, JPL, and NIST has reduced timing jitter in SNSPDs from ~15 ps to as low as 2.7 ps FWHM
- Achieved through high switching current and low noise readout
- NbN Detectors were fabricated at MIT and measured at JPL
- Devices had small active area to eliminate geometric jitter, but differential readout has been demonstrated to achieve low jitter on large-area devices





Specialized low-jitter NbN SNSPD

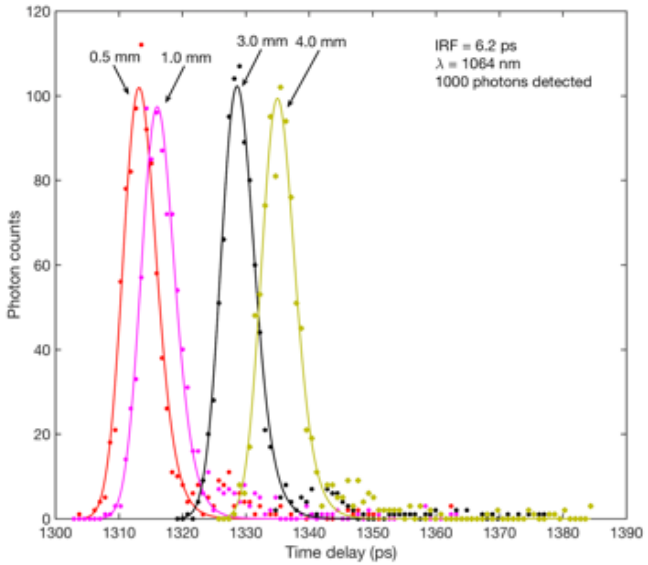


Dependence of timing jitter on photon energy

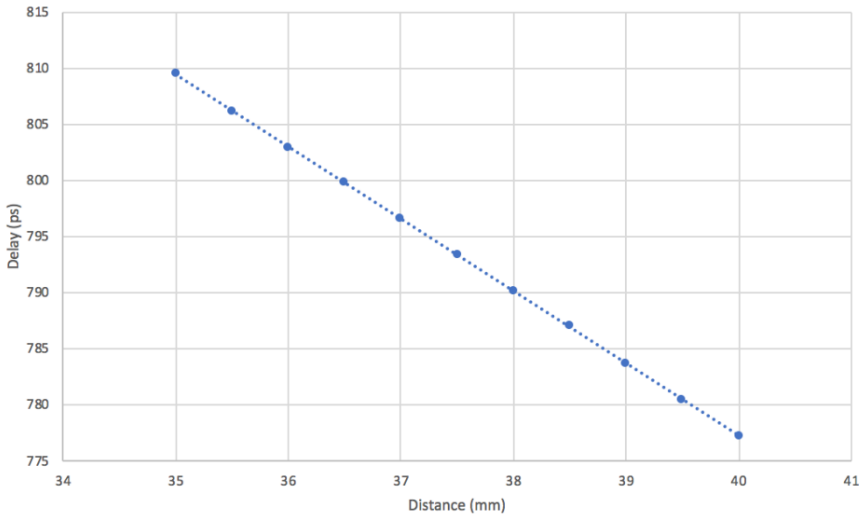
Korzh et al, arXiv 1804.06839 (2018)

Ultra-high resolution in laser ranging

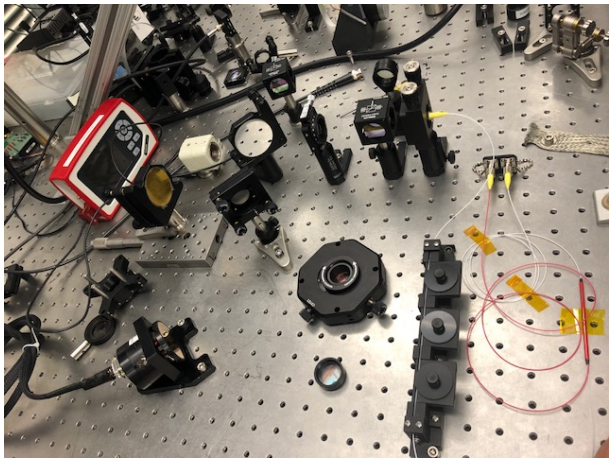
- Improvement in time resolution from ~20 ps to < 3 ps translates into millimeter-scale ranging from each photon
- Dramatic SNR advantage in photon counting lidar systems
- Now performing tabletop laser ranging experiment with record-setting SNSPD and world's fastest timing electronics
- Measured 4.5 ps instrument response function using time-tagging card



Raw data from laser ranging experiment showing mm resolution



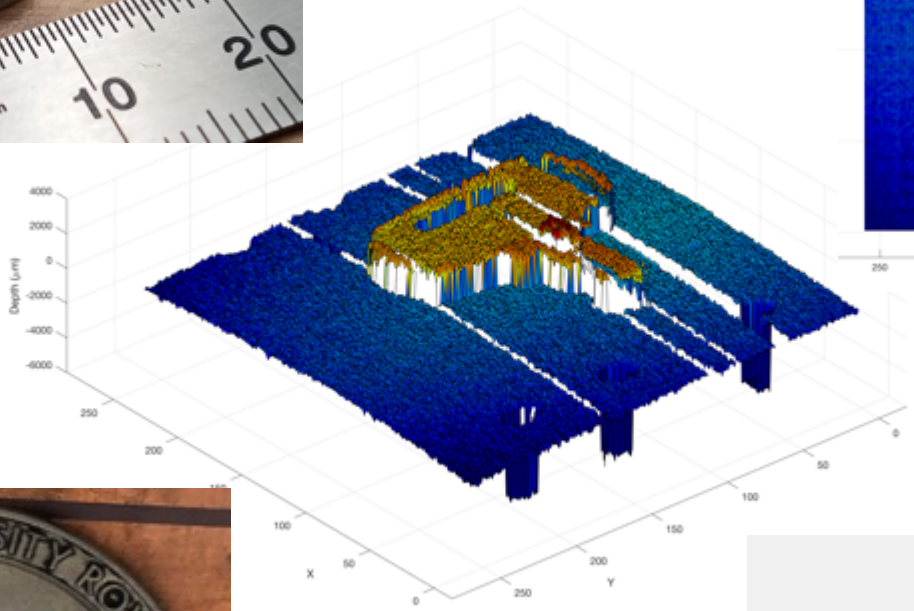
Tracking of mirror position with photon timing

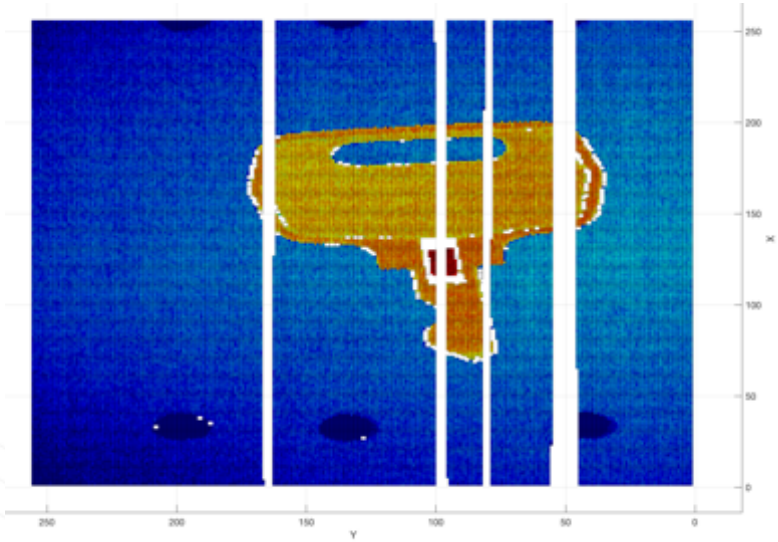


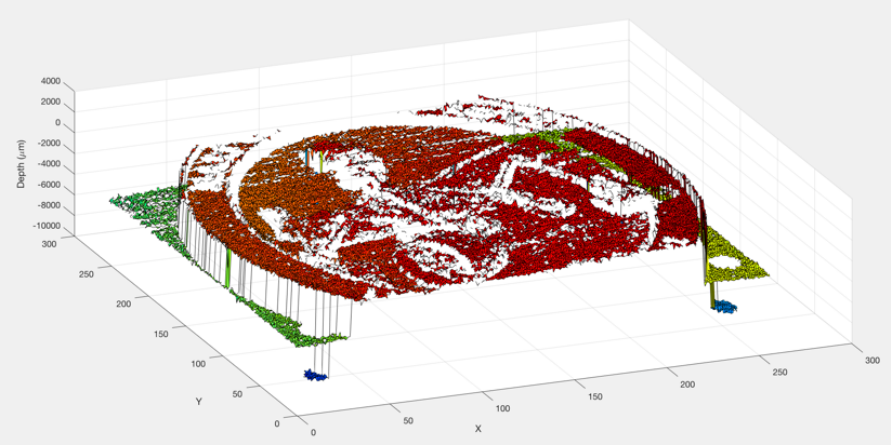
Tabletop laser ranging experiment

Ultra-high resolution in laser ranging

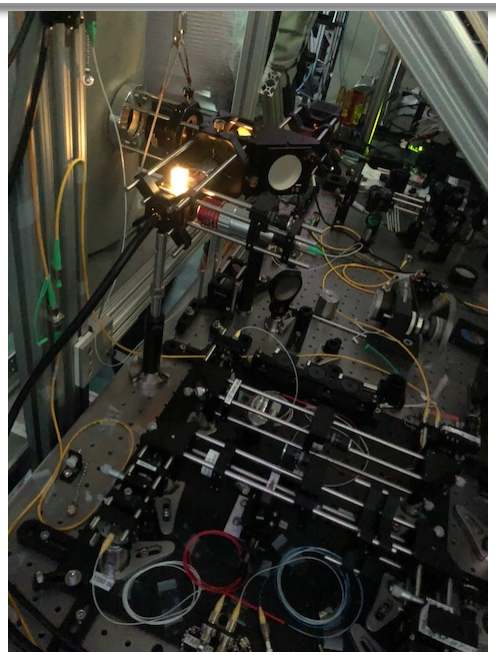
Jet Propulsion Laboratory
California Institute of Technology



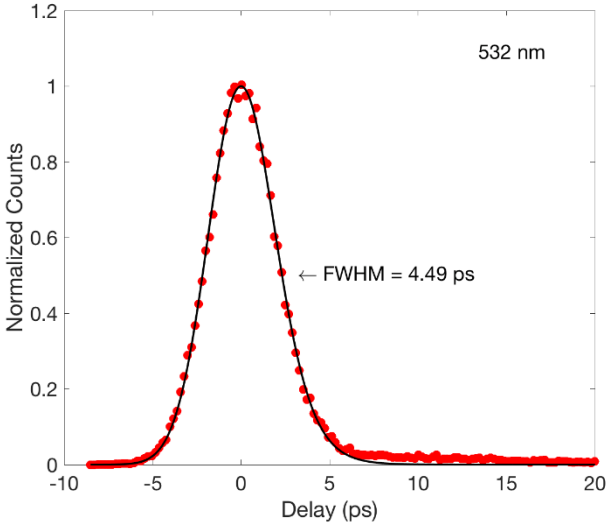


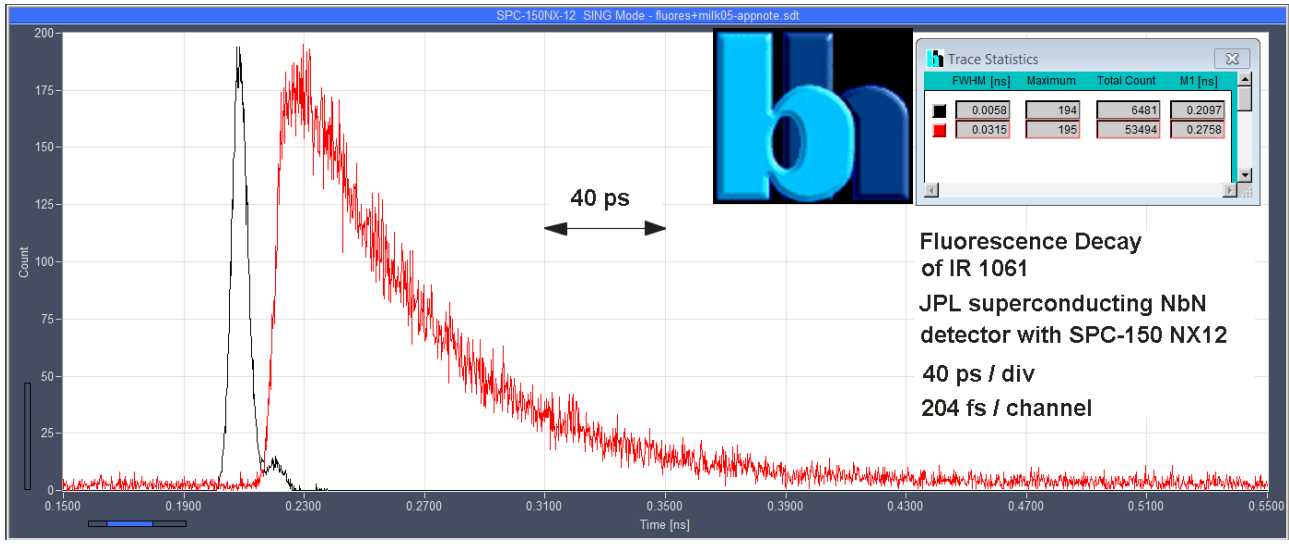


Fluorescence Lifetime Measurements



- Used ultra-low-jitter SNSPDs and modified Becker & Hickl SPC-150-NX to time-tag photon arrivals with < 5ps FWHM
- Measured lifetime of IR-1061 dye in dicholoromethane: 43 ps
- Demonstrates capabilities of ultrafast SNSPDs for FLIM and FRET applications





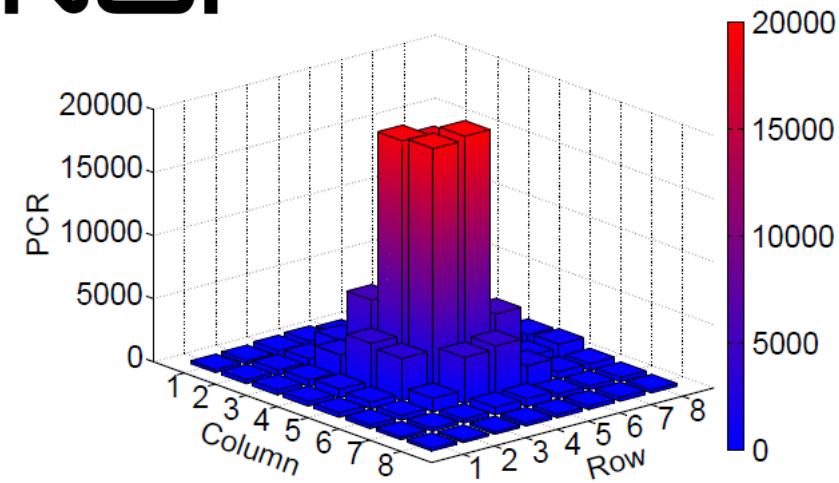
Time tag data with SNSPD

Fluorescence lifetime measurement of IR-1061 at JPL

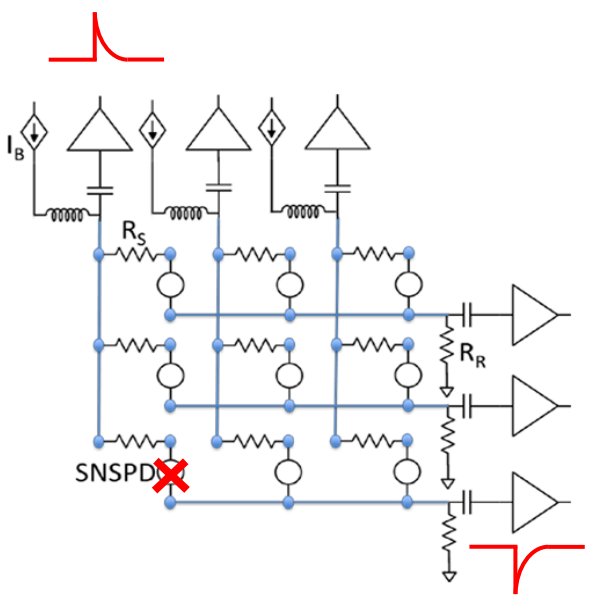
Prospects for Imaging Arrays

NIST

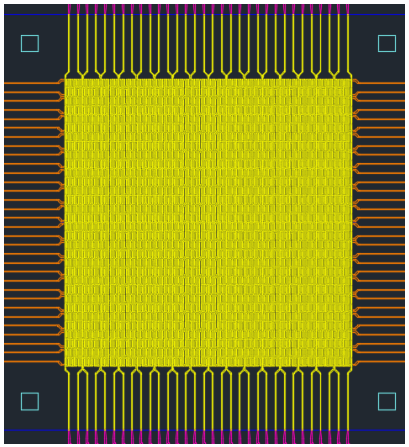
Allman et al, APL (2015)

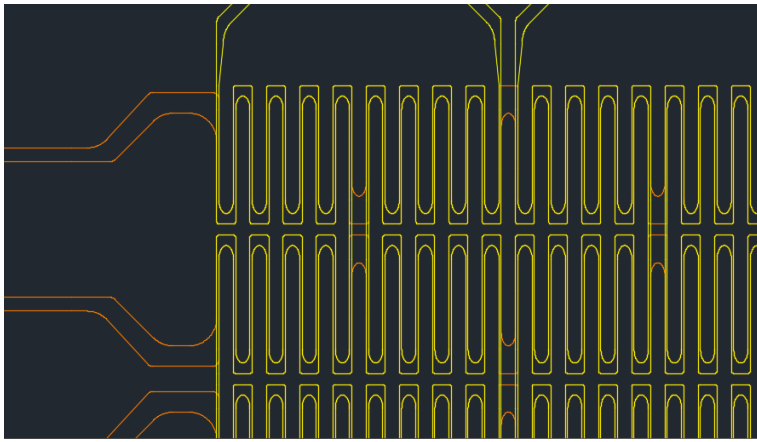


- 64 pixel (8 x 8) sparse WSi SNSPD array demonstrated for time-correlated imaging
- Row-Column readout strategy allows 64 pixels to be read out using 16 lines
- Kilopixel 32 x 32 array in development using “thermal” row-column scheme
- Close collaboration between JPL and NIST
- Potential applications include quantum imaging, biomedical imaging, photon counting lidar, imaging quantum receivers



Operating Concept

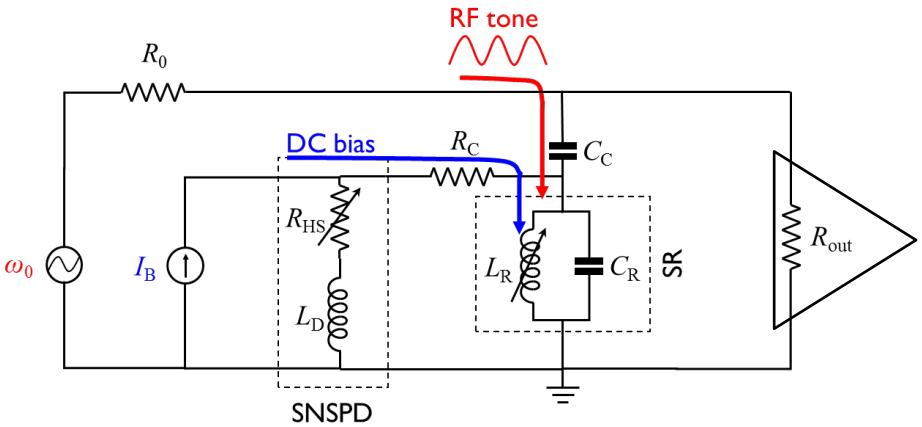




Example designs for 32 x 32 thermal row-column SNSPD imager

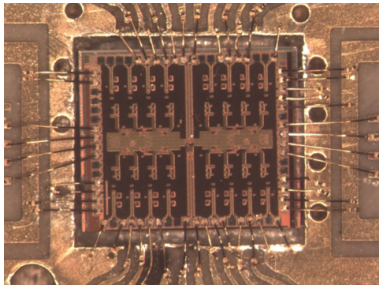
Other Multiplexing Strategies

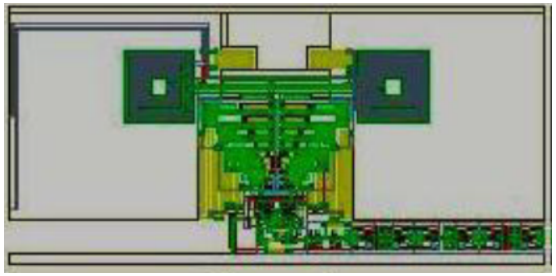
Frequency Domain



- Similar trade space to MKIDs

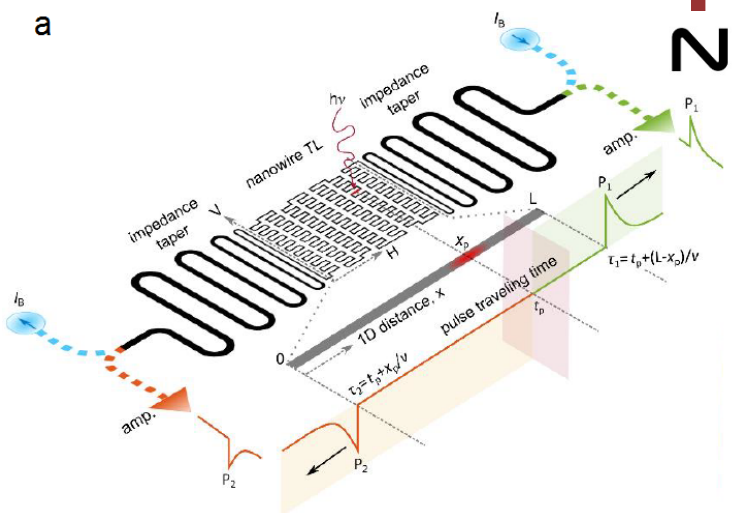
Cryogenic ROICs



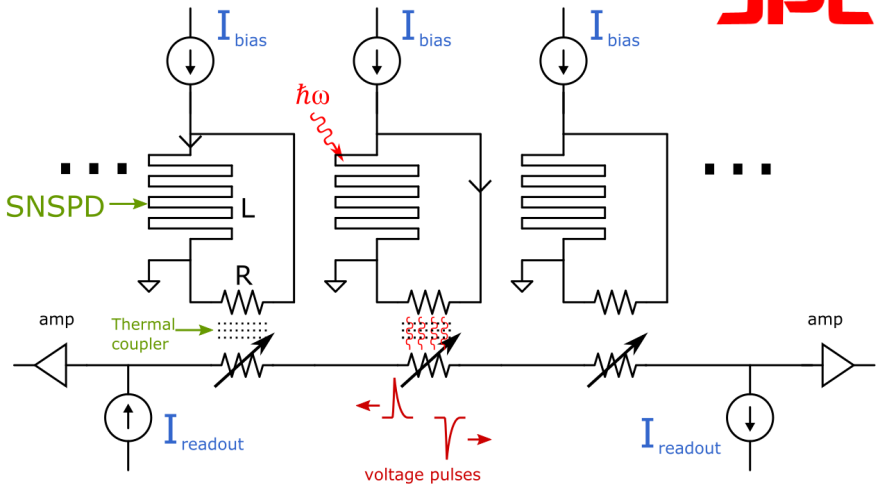


- SiGe and superconducting SFQ readout circuits are under investigation

Position Sensitive Nanowire

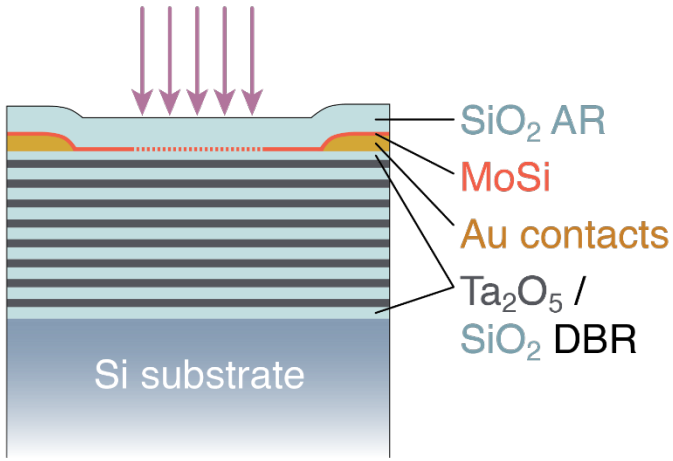


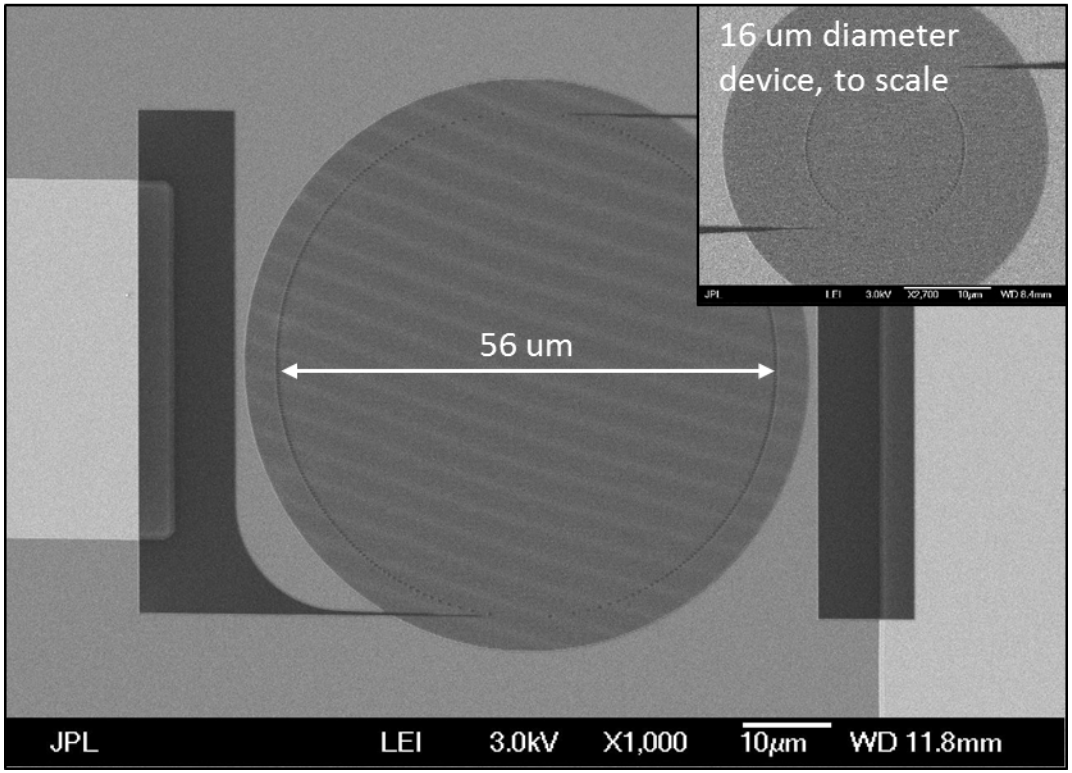
Thermally Coupled Imager



Ultraviolet SNSPDs for Quantum Computing

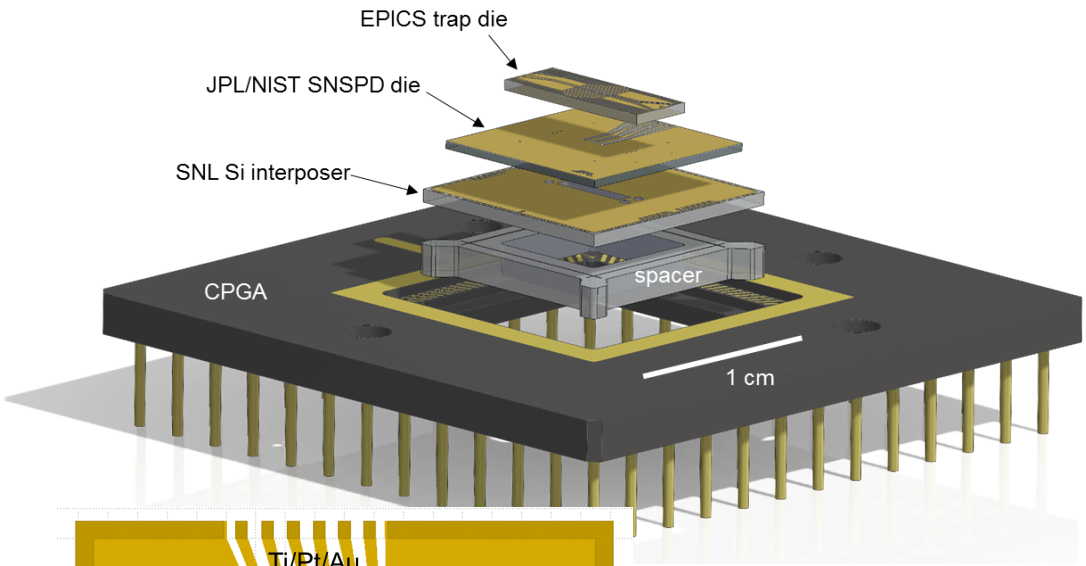
- Fiber-coupled MoSi UV SNSPDs for applications in ion trap quantum computing
- 80% Efficiency at 370 and 315 nm, single photon sensitivity at 245 nm
- DBR mirrors to enhance absorption
- 4.2 K operating temperature
- mHz dark count rates when coupled to optics, < 7e-5 cps intrinsic dark count rates



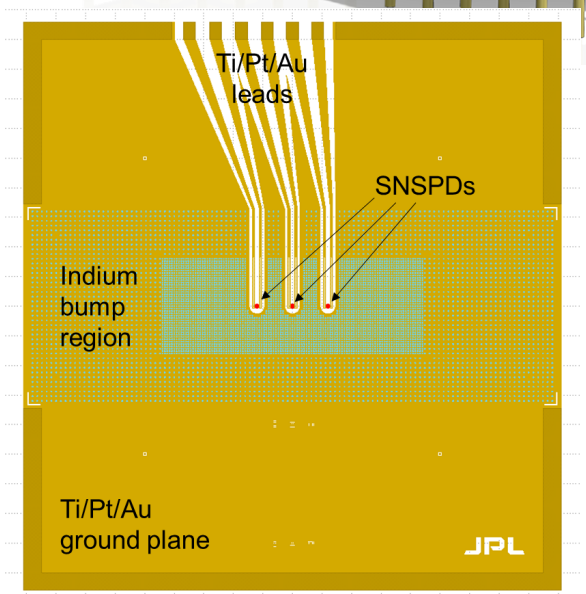


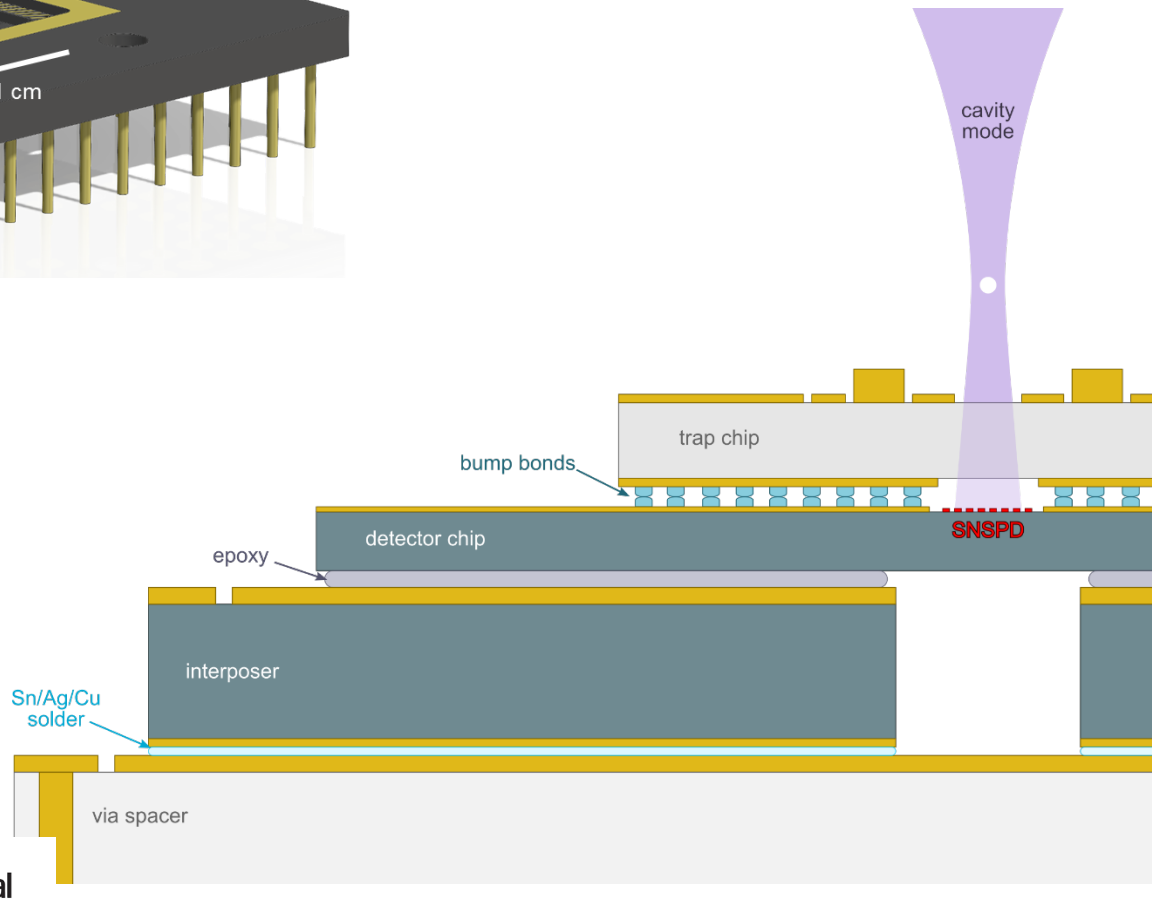
NIST Duke UNIVERSITY Sandia National Laboratories

Integration with Ion Trap Chips



- Hybrid integration between ion trap chips and free-space UV SNSPDS
- Collaborative effort between JPL, NIST, Sandia, and Duke University

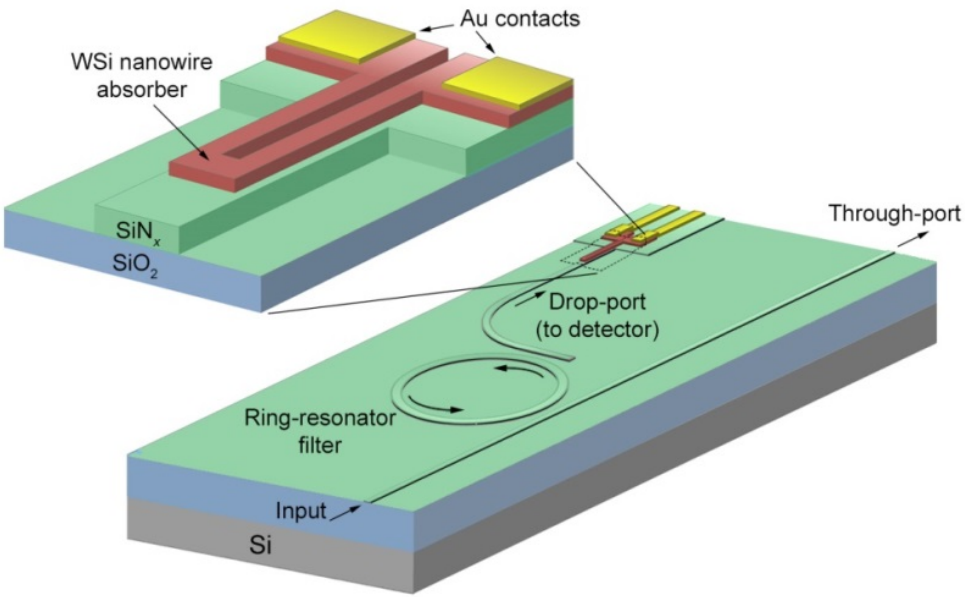


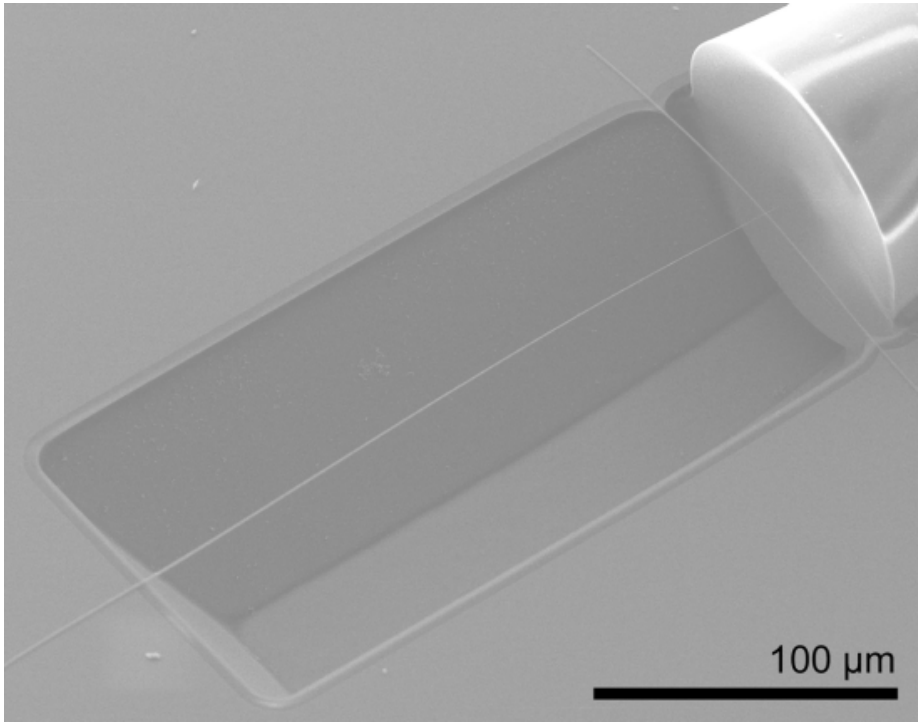


NIST Duke UNIVERSITY Sandia National Laboratories

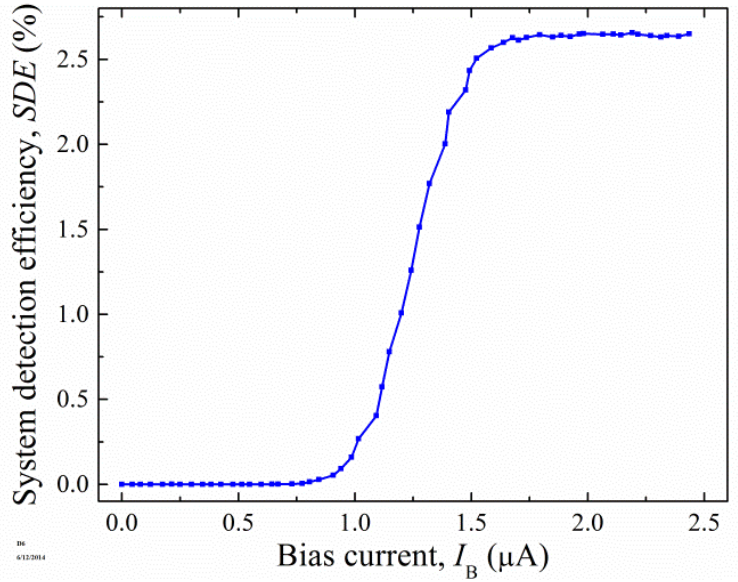
On-Chip Integrated SNSPDs

- WSi SNSPDs coupled to SiN waveguide photonics platform
- Can be integrated with on-chip ring resonators or echelle grating to form channelizing spectrometer or DWDM receiver for QKD
- Can be integrated with on-chip heralded single photon sources, photonic processors, or photonic trapped ion systems
- Can realize a robust, on-chip cryogenic spectrometer, particularly in the mid-IR

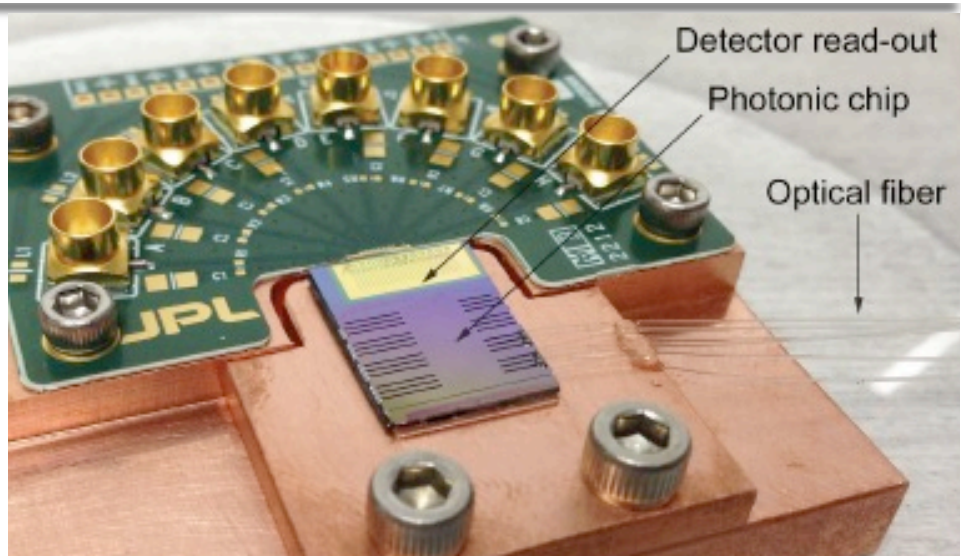




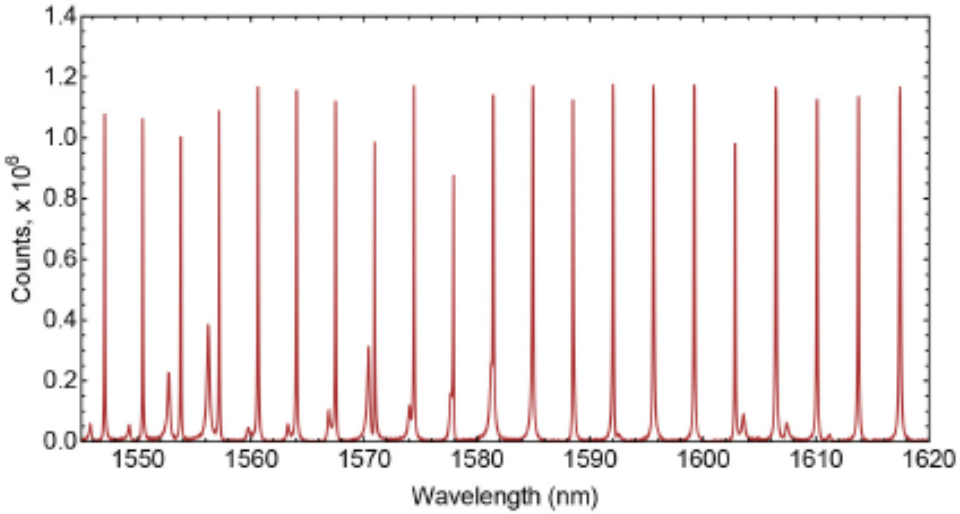
On-Chip Integrated SNSPDs

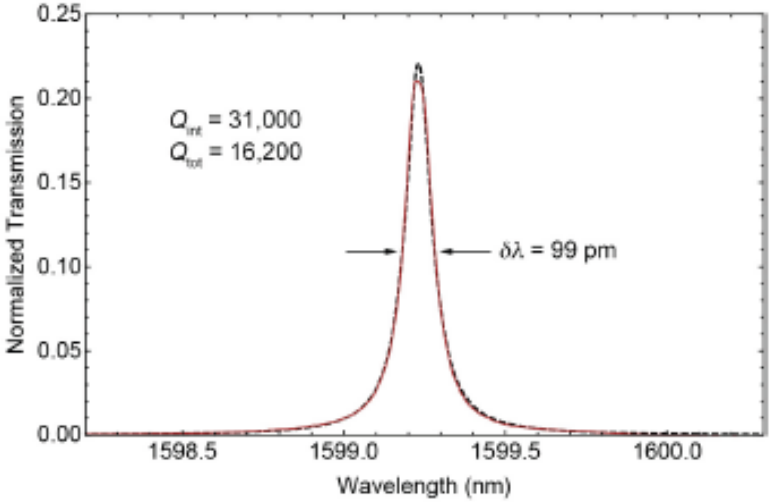


WSi SNSPD in waveguide with bias plateau



Cryogenic self-aligned fiber packaging





Wavelength selectivity of count rate using SNSPD integrated with photonic ring resonator

Summary of Capabilities

- Efficient time-correlated single-photon counting with unrivaled performance from deep UV to mid-IR
- > 90% system detection efficiency
- < 3 ps time resolution
- < 1 mHz intrinsic dark count rates
- > 1 Gcps maximum count rates
- Single photon sensitivity demonstrated from 245 nm to 9.9 μm at JPL
- Demonstrated 64-pixel arrays
- Multiple pathways for scalability to kilopixel arrays
- Compatibility with integrated photonic devices