Integrated Quantum Information Platforms at MIT
Lincoln Laboratory

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NY Creates Seminar

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Outline

- Platforms for quantum information processing
- Trapped-ion quantum computing and sensing
  - Concept for trap array with integrated controls
- Integrated Photonics Development
  - Visible platform: $\text{Al}_2\text{O}_3$/PECVD SiN (low loss, multi-layer, CMOS-compatible)
  - Ion operations with multiple wavelengths of light, on-chip
  - Expanded photonics platform: potential for enhanced QIP functionality
- Integrated Electronics
  - Monolithic integration of electronic controls for trapped ions
  - Photon detection and 3D integration
- Near-Term Collaborations Utilizing the Ion Platform
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MIT-LL Diamond Quantum Systems Seed Applications

**Diamond Growth and Fabrication**

- Nitrogen vacancy diamond magnetometers improve navigation without GPS
- Cavity readout of diamond and alternate solid-state materials opens new class sensors
- Silicon vacancy defect centers in diamond enable scalable quantum memories, a core element of networks

**Quantum Control**

- RF initialization
- Optical readout

**Small SWaP Devices by Quantum Engineering**

- Quantum Networks
  - Silicon vacancy defect centers in diamond enable scalable quantum memories, a core element of networks

**Magnetic Imaging Applications**

- Quantum-grade “diamond magnetic microscope” enables high spatial resolution magnetic imaging

Connecting quantum diamond development with system-level applications enables new sensing paradigms.
Superconducting quantum computing investment has enabled robust external programs pursuing next generation quantum computing and enabling the broader community.
Robust Trapped-Ion Quantum Computing

Ion platforms with in-chip routing of optical and electronic control signals

Integrated Chip-Based Trapping

Quantum Computing & Sensing

Advanced Multi-Zone Quantum Control

Integrated ion platform enables core mission areas of advanced quantum computing and portable precision timing and collaborations through the National Quantum Initiative

*SBS: stimulated Brillouin scattering

First demonstration of an integrated chip optical clock controlled by a compact stimulated Brillouin scattering (SBS) laser.
• Platforms for quantum information processing

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• **Near-Term Collaborations Utilizing the Ion Platform**
• 53-qubit quantum sim. with indiv. ion-qubit control (UMD)
• Programmable, verifiable 20-qubit quantum sim. (Innsbruck)
• Quantum simulation of water molecule (IonQ/UMD)
• Gate teleportation between separated qubits (NIST)
• Six-qubit arrayed-architecture/motion demo (HQS)
• Two-qubit gates >99.9% fid. (NIST) and 99.8%, 1.6 us (Oxford)
Currently, the best clock in the world: a single Al\(^{+}\) ion controlled via a single Mg\(^{+}\) ion using quantum logic

- Fractional frequency uncertainty below 10\(^{-18}\) (1 s in 33 billion yr)
- Sensitive to gravitational redshift at the few-cm level
- More precise than best lattice clocks (but not more stable, due to fewer atoms)

Enables not only precision timing but basic science
Trapped-Ion Qubit Approach

**Ion**
- Utilize Sr atom with one electron removed (Sr⁺)

**Qubit State**
- Utilize state of outermost electron (Ground vs. Metastable excited state)

**Ion Trapping**
- Oscillating quadrupole field confines ion
Trapped-Ion Qubit Approach

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“Bulk” linear Paul Trap (PTB)
Surface Electrode Ion Traps

Shrinking and Planarizing the Four-Rod Geometry

- Quadrupole unfolded into a plane
- Produces an effective 3D harmonic well above the chip surface

Surface electrode linear Paul trap (MIT LL)

Sr$^+$ ions, 50 um from trap surface, and approximately 5 um apart
Trapped Ion Quantum Information Processing
Progress & Challenges

Progress
• Very long coherence times and low error rates
  – $T_{\text{coh}} > \text{min demonstrated}$
  – Errors $\sim 10^{-3}$ per operation
  – Approx. 20 controllable qubits
  – Some of the best clocks are based on trapped ions

Remaining Challenges
• Many more ion qubits needed, with high fidelity
  – Individual control beams, photon detection, and electronics for every ion
  – More portable, robust controls for sensors/clocks

Required optics for few-qubit experiments (partial)
Potential Quantum Computing/Sensing Array Cell

- Integrated waveguides for light fan-out
  - Grating coupler optics direct light to ions
- Detection on-chip
- Tile cells in array for multi-qubit processing
  - Ions move to interact with neighbor ions

Tiling Ion Cells

(Movie)
Trapped-Ion Array Critical Elements
Medium-Term Unit-Cell Integration

- Ion chains and multi-qubit logic
- Integrated electronic control
- Co-located APDs beneath grid
- Integrated single-photon detection
- 2D ion trap array on multilayer chip
- Dual-cell physical architecture concept
- Ion quantum control with photonics integrated on chip trap

Sr⁺, Ca⁺
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• Near-Term Collaborations Utilizing the Ion Platform
Reduced Beam-Pointing Instability

- Free space optics are supported outside the vacuum chamber far from the ion
  - Long lever arms
  - Subject to acoustic, thermal, and air-flow perturbations

- Chip-integrated optics eliminate many of these shortcomings
  - Stable on-chip beam paths (can be fiber coupled to chip)
  - Final optic <100 um from ion
  - This last free-space path (grating-to-ion) is air-free
Addressing Arrays of Ions

- Addressing many ion sites a challenge with free-space optics, particularly in 2D
- Chip-integrated beam paths reduce optics footprint
- On-chip splitters for fan-out

Array-clock concept
Single-Mode Waveguides

- High-index core surrounded by low-index cladding
  - Typically sub-square micron MFD
- Like a fiber on a chip, but can be patterned with precise alignment to ion trap
  - Straightforward routing (bend radius depends on wavelength)
Grating-Based Waveguide-to-Beam Couplers

- At distal end of waveguide, periodically vary the index contrast
  - Can vary presence or depth of core material
  - Grating formed can diffract light into a beam
  - Emitted angle depends on period, wavelength, indices, etc.
  - Varying duty cycle and tooth curvature along waveguide can provide focusing

- Requires wavelength-scale feature definition

Tightly Focused Beams

- Reduced beam-pointing instability also reduces need to account for beam wandering
  - Beams can be smaller at ion locations; few-um diameter beam spots: grating-based optics
  - Higher useful intensity for given beam power
  - Potentially lower crosstalk

Mehta et al., Nature Nanotech. 11, 1066 (2016)
Individual Ion Addressing

- Grating coupled beam diam. 4 um along trap axis
  - Ion separation ~ 5 um
- Can address single ion in chain
- Movie: quantum jumps in center Sr\(^+\) ion

Diffraction-limited beam size from integrated optics

\[ \text{Mehta et al., Nature Nanotech. 11, 1066 (2016)} \]
Integrated Photonics Multilayer Platform

- Fabricated in LL’s 8” wafer, 90-nm microelectronics laboratory
  - Low-loss, high-confinement routing
    - < 0.5 dB/cm from 600-1100 nm in SiN
    - < 3 dB/cm from 370-600 nm in Al2O3
  - Complete passive component library
    - High-efficiency grating couplers for all \( \lambda \)
      - 60% grating efficiency demonstrated in red
    - Multi-layer alumina-to-SiN transitions
    - On chip tapers for fiber IO
    - Crossings, splitters, couplers
  - Metal layers beneath photonic elements
    - Allows for ground plane to provide electronic isolation from the silicon

Sorace-Agaskar et al., IEEE JSTQE 25, 8201515 (2019)
West et al., APL Photonics 4, 026101 (2019)
Visible Light Platform Development (SiN, Al₂O₃)

Selected Components

- **Input-Output Couplers**
  - 100 μm

- **Crossings**
  - 150 μm

- **Focusing Grating Couplers**
  - 100 μm

- **Splitters**
  - 100 μm

- **Waveguides**
  - 500 μm

Platform information:

- Designs cover 370 - 1092 nm (Yb+, Sr+, Ca+)
  - ~10 fundamental devices at 14 distinct wavelengths

- Performance:
  - SiN Loss < 0.3 dB/cm (Yellow to NIR)
  - Al₂O₃ Loss 1-3 dB/cm (NUV to Green)

- Supports multiple photonic layers and metallic trap layers

C. Sorace-Agaskar et al., *IEEE JSTQE*, 2019
Fiber Attach and Installation in Cryogenic UHV System

Fiber feedthrough

1 cm chip
Multi-Wavelength Integrated Optics

• Operations on Sr$^+$
  – 461/405 nm photo ionization
  – 422 nm cooling/detection
  – 1092 nm repump
  – 674 nm sideband cooling, coherent operations
  – 1033 nm qubit quenching

• Verified ex-situ beam profiles in-situ with ion

• Photonic illuminated detection
  – 99% detection fidelity using integrated delivery of light

• Vibration-resilient qubit coherence
  – Common-mode platform vibration

Niffenegger et al., Nature 586, 538 (2020)
Multi-Qubit Gates with Integrated Photonics

- ETH Zurich: complementary work
  - Single wavelength integrated in chip for Ca$^+$ logic (729nm)
  - High-fidelity two-qubit gates (F ~ 99.3%)
  - Good on chip coupling (~2 dB loss) using multi-layer edge-coupler

- With multi-wavelength capabilities, provides a platform with significant potential
  - Need to address potential trade offs
  - Scatter, low input coupling, power handling

Mehta et al., Nature, 586, 533 (2020)
**Expanded Silicon Nitride Platform**

### Pick-and-Place Component Integration

**InP Laser**
- 312 mW single mode laser output on-chip

**High-Speed InP Photodiode Array**
- Current: 45 GHz, 0.05 A/W
- Future: 80 GHz, 0.2 A/W

### Ultra-Low-Loss, Low-Confinement SiN

- 0.5 dB/m Loss

### Bonded Thin-Film Materials

**LiNbO2 (Modulators)**
- Passive loss 0.4 dB/cm
- Preliminary demonstration of modulation

**III-V Films**
- Individual fabrication steps successfully demonstrated
- 90% bonding yield

### Monolithic Integration

**Silicon Photonics**
- Low loss preserved with integration

**Heteroepitaxial III-V Growth**
- Low loss preserved with integration
Photonic Multi-Chip Module

4 Element Array

PIC Hybridization Submount

Silicon Nitride PIC on Silicon

14 Insert Slots

8mm

Input Facet with III-V SCOWA

312 mW at 2A SCOWA bias

InP SCOWA Insert Devices


**SCOWA:** Slab-coupled optical waveguide amplifier

**SCOWECL:** Slab-coupled optical waveguide external-cavity laser

**SMSR:** Side-mode suppression ratio

Presentation Name - 29
Author Initials MM/DD/YY
Thin-Film Lithium Niobate Integrated with SiN PICs

Heterogeneous LiNbO$_3$-$\text{Si}_3\text{N}_4$ waveguide

TE fundamental mode

$\lambda = 1550$ nm  
$n_{\text{eff}} = 1.6644$  
$n_g = 1.9242$

Extracted Loss:  
$\sim 0.44$ dB/cm

Al$_2$O$_3$ based ALD bond demonstrates one of the lowest measured losses in LN-SiN ring resonators

S. Ghosh, S. Yegnanarayan (MIT-LL)
Silicon Photonics Platform Module

Selected Components

Germanium Photodetectors
- Responsivity = 0.8 A/W, Dark current = 6 nA
- BW > 15 GHz

High-Speed Modulators
- $V_{\pi}L = 1$ V-cm
- BW > 15 GHz

Narrow Band Optical Filters
- Loss << 1 dB
- Extinction > 20 dB
- BW ~ 1.2 GHz

Waveguide Crossings
- Loss < 0.05 dB
- Cross-talk < -50 dB

- And many others…

• Process information:
  - Good performance, waveguide loss ~ 1 dB
  - New Ge reactor will allow for trusted processes
  - Cadence based process design kit
  - Preliminary work on integration with CMOS, III-Vs, and SiN
    • No increase in loss with Si-SiN integration

C. Sorace-Agaskar et al. (MIT-LL)
Heteroepitaxial III-V/SiN Integrated Photonics (HIP)

**Objective:** Realize SiN waveguide-coupled III-V devices (e.g., modulators, photodiodes, opt. amplifiers)

**Status:**
- Demonstrated growth of GaAs/AlGaAs on silicon substrates with flush interface to SiO$_2$ facets
- Threading dislocation density of $4 \times 10^6$ cm$^{-2}$ for GaAs/AlGaAs heterostructures grown selectively on Si, sufficient for high-performance optoelectronic devices
- Demonstrated efficient optical coupling between heteroepitaxial III-V and SiN waveguides

Heidelberger, Sorace-Agaskar (MIT-LL); Lee (UIUC)
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Integrated Electrode Control

- Ion movement brought about by dynamically varying electrode voltages (+/-8 V range)
- DACs integrated in CMOS
  - Low voltage CMOS for DAC
    - Compact, best technology nodes
  - High voltage CMOS amplifier
    - Larger, physically buffered circuits
- In-house design; foundry fabrication for proof-of-principle demos

DAC: Digital-to-analog converter
• Linear surface-electrode trap chip (~2mm x 3mm) with 16 DACs integrated under trap electrodes
  – Inputs are for SPI bus and for power ($V_{dd}$, $V_{ss}$, etc.)
• Only serial digital inputs need updating to transport ions
Ion Motion Using On-Chip Electronics

Three serial lines control 16 electrodes

Movie: Ion movement using integrated DAC control

Demonstrated trapping and moving of ions using integrated electronics

• Average motional state of the ion, $\overline{n}$, is directly sensitive to voltage noise on trap electrodes

$$\overline{n} = \frac{q^2}{4m\hbar\omega_t} \frac{S_V(\omega_t)}{D_{eff}^2}$$

• Idea: use an analog switch between the amplifiers and the electrodes to isolate the ion from voltage noise
  – Electrode-isolation switch (EIS)
  – Since electrode is primarily a capacitive load, voltage will be maintained for reasonable times
  – Electronic noise can be greatly reduced in this configuration

• Electrode-isolation switch (EIS) on each channel uses FETs to create large open-state resistance between DAC and electrode
  – Measured noise spectrum of DACs on bench
  – Verified level by measuring ion heating rate (proxy for electric-field noise)
  – Heating consistent with direct measurement (for ~50K chip temperature)
Avalanche Photodiodes for Readout

- On-chip Geiger-mode avalanche photodiodes (APDs) for ion state readout
  - Replace external high-NA lens and photomultiplier tube (optics free)
- Trap-integrated APDs tested on the bench (room temp.)
  - Preliminary external detection efficiency: ~25% near 422nm
  - DCR a few kHz
  - Minimal interference from application of trapping-level RF
- Currently testing with ions

Recent designs: Ryu, Donlon, Aull et al., unpublished (2021)
3D Integration of Optics and Control Electronics into Trap Chips

- **Top substrate**
  1. Qubit layer
     - Ions
     - Electrodes
  2. Optical control layer
     - Waveguides
     - Grating couplers
     - Potential modulators
  3. Readout/transfer layer
     - APDs with grid/ITO
     - Substrate with TSVs

- **Bottom substrate**
  - Electronic control layer
    - CMOS, wiring, etc.

- **Materials that allow for 3D integration are likely required**

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ITO: Indium tin oxide
TSV: Through-substrate via

Lincoln Laboratory
Massachusetts Institute of Technology
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Integrated Electronics/Photonics for Sensor Platform

- Collaboration to develop portable optical clocks: ion arrays with integrated electronics
  - (Photonics integration along parallel path)
  - Electronics used to update trapping potentials to reduce systematic frequency uncertainties
  - Also to bias and read out integrated APDs
  - Sensor application: target room temperature

- Address power, speed, noise – tradeoff as required
  - More bits or DAC precision may be necessary

- On-chip programming based on measurements

- For QC, CMOS can be optimized for cryogenic operation
  - Design and fab must be altered
Integrated Collection for Remote Entanglement Generation

- Integrated collection optics
  - Collection grating to optimize light gathering of ion spontaneous emission
  - Based on emitting grating couplers, but tailored for a very different mode
  - REG on-chip; ions trapped separately; multiplex multiple ion sites to enhance speed

- Working with Duke/SNL toward Ba\(^+\) ion wavelength for on-chip collection (QSA)
- Also looking at Sr\(^+\) with UIUC (HQAN)
- Such collection could also allow waveguide coupling to detectors for state readout

Options: Polarization or time-bin based entanglement
• Ca\(^+\) is a great candidate for helper ion for a Mg\(^+\) sensing/logic ion
  – Low, closely matched mass; good state detection; nice wavelengths
  – Mg\(^+\) free from resonant optical fields
• Integrated optical elements for Ca\(^+\) control
• Trap-integration of current carrying leads
• Gates using magnetic field gradients can avoid spontaneous emission
  – Precise RF electronics rather than lasers
• Detectors can be integrated for robust control with no free space optics

“All-Electronic Ion Qubit” concept incorporates multiple techniques and the integration of several technologies

Integrated photo-detector: Todaro et al., PRL 126, 010501 (2021)
MIT-LL (and MIT) Ion Team

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