Quantum Memories in Photon-Atomic-Solid State Systems (QuMPASS)
July 25, 2013

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University of Iowa

Spin physics
Coherent dynamics

Atomic physics
Quantum optics

Nanofabrication

Optical networks

Quantum control

Electronic structure
MURI Concept & Approach
Integration of atomic and solid state systems

**Scientific Goals for a Hybrid Quantum Memory System**

- Quantum memories that efficiently couple and store quantum states of light in material systems consisting of ensembles of cold atoms and/or diamond/SiC color centers

- "Chip" quantum connectivity for the quantum memories provided by photons over integrated optical networks

- Single photon frequency conversion for interfacing atom and color center quantum elements.

- Fundamentally new toolkit for studying atomic physics with light.

- Chip-scale atom trapping
- Single photon frequency conversion
- Mitigate decoherence
- Tune spin-photon coupling
- Integrate single spins "on demand"
- Fabricate high-Q diamond & SiC cavities
## Cast of Characters

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<th>Institution</th>
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<th>GS</th>
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<tr>
<td><strong>UC-Santa Barbara</strong></td>
<td><strong>David Awschalom</strong></td>
<td>Professor of Physics. Expertise: spin dynamics and coherence in semiconductor quantum structures, nanophotonics and magnetics, solid state quantum information processing. Member NAS, NAE.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td><strong>Ania Jayich</strong></td>
<td>Asst. professor of Physics. Expertise: nanoscale imaging of spin and charge, quantum computing, nanofabricating hybrid quantum systems of spins, phonons, photons. PECASE, AFOSR YIA</td>
<td>1</td>
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<tr>
<td><strong>Caltech</strong></td>
<td><strong>H. Jeff Kimble</strong></td>
<td>Professor of Physics. Expertise: quantum information, quantum dynamics of open systems, quantum measurement, cavity QED, realization of quantum networks. Member NAS.</td>
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<tr>
<td></td>
<td><strong>Oskar Painter</strong></td>
<td>Professor of Applied Physics. Expertise: nanofabrication, semiconductor cavity QED, cavity optomechanics, integrated atomic and photonic systems at the nanoscale.</td>
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<tr>
<td>Ames Lab/Iowa State</td>
<td>Scientist I. Expertise: Quantum non-equilibrium dynamics and decoherence in many-spin systems, quantum control of electronic and nuclear spins in solids, spins in semiconductors, spin impurities in diamond and silicon.</td>
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</tr>
<tr>
<td>University of Iowa</td>
<td>Professor of Physics. Expertise: spin dynamics in semiconductors and metals, carrier dynamics in narrow-gap semiconductor superlattices, single-dopant properties in semiconductors, solid state quantum quantum computation. Fellow AAAS, APS.</td>
<td>0</td>
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Student and faculty exchanges occurring across all institutions: **TOTAL 9 19**
Engineering shallow spins with N delta-doping

- $^{15}$N delta-doped layer (1-2 nm thick) defines depth of NV
- Doped NV has nm-scale depth dispersion ($\sigma < 4$ nm), isotopic control

Long and reproducible spin coherence
$T_2 > 100 \mu s$ $d = 5$ nm, $> 800 \mu s$ 50 nm

Single electron (proton) spin coupling possible by 1 sec (1 min) averaging

Fabrication of high quality single crystal diamond films ~ 100 nm thick as building blocks for optical cavities with delta-doping

Formation of optically-isolated photonic cavities

- Stamp onto PMMA and subsequent removal of PMMA to form undercut cavities.

Doped diamond membranes: mapping and single spin design

Diamond thin film photonics

High Q’s with the possibility of deterministic coupling

Cavity Q ~ 3,000 and V ~ 0.46 (\(\lambda/n\))^3 at 637.6 nm was observed

Cavity Q ~ 14,000!
Magnetic dipole coupling between inequivalent spins are observed
Interacting yet separately addressable quantum states
Coherent and incoherent interaction components are distinguished.

SiC thin film photonics

SiC microdisk $Q > 9200$ (our instrumental resolution)

High $Q$ derived from selective wet chemical etch on an all-SiC substrate

Dry etch procedures for high resolution SiC structures established
Novel spin centers in diamond

Are there other centers for improved spin manipulation or memory?

- Use spin-orbit interaction for spin manipulation with electric fields

- Internal degrees of freedom more isolated from the lattice (d levels)

- Strong possibilities for photon-spin entanglement through Faraday rotation

Calculation of the wave function of the spin centers – more spread out than DFT suggests…

More spread than NV  More localized than NV

Full photonic control of a single spin

- coherent all-optical control of individual electron spins
- borrow atomic physics technique: use lambda system dynamics
- coherent population trapping with spins
- applicable to many defects in semiconductors

Demonstrate set of control schemes along arbitrary bases:

**Initialization and Readout:**
Coherent Population Trapping

| 0_g ⟩
| +1_g ⟩

**Unitary Rotation:**
Stimulated Raman Transitions

| 0_g ⟩
| 1_g ⟩

Lambda system in NV center:

- Time-domain control of single spins via light
- Techniques enable investigation of new solid-state qubits

Quantum dynamics and coherence protection

- Model and optimize dynamics of spins and coupling to photons
- Exact simulations: time-dependent Schrodinger eqn (<30 spins, $10^9 \times 10^9$ Hilbert space)
- Approximate simulations – modeling < $10^4$ spins

Protected memory: isolate qubits

Protected quantum interface: isolate environment, preserve coupling between qubits

Quantum control

Using time-dependent magnetic field and/or optical pulses to ensure desired evolution of the system

de Lange et al., Science 330, 60 (2010)
Large area arrays of single crystal posts

- 300 nm diameter, 1 µm long single crystal diamond nanoposts
- 100 nm diameter, 1 µm long single crystal diamond nanoposts

Large-area arrays, high uniformity
Up to 3 microns long, 100 nm diameter

Part of a 3 mm X 3 mm patterned diamond

Probes with integrated spins for imaging hybrid structures
Single-crystal diamond cantilevers

Suspended cantilever

10 μm

High mechanical Q!

Ovartchaiyapong et al, APL 101, 163505 (2012)

Confocal image of cantilever

ESR spectrum of NV in cantilever

Overlaid image: confocal image of AFM tip over diamond NV’s

Combined AFM/confocal setup (Couple & scan NV centers on tip to PCs)

- Overlaid image: confocal image of AFM tip over diamond NV’s
- 532 nm laser
- AOM
- APD
- scanning mirror
- objective
- AFM tip
- Bulk diamond or nanocrystals

Fluorescence image of NV centers
Reflectance image of AFM tip

1 μm
Medium-scale decoherence-protected quantum registers

Apply resonant decoupling idea to:
• identify $^{13}$C nuclei, weakly coupled, suitable for quantum register
• perform individual electron-nuclear quantum gate on each pair,
• combine them to achieve fully operational register

Use nuclear spins as a local memory
• Identified six $^{13}$C nuclear spins, 0.5-1 nm from NV center, couplings 20-80 kHz
• Demonstrated robust e-n operations on independent addressed spin pairs

Atomic quantum memories in nanoscale optical circuits

- Develop the scientific and technical capabilities to achieve functional quantum memories that efficiently couple and store quantum states of light in ensembles of cold atoms, including reading and writing entanglement states of matter and light.

- We will accomplish these goals by way of efficient “on chip” quantum connectivity provided by photons over integrated optical networks.

Transition advances in quantum optics with atomic ensembles into the world of lithographically fabricated quantum optical circuits.

Fluorescent image from 4 atomic ensembles (quantum memories)
Globally store entangled state
Kimble group (2010)
1-D Nano-traps for quantum optical memories

Implementation of a nano-fiber optical trap

“Demonstration of a State-Insensitive Nano-fiber Trap”
[Accompanied Physics Synopsis section]

Optical depth = 66 ± 17
OD/atom ≈ 8%

Linewidth = 5.7 ± 0.1 MHz
Frequency shift < 0.5 MHz

Trap lifetime τ ≈ 15 ms
extended to τ ≈ 150 ms with PG cooling

Nano-fiber optical trap for ≈ 800 Cs atoms 200 nm from surface

Advancement of optical interfaces to/from quantum memories

Theoretical protocols for functional QM (i.e., quantum logic)


Design of atomic traps in 1-d photonic crystals
with strong single atom-photon interactions
Kimble – Painter groups
Atomic quantum memories in nanoscale optical circuits

• Develop the scientific and technical capabilities to achieve functional quantum memories that efficiently couple and store quantum states of light in ensembles of cold atoms, including reading and writing entanglement states of matter and light.

• Engineer efficient “on chip” quantum connectivity by photons over integrated optical networks.
Cold atom device loading - Kimble & Painter Groups

\( N_f \approx 10^7 \) Cs atoms at \( \rho \approx 10^{12}/\text{cm}^3 \)
\( T \approx 10\mu\text{K} \)

\( N_f \approx 5 \times 10^6 \) Cs atoms at \( \rho \approx 10^{11}/\text{cm}^3 \)
\( T \approx 20\mu\text{K} \)

SiN device - ~ 300nm x 200nm waveguide terminated by 1-d mirror

Optical fiber butt-coupled to SiN device

Evanescent atom-light coupling
Nano-Scale Quantum Optical Circuits with 1-D Photonic Crystals

**Dual beams:** 1-d photonic waveguides with conventional through holes
- Fabrication difficulties due to small hole sizes

**Band structure calculated from SEM measurements**
- Cesium D2 line at 852.3nm
- Cesium D1 line at 894.6nm

Band structure in good agreement with our reflection measurements using Mach-Zehnder interferometer (w/o atoms)

- This structure is currently in vacuum chamber
- Attempting to measure absorption of guided probe mode in dielectric band (near Cs D1 line) due to cold atoms near/within the photonic crystal waveguide
## Budget plan

### BASE PERIOD:

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Significant accomplishments to date

- Developed digital doping of spins in nanometer-scale diamond plane

- Demonstrated all-optical control of single spin quantum states along arbitrary bases

- Measured and manipulated spin states in polytypes of SiC

- Fabricated photonic cavity structures and spin coupling with diamond and SiC

- Designed and measured single crystal diamond cantilevers with spins

- Performed atom trapping along optical nanofibers in a state-insensitive optical trap

- Theoretically investigated atoms trapped along a nanoscopic optical waveguide

- Designed one-dimensional photonic crystals for strong 1D atom-photon interactions

- Substantial advances in solid state spin cavity fabrication
  photonic crystal cavities with $Q \sim 3,000$ and $V \sim 0.46 (\lambda/n)^3$
  suspended diamond micro-disk cavities with $Q > 10,000$
  SiC microdisks with $Q > 9000$