Leveraging Silicon Carbide Defects to Build Quantum Information Hardware

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Quantum information technologies

Quantum Internet

Quantum Simulation & Computing

Quantum Sensing


Solid state quantum emitters

**Quantum Dots**
- + bright, strong cavity coupling
  - - inhomogeneous

**Color Centers in Bulk**
- + homogeneous, long coherence
  - - weak cavity coupling

**Emitters in 2D Materials**
- + compact
  - - inhomogeneous, weak coupling
Color centers

Lattice point defects

Localized electronic orbitals

$V_{Si}^-$ in 4H-SiC

Quantum Technology Backbone

Quantum Internet
- Single-photon emission for QKD
- Indistinguishable photon emission for entanglement distribution
- Spin-photon entanglement and long spin coherence for quantum repeaters

Quantum Computing
- Cluster entangled state generation for the measurement-based quantum computing

Quantum Simulation
- Emitter-cavity systems simulating condensed matter physics

Quantum Sensing
- ODMR for magnetometry and thermometry

Passive photonics
- Nanopillars
- Waveguides

Active photonics
- Nanocavities
- Coupled cavity arrays
NIR emission
Majety et al., arXiv:2111.00136

Inversely designed devices
Lukin et al., Nature Photonics (2020)

Integration preserves properties
Integrated Quantum Photonics in Silicon Carbide

Hong-Ou-Mandel interferometer on chip

Coupled cavity arrays with color center ensembles

Emitter-cavity interaction

\[ \kappa = \frac{\omega}{Q} \]  
(cavity decay rate)

\[ g \sim \frac{1}{\sqrt{V}} \]  
(emitter-cavity coupling strength)

\[ \gamma \]  
(dipole decay rate)

Weak coupling regime: \( g < \frac{\kappa}{2} \)

Purcell enhancement of the emission rate

\[ F_P = \frac{3}{4\pi^2} \left( \frac{\lambda_c}{n} \right)^3 \left( \frac{Q}{V} \right) \]

ZPL enhancement

Strong coupling regime: \( g > \frac{\kappa}{2}, \frac{\gamma}{2} \)

nanocavities  
high Q factors  
emitter positioning

UC DAVIS  
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Polariton – hybridized light-matter state

\[ |\text{light}\rangle + e^{i\varphi} |\text{matter}\rangle \]
\[ \frac{\sqrt{2}}{2} \]

\[ g > \frac{\kappa \gamma}{2} \frac{\sqrt{N}}{2} \]

Jaynes-Cummings model

Tavis-Cummings model

\[ g \sqrt{N} > \frac{\kappa \gamma}{2} \frac{\sqrt{N}}{2} \]
\[ g \sqrt{N} \gtrsim \Delta \]

inhomogeneous broadening (mainly strain)

Jaynes-Cummings and Tavis-Cummings experiments

\[ N = 1 \text{ emitter in cavity} \quad N > 1 \text{ emitter in cavity} \]

Single atom

Quantum dot

Superconducting circuit

Rare-earth doped crystal

Active photonics in silicon carbide

6H-SiC, smart-cut

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3C-SiC on Si

4H-SiC, variable approaches

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*Photonic crystal cavities
SiC cavity fabrication

Photo-electro-chemical etching
demonstrated coherent control

SiC on insulator
record Purcell enhancement

Faraday cage etching
arbitrary samples, scalable

120x enhancement
Triangular SiC waveguides

Color centers in SiC triangular photonics

Stable optical emission and nearly-identical V2 emitters in triangular SiC waveguides
spin $T_2 = 0.84 \pm 0.01$ ms

Single-mode propagation

Collaboration with Astakhov, Son, Ul-Hassan, Kaiser, Wrachtrup groups
Efficient collection and detection of emission

Photonic crystal mirror

S. Majety, [M.R.] et al., arXiv:2208.05569
Superconducting detector integration

NbN SNSPD integration with 3C-SiC

NbTiN integration with 4H-SiC

Triangular SiC nanobeam cavities

\[ V \approx 2(\lambda/n)^3 \]
\[ Q \approx 10^7 \]
Design can be expanded into a large 1D coupled cavity array (CCA) with emitters

Applications of triangular SiC cavities

Quantum repeaters

Cluster entangled state generation

Quantum light generation

$N$ atoms in a cavity

$g_N = g\sqrt{N}$

$N$ atoms

$g_n = g$

$H_{TC} = \omega_c a^+ a + \sum_{n=1}^{N} [\omega_{e,n} \sigma_n^+ \sigma_n^- + g_n (\sigma_n^+ a + a^+ \sigma_n^-)]$

interaction strength increases with $\sqrt{N}$

subradiant state polariton

Tavis-Cummings model & inhomogeneous broadening

M.R., K. Fischer, J. Vuckovic, AAMOP Vol. 66 Ch. 3 (Elsevier, 2017)
Photon Blockade (PB) in multi-emitter-cavity systems

- Polaritonic PB
- Subradiant PB

$N = 1$  $N = 2$  $N = 2$

Excited atom time evolution in a lossy cavity

- $N = 11$ Tavis-Cummings model
  - More frequent Rabi oscillations
  - Excitation not fully lost to environment

- $N = 1$ Jaynes-Cummings model
  - Rabi oscillations
  - Excitation fully lost to environment
Open Quantum System Tavis-Cummings Dynamics

Exact approach

- Quantum Master Equation – *exponential* memory and runtime scaling
Atom / a two-level system / qubit

\[ c_1|100 \ldots 0\rangle + c_2|010 \ldots 0\rangle + c_3|001 \ldots 0\rangle + \cdots + c_N|000 \ldots 1\rangle \]

How do the atomic amplitudes evolve in a lossy cavity?

Collaboration with Marinkovic group
Quantum mapping of the Tavis-Cummings dynamics

Hamiltonian + interaction picture

Schrödinger equation + single excitation

System density matrix + quantum circuit mapping

Trace out the environment + Laplace transform

Collaboration with Marinkovic group
Quantum Mapping Algorithm of Resonator Interaction with $N$ Atoms (Q-MARINA)

Digital quantum modeling of an analog quantum system – time and space complexity $O(N)$

Tavis-Cummings time evolution for $N = 7$

QuTiP
(exact QME solution)

Q-MARINA Qiskit QASM
shots = 40,000

Matching oscillations and intensities

$\kappa = 5, g = 10$
Tavis-Cummings time evolution scaling

**exponential** QME runtime scaling

**linear** Q-MARINA runtime scaling

**exponential** QME memory scaling

**linear** Q-MARINA memory scaling

Q-MARINA tests on IBM Q hardware

\( N = 2, \kappa = 5, g = 10, \text{shots} = 10,000 \)

\( N = 3, \kappa = 5, g = 2, \text{shots} = 10,000 \)
NISQ-design of analog quantum photonic hardware

\[ q = \text{QuantumRegister}(16) \]
\[ qc = \text{QuantumCircuit}(q) \]
\[ \cdots \]
\[ \cdots \]
\[ \text{result} = \text{execute}(qc, \text{backend = backend, shots = 1024}); \text{result}() \]

\[ |\text{light}\rangle + e^{i\varphi} |\text{matter}\rangle \]
\[ \frac{1}{\sqrt{2}} \]

Photonic device
All-photonic quantum simulators

All-photonic quantum simulation
• Superfluid-Mott insulator transition
• Fractional Quantum Hall effect
• Localization effects

Localization vs. delocalization
Cavity-emitter interaction vs. cavity-cavity hopping

Coupled cavity arrays with multiple emitters

Modeled by the Tavis-Cummings-Hubbard Hamiltonian

\[ H_{TCH} = \sum_{i=1}^{n} \left\{ \Omega_i a_i^\dagger a_i + \sum_{j=1}^{N_i} \left[ \omega_{i,j} \sigma_{i,j}^+ \sigma_{i,j}^- + g_{i,j} \left( a_i^\dagger \sigma_{i,j}^- + \sigma_{i,j}^+ a_i \right) \right] \right\} - \sum_{i=1}^{n-1} J_{i,i+1} \left( a_i^\dagger a_{i+1} + a_{i+1}^\dagger a_i \right) \]

Localizing terms

Delocalizing terms
Spectrally disordered emitters in CCAs

Energy spectrum ($N=5, M=3$)

Collaboration with Scalettar group

Participation ratio metrics for wavefunctions

Nodal Participation Ratio $P_N$
Is the wavefunction delocalized across all nodes?

$$P_N = \left[ \sum_l^N \left( \langle N_{ph,l} \rangle + \langle N_{e,l} \rangle \right)^2 \right]^{-1}$$

Polaritonic Participation Ratio $P_P$
Is the wavefunction light-matter hybridized?

$$P_P = \left[ \left( \sum_l^N \langle N_{ph,l} \rangle \right)^2 + \left( \sum_l^N \langle N_{e,l} \rangle \right)^2 \right]^{-1}$$
Multi-emitter coupling vs. inhomogeneity

Metrics for $N=5$, $\Delta=\text{const}$

- More localizing
- More delocalizing

- Homogeneous
- Inhomogeneous

Light-matter interaction engineering
- Quantification of cavity QED effects
- Number of emitters needed to design a highly polaritonic state
- Parameters that optimize polaritonic character for a specific wavefunction
- Localizing vs. delocalizing configurations

Collaboration with Scalettar group
Summary: SiC Quantum Tech Backbone

- Quantum Sensing
- Quantum Internet
- Quantum Computing
- Quantum Simulation
Thank you!