

Engineering Quantum Systems: From Qubits and Networks to Hybrid Quantum Matter

Tian Zhong

Pritzker School of Molecular Engineering, University of Chicago IL USA

The ability to control individual quantum systems—spins, photons, and solids—has enabled new approaches to computing, communication, and sensing. Extending this control from individual qubits to quantum matter calls for engineering both the microscopic constituents of a material and the electromagnetic fields through which they interact. In this talk, I will describe our efforts to develop quantum systems from the bottom up, beginning with long-coherence rare-earth qubit and quantum memories and progressing toward photonic control of nonequilibrium electronic states. The connecting theme is the co-design of materials and their optical environment, using thin-film growth and device integration to create quantum functionality.

Our approach begins with bottom-up rare-earth quantum materials grown by molecular-beam epitaxy. By engineering the composition, crystalline environment, and interfaces, we seek to build the quantum coherence and optical interfaces required by quantum devices into the material itself. Telecom-wavelength erbium spin-photon interfaces combine long optical and spin coherence with compatibility with photonic and superconducting circuits, linking localized quantum degrees of freedom to photons that can propagate through optical fiber. I will discuss how epitaxial materials development and heterogeneous integration together provide a foundation for entangling spins to photons and, ultimately, optically interconnected quantum nodes. Building outward from these interfaces, we have also demonstrated a direct telecom quantum link between integrated entanglement source and erbium solid-state quantum memory, exploiting their intrinsic spectral matching without quantum frequency conversion. This connection illustrates how different quantum technologies can retain their individual strengths while communicating through native optical interfaces, and how materials and interface engineering can enable hybrid quantum networks.

We extend this approach to quantum matter by growing an ultrathin Bi_2Se_3 topological-insulator film directly on an on-chip silicon photonic-crystal cavity. This integration combines epitaxial growth and optical confinement while preserving access to time- and angle-resolved photoemission spectroscopy. Under resonant ultrafast excitation, we directly observe cavity-driven Floquet-Bloch sidebands with delayed buildup and a response prolonged beyond the incident pulse. The cavity thus controls both the spatial confinement and temporal evolution of the drive, establishing a platform for using engineered photonic environments to manipulate nonequilibrium electronic states.

These efforts share a common strategy: engineer quantum functionality from the material upward, and use innovations in heterogeneous integration to bring distinct quantum degrees of freedom into controlled interaction. This strategy enables a range of systems, from spin-photon interfaces and long-distance quantum networks to cavity-driven quantum matter. I will conclude with an outlook on how co-designing materials and photonic structures may expand this range toward hybrid quantum interconnects and new forms of hybrid quantum matter.

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