Correlated Structural and Optical Characterization of Hexagonal Boron Nitride

Hexagonal boron nitride (hBN) plays a central role in nanoelectronics and nanophotonics. Moreover, hBN hosts room-temperature quantum emitters and optically addressable spins, making the material promising for quantum sensing and photonics. Despite significant investigation of the optical and structural properties of hBN, the role of contamination at surfaces and interfaces remains unexplored. We prepare hBN samples that are compatible with confocal photoluminescence (PL) microscopy, transmission electron microscopy (TEM), and atomic-force microscopy (AFM), and we use those techniques to quantitatively investigate correlations between fluorescent emission, flake morphology, and surface residue. We find that the microscopy techniques themselves induce changes in hBN's optical activity and residue morphology: PL measurements induce photobleaching, whereas TEM measurements alter surface residue and emission characteristics. We also study the effects of common treatments—annealing and oxygen plasma cleaning—on the structure and optical activity of hBN. The methods can be broadly applied to study two-dimensional materials, and the results illustrate the importance of correlative studies to elucidate factors that influence hBN's structural and optical properties.

Pia Bhatia & Jordan Gusdorff

Graduate Students, University of Pennsylvania

A Machine Learning Approach to Real-Time Simulation of Quantum Dot Devices

Spin qubits in quantum dot devices offer significant advantages for scalable quantum computing. However, progress is currently hindered by the lack of accurate and high-performance simulation methods for real devices. Physics-based simulation methods, while precise, are often too slow for practical use, and qualitative models fail to capture the influence of physical gate layouts and wafer structures, making them inadequate for simulating real device behavior.

In this work, we introduce a new simulation approach capable of simulating real devices from the cold start with real-time performance. By leveraging a critical phenomenon identified in physics-based simulations, we train a convolutional neural network (CNN) to infer the qubit layer potential with high accuracy. Our GPU-accelerated CNN achieves over 1000× speedup in potential inference while maintaining an average accuracy of 96\% compared to the physical model.

Integrated into our experiment control stack, the simulator produces results with real-time-performance comparable to live measurements on real devices at 9mK. It accurately reproduces key tuning features. Important device quantities such as cross-capacitance and charging energy are comparable to those observed in real hardware.

Shize Che

Graduate Student, University of Pennsylvania

Engineering Optical Responses through Ultrafast Control of Subcycle Dynamics

Tailoring the properties of quantum materials on demand is a central goal of condensed matter physics. Over the past decade, Floquet engineering has emerged as a pathway to modulate a material's optical properties on ultrafast timescales through strong periodic driving. Much of this work has focused on how the energy levels of a system are shifted by this driving. However, a recent pump-probe experiment on Sr_2CuO_3 demonstrates that this framework must be expanded to explain how optical responses can be altered even when a system's energy levels remain unchanged. In this poster, we present a theoretical framework to understand these findings. Inspired by quantum control protocols, we show that the coherent control of a quantum state's subcycle dynamics leads to significant modifications of its optical response. To demonstrate this and connect to the experiment, we consider a strongly driven system consisting of a ground state and two degenerate excitonic states. We show that the reduction of third-order optical nonlinearity and the appearance of Floquet sidebands can be understood through the subcycle rotation of the excitonic states on the Bloch sphere.

Deven Carmichael

Graduate Student, University of Pennsylvania

Highly-crystalline HPHT ultrasmall nanodiamonds as platforms for NV centers

Nanodiamonds are a platform of growing interest for numerous quantum applications. The environment-sensitivity of the color centers that they host can be combined with the remarkable spatial resolution provided by their small sizes to push the boundaries of quantum sensing. We use a high-pressure high-temperature synthesis method from molecular precursors to produce nanodiamonds of controlled size ranging from 1 to 15 nm. The high crystallinity of the particles is established by transmission electron microscopy, Raman and X-ray absorption spectroscopy. The natural presence of nitrogen in these nanodiamonds allows the formation of nitrogen vacancies (NV) upon irradiation/annealing and oxidative treatment favors the formation of negatively charged NV centers suitable for optically detected magnetic resonance (ODMR). These measurements on our nanodiamonds show an electron spin coherence time in the µs range.

Gus Braun

Postdoctoral Researcher, Columbia University

Light-induced switching to a topological superconducting state

Topological superconductivity holds immense promise for quantum technology applications, hosting non-Abelian excitations that enable a platform for robustly storing and manipulating quantum information. Realizing this phase experimentally has long been a challenge, but in the meantime tremendous progress has been made in probing and controlling collective modes in superconductors using light. In this work, we propose a protocol whereby a conventional superconducting state may be "switched" via an ultrafast light pulse to a metastable topological superconducting phase [1]. We discuss general guiding principles for identifying a sub-gap collective mode corresponding to "p-wave" fluctuations in an "s-wave" superconductor, and highlight an intriguing component to the key coupling parameter that is dominated by the quantum geometry of the Bloch wavefunctions near the Fermi surface. Our scheme is broadly applicable to centrosymmetric superconductors with strong spin-orbit coupling, and is in a frequency range accessible by current terahertz spectroscopy experiments.

[1] Gassner, S., Weber, C. S., and Claassen, M. Light-induced switching between singlet and triplet superconducting states. Nat. Commun. 15, 1776 (2024).

Steven Gassner
Graduate Student, University of Pennsylvania

Controlling incorporation site formation of rare-earth ions through delta doping

Europium-doped gallium nitride (GaN:Eu) is a promising platform for classical and quantum applications. When grown using organometallic vapor-phase epitaxy (OMVPE), the dominant red emission from Eu exhibits an inhomogeneous photoluminescence (PL) spectrum due to contributions from several non-equivalent incorporation sites (named OMVPE 1-8) that can be distinguished with excitation-emission spectroscopy. Energy transfer from the GaN bandgap to the majority site, OMVPE4, is inefficient, limiting the performance of GaN:Eu LEDs. In this work, we perform site-selective spectroscopy to characterize the photoluminescence properties of delta-doped multilayered structures with varying layer thicknesses and demonstrate that they selectively enhance this majority site when compared to uniformly-doped samples. By changing the thicknesses of the undoped and doped layers, we demonstrate devices highly suitable for very different applications. Two delta-doped samples achieve much greater PL intensity per nm of doped Eu than a uniformly-doped sample, which is highly desirable for creating power-efficient LEDs. Another delta-doped sample contains a single optically detectable Eu incorporation site, resulting in a narrow, homogeneous emission spectrum that is necessary for quantum technologies such as quantum memories. This application of delta-doping has the potential to be a broadly applicable technique for engineering desirable defect properties in rare-earth doped semiconductors.

Amelia Klein
Graduate Student, University of Pennsylvania

Investigating Electron-Nuclear Entanglement Among Spins in InGaAs Quantum Dots

Quantum applications (sensing, quantum networks, etc) of solid-state spin-photon interfaces such as quantum dots (QDs) and color centers require coherent control of the electron-nuclear spin interactions. We show how to design high-fidelity quantum gates and achieve dynamic nuclear polarization through a general, practical framework for analyzing electron-nuclear entanglement. We apply our methods to InGaAs QDs and show how to control nuclear spins and their entanglement in experimentally relevant parameter regimes.

Isabela Gnasso
Graduate Student, Virginia Tech

Frequency and Q Factor Tunable Microwave Resonator for Spin Qubits

Spin qubits in semiconductors, which have demonstrated long coherence times and are compatible with existing semiconductor fabrication infrastructure, are among the most promising hardware systems for quantum computing. In recent years, it has been shown that these spin qubits can be coupled to photons in superconducting microwave resonators. This coupling mechanism allows for fast control, high-fidelity readout, and long-distance connectivity. Here, we present a novel microwave resonator design, which is able to be frequency and Q factor tuned in situ, offering broad functionality in the context of spin-photon coupling operations. We demonstrate frequency tunability from 10.35GHz up to 10.426 GHz, and Q tuning from 1000 to approximately 5000. Further, we show that the resonator is able to be orthogonally controlled along either axis.

Jonathan Hess
Graduate Student, University of Pennsylvania

Geometric approach to stabilizer state decompositions

An approach taken by many to improve classical simulations of quantum computation is to build upon the Gottesman-Knill theorem, which states that a restricted class of operators acting on the so-called stabilizer states are efficiently classically simulatable, which has given rise to numerous methods to assist in universal computation. We present a preliminary technique for decomposing arbitrary state vectors into approximate low-rank superpositions of stabilizer states, which is useful for example with quantum frame-based computational methods. Our technique utilizes algorithms from signal processing theory, for which we obtain error bounds using the geometry of stabilizer states and results about high-dimensional sphere packings, presented alongside geometric motivation.

Daley McMahon
Graduate Student, University of Pennsylvania

Single Gate Multipartite Entanglement of Diamond Quantum Register

Multipartite entanglement is an essential aspect of quantum systems to achieve complex algorithms, error correction and enhanced sensing. In defect solid state systems, such Nitrogen-Vacancy (NV) centers in diamond, multipartite entangled states have only been created through long, sequential dynamical decoupling control sequences. In addition to being time consuming, each 2-qubit gate induces considerable cross talk on all other qubits. Here, we showcase the first parallelized entangling gate by first using it to create a 4-way GHZ state in only 14.8μs. We then efficiently examine the multi-qubit gate fidelity independent of state preparation and measurement errors to show an improved gate fidelity of 0.91 compared to sequential 2-qubit gates that showed a fidelity of only 0.73. This achievement lays the foundation for achieving scalable entanglement generation in defect solid state systems.

Joseph Minnella
Graduate Student, University of Pennsylvania

Room-temperature quantum emission from Cu_Zn-V_S defects in ZnS:Cu colloidal nanocrystals

We report room-temperature observations of CuZn-VS quantum emitters in individual ZnS:Cu nanocrystals (NCs). Using time-gated imaging, we isolate the distinct, ~3-μs-long, red photoluminescence (PL) emission of CuZn-VS defects, enabling their precise identification and statistical characterization. The emitters exhibit distinct blinking and photon antibunching, consistent with individual NCs containing two to four CuZn-VS defects. The quantum emitters' PL spectra show a pronounced blue shift compared to NC dispersions, likely due to photochemical and charging effects. Emission polarization measurements of quantum emitters are consistent with a σ-character optical dipole transition and the symmetry of the CuZn-VS defect. These observations motivate further investigation of CuZn-VS defects in ZnS NCs for use in quantum technologies.

Yossi Panfil
Postdoctoral Researcher, University of Pennsylvania

BARQ: An automated robust quantum control design method

Noise and decoherence constitute two of the main obstacles that prohibit quantum computers from beating classical computation for applications of practical interest. Along with improvements in quantum hardware, finding smart control schemes that suppress noise is a necessity to mitigate such a problem and enable both near-term and fault-tolerant quantum computation. All existing methods share the commonly accepted tradeoff that the target gate cannot be independently fixed when additional pulse characteristics are sought during optimization. In this poster, I will present a systematic method that by-design eliminates such a tradeoff. By using the recently developed Space Curve Quantum Control formalism in which quantum evolution is mapped to geometric space curves, we sidestep the solution of the Schrödinger equation and turn our attention to optimizing various 3D shapes. Utilizing a special class of curves defined through a set of control points, we propose the Bézier Ansatz for Robust Quantum (BARQ) control method. In BARQ, some control points are used to fix any desired gate with unit fidelity while the positions of the rest are numerically optimized only for pulse features. The method does not require any hardware-specific information and is readily available through the developed Python package qurveros.

Evangelos Piliouras
Graduate Student, Virginia Tech

Scalable microwave modulation at cryogenic temperatures for qubit control using high-kinetic-inductance superconductors

M. Pushp, N. D. Johnson, Bo Zhen, A. J. Sigillito

Most quantum computing architectures rely on microwave pulses to manipulate qubits. However, when scaling systems to very large numbers of qubits, delivering vector-modulated microwave signals to cryogenic environments can be a challenge, especially in dilution refrigerators where cooling power is limited to microwatts. On-chip generation of the qubit control signals can help to reduce cabling overheads and enable scalability. High kinetic inductance superconducting materials, owing to their low loss and tunable inductance serve as a potential candidate for on-chip modulation of microwave signals in dilution refrigerators. Here, we report on continued efforts to develop a multi-channel cryogenic qubit control architecture that can address multiple qubits while only utilizing only a single local oscillator.

[1] Annunziata et al., Nanotechnology 21, 445202(2010)
[2] Jonas Zmuidzinas, Annual Review of Condensed Matter Physics 3, 169 (2012)

Mridul Pushp
Graduate Student, University of Pennsylvania

Towards excited state control and readout of quantum dot spin qubits via THz radiation

Semiconductor spin qubits are a leading quantum computing technology with single and two-qubit gate fidelities exceeding the fault-tolerant threshold [1-3]. However, extending proof-of-principle devices to large scale quantum processors will likely require new approaches to control and readout. Here, we propose the use of spin-selective orbital transitions driven by coherent terahertz radiation to enable new approaches to both quantum control and readout. In this poster, we describe our experiment setup, which includes an optical dilution refrigerator equipped with a THz source. We will outline the physical mechanisms for control and readout and share preliminary data.

[1] Xue et al., Nature. 601, 343 (2022)
[2] Noiri et al., Nature. 601, 338 (2022)
[3] Mills et al., Sci. Adv. 8, eabn5130 (2022)

Seong Woo Oh
Postdoctoral Researcher, University of Pennsylvania

Shuttling electrons between Si/SiGe quantum dots using resistive top gate

Semiconductor quantum dot qubits have reached the error threshold regime, yet many scaling challenges remain. To support the network topologies needed for quantum error correction coherent transport of spin qubits between quantum processing regions is required. Spin qubit shuttling schemes demonstrated to date rely on patterned interdigitated gates across the length of the shuttle lowering fabrication yield. We present a novel device which could simplify the structure needed to achieve coherent qubit shuttling. Two double quantum dots (DQD) with accompanying sensor dots are connected by a ~12 μm Niobium silicon (NbSi) top gate, a material chosen for its high resistivity at millikelvin temperatures. The NbSi top gate connecting the DQDs creates a channel which can store charge, and be emptied of charge allowing a path for single electrons to travel. The large resistivity allows for a potential difference to be established imparting a force on single charges while adding minimally to the heat load. In theory nanosecond scale transit times can be achieved. Two designs are discussed and initial data is presented about the behavior of the device.

Robert Spivey
Postdoctoral Researcher, University of Pennsylvania

Single Photon Generation from Cavity Higgs Polaritons

Single photon generation is a key step in enabling optical quantum computing. Current single photon emitters are almost exclusively characterized by a geometry of localized quantum dots/atoms, where efficiency plummets when emitters couple to one another. In contrast to this conventional picture we leverage quantum coherence of a collective order parameter to theoretically demonstrate high efficiency single photon emission by an extended material. The platform is a superconductor described by a Ginzburg-Landau order parameter embedded in a terahertz cavity coupled to light via minimal substitution for spatial gradients. We rigorously compute the normalized two photon coherence function at coincidence and find that it can approach zero in high quality factor cavities corresponding to single photon emission.

Spenser Talkington
Graduate Student, University of Pennsylvania

QTurbo: A Robust and Efficient Compiler for Analog Quantum Simulation

Analog quantum simulation leverages native hardware dynamics to emulate complex quantum systems with great efficiency by bypassing the quantum circuit abstraction. However, conventional compilation methods for analog simulators are typically labor-intensive, prone to errors, and computationally demanding. This paper introduces QTurbo, a powerful analog quantum simulation compiler designed to significantly enhance compilation efficiency and optimize hardware execution time. By generating precise and noiseresilient pulse schedules, our approach ensures greater accuracy and reliability, outperforming the existing state-of-the art approach.

Junyu Zhou
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