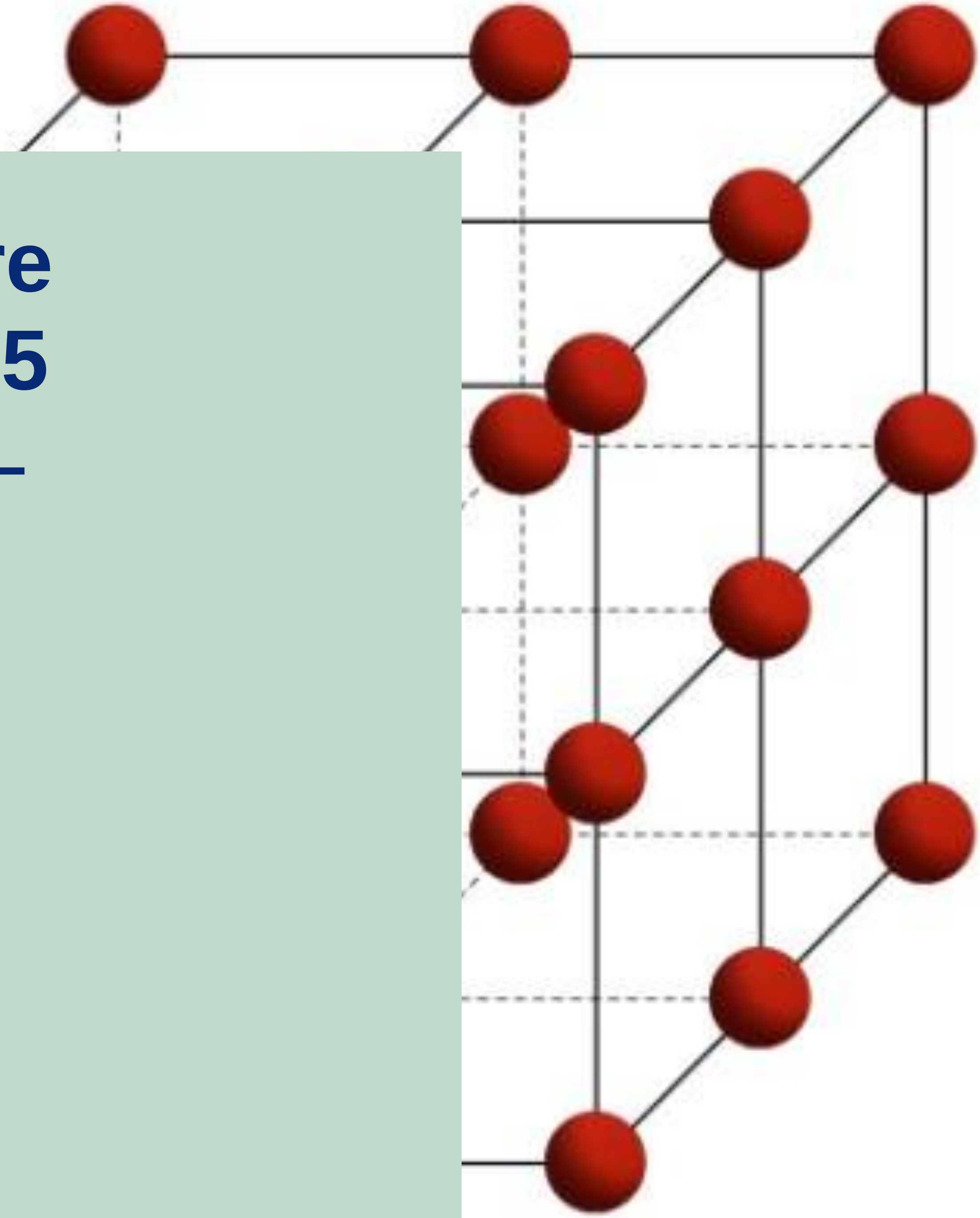


Centre 2024-5

AUGUST 6

Centre for Physics of Materials
Tami Pereg-Barnea and Bradly Siwick

INTRODUCTION

The development of new materials and new technologies is dependent on our understanding of the laws of physics which govern the behavior of large numbers of particles held together by their mutual interactions. We therefore study the fundamental properties of materials by subjecting them to various external perturbations (or probes) and piecing together the measured properties into a story (a theory). The emergent picture allows us to relate material and device properties to the fundamental building blocks of the system. This not only enhances our understanding of many-body physics but also allows better control of material development.

The CPM is living up to its mission to be a focal point for McGill researchers working on the development of new materials and the study of their physics. This year CPM researchers uncovered new phenomena and behaviour of materials, some of which are highlighted in this annual report. Dimond NV centers are studied as qubits in the Childress lab, while Coish's group proposes how to quantum-enhance interferometry. The Gervais lab is finding unusual Hall properties in bismuth and in the Grutter lab 2D materials host localized states. In Guo's group a new generation of microelectronics is simulated and the Provatas group studies cooling of liquids. In the Pereg-Barnea group long-range entanglement in quantum circuit was found and in Sankey's lab extreme tunning of a mechanical mode was made. This was a very productive year all round!

On top of research in individual groups the CPM has helped to connect its researchers through common activities and shared facilities. Our weekly seminars, workshop and conferences are educating our HQP and connecting our community.

Members

Principal Investigators

Chris Barret (Chemistry)
Kirk Bevan (Materials Engineering)
Lilian Childress (Physics)
Richard Chormik (Materials Engineering)
William Coish (Physics)
David Cooke (Physics)
Paul Francois (Physics, UMontreal)
Guillaume Gervais (Physics)
Martin Grant (Physics)
Peter Grütter (Physics)
Hong Guo (Physics)
Michael Hilke (Physics)
Patanjali Kambhampati (Chemistry)
Anne-Marie Kietzig (Chemical Engineering)
Bruce Lennox (Chemistry)
Eric McCalla (Chemistry)
Tami Pereg-Barnea (Physics)
Nikolas Provatas (Physics)
Walter Reisner (Physics)
David Ronis (Chemistry)
Dominic Ryan (Physics)
Jack Sankey (Physics)
Lena Simine (Chemistry)
Brad Siwick (Physics and Chemistry)
Mark Sutton (Physics)
Thomas Szkopek (Electrical Engineering)
Paul Wiseman (Physics and Chemistry)
Songrui Zhao (Electrical Engineering)

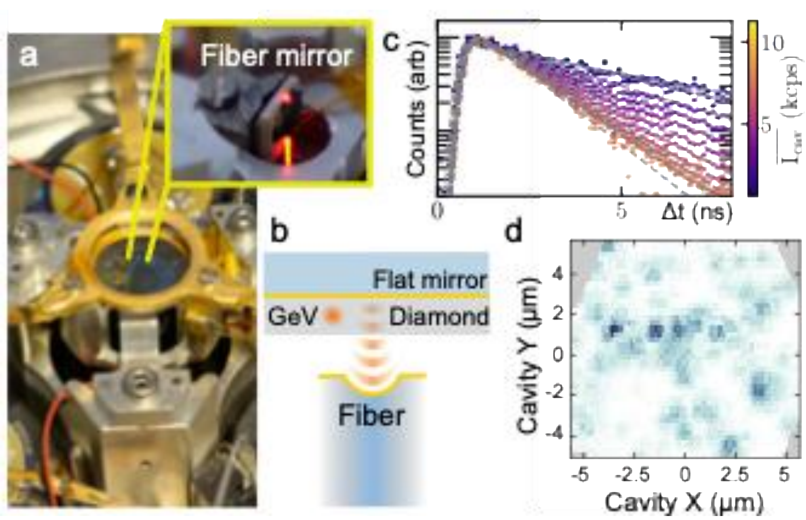
Staff

Robert Gagnon
Juan Gallego
John Smeros
Richard Talbot

Research Highlights

Childress

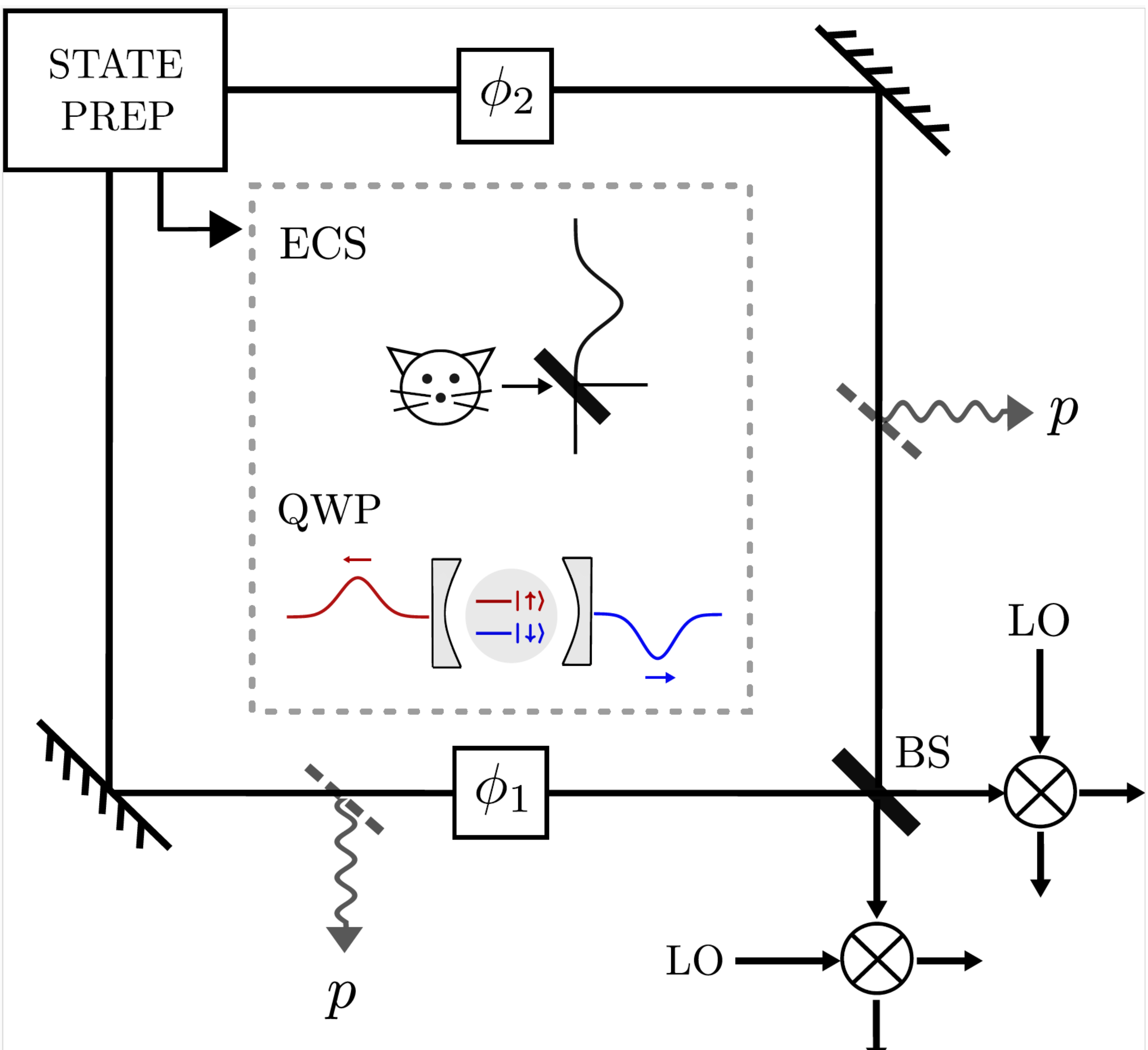
Cavity QED systems that strongly couple an atomic-like system to photons are a key building block for quantum networks, providing a critical mechanism for efficient transduction of quantum information between one or more long-lived qubits. One approach utilizes atomic-like defects in diamond as material qubits, and encloses them within an open-geometry Fabry-Perot microcavity. Such systems permit the selection of defects with favorable properties and *in situ* optimization of defect-cavity overlap, and function with minimally fabricated diamond membranes that preserve the defect optical coherence. In 2024, our group demonstrated Purcell-enhanced emission from single GeVs in diamond at cryogenic temperatures using a scanning fiber-based optical microcavity, observing lifetime reduction factors up to 4.5 and demonstrating a cavity-coupling rate exceeding 300 MHz with a clear path towards cooperativity > 1. We showed out the narrow cavity linewidth can be exploited for defect spectroscopy, observing large orbital strain splittings that bode well for GeV spin coherence. Our results also indicate a substantial quantum efficiency for GeV defects, highlighting their favorable properties for quantum networking applications.



(a) Cryogenic FFPC showing flat mirror and fiber mirror (inset). (b) Schematic of (a). (c) GeV lifetime varies by >4x on (orange) and off (blue) cavity resonance. (d) Cavity-coupled GeV fluorescence (arb. units) as the cavity mode scans over the diamond.

Coish

Highlighted here is the work published as Z M McIntyre and W A Coish, Phys. Rev. A 110, L010602 (2024). In this work, the authors proposed a phase-sensitive (homodyne) detection scheme to perform quantum-enhanced precision interferometry and showed that this method is optimal for class of quantum states known as path-entangled coherent states. This is notable because homodyne measurements do not require elaborate photon counting schemes, and the resulting sensitivity is independent of the value of the phase shift itself, meaning that the resulting measurement schemes can be implemented non-adaptively.



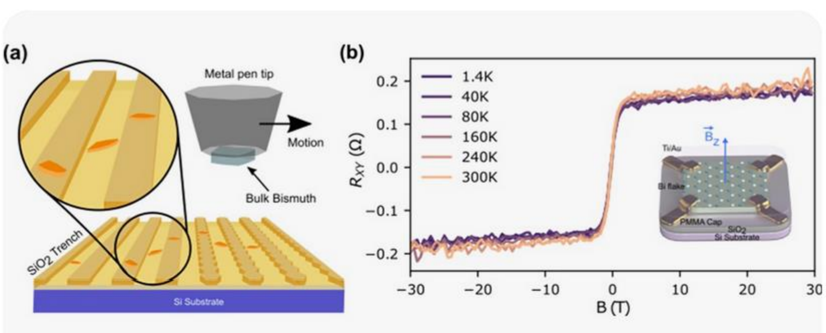
Gervais

Gervais lab found unexpected promise for green electronics in flakes of bismuth revealed by a temperature independent Anomalous Hall effect. The work is published in Physical Review Letters:

[*Observation of Temperature Independent Anomalous Hall Effect in Thin Bismuth from Near Absolute Zero to 300 K Temperature*]

Oulin Yu, F. Boivin, A. Silberztein and G. Gervais, Phys. Rev. Lett. 134, 066603 (2025).

Ultra-thin bismuth holds unexpected promise for green electronics: researcher
mcgill.ca



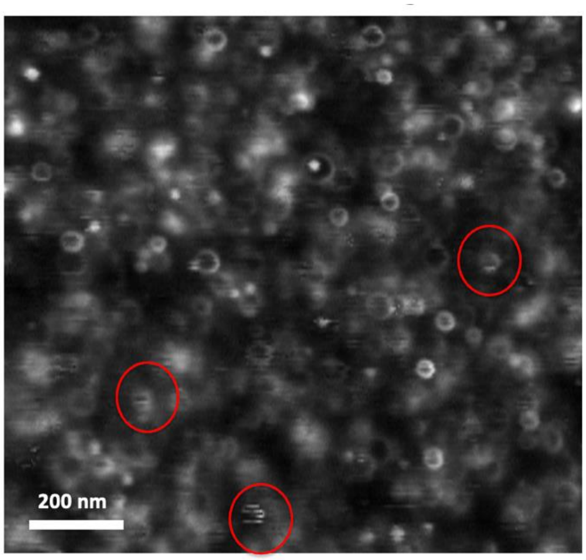
Bismuth Breaks the Rules: Mysterious Magnetic Effect Stays Unchanged Across Extreme Temperatures - MagLab
nationalmaglab.org

Grutter

Semiconductor interfaces often have isolated trap states which modify electronic properties. We have developed a framework to quantitatively describe a metal-insulator semiconductor (MIS) device formed out of a metallic AFM tip, vacuum gap, and semiconducting sample. This framework allows the measurement of local dopant concentration, bandgap and band bending timescales with nm scale resolution of different types of defects on semiconductors such as Si, 2D $MoSe_2$ and pentacene monolayers [1].

In 2024, we have characterize individual defects at the Si-SiOx interface using this method. We show that surface charge equilibration timescales, which range from 1–150 ns, increase significantly around interfacial states [2]. We conclude that dielectric loss under time-varying gate biases at MHz and sub-MHz frequencies in metal-insulator-semiconductor capacitor device architectures is highly spatially heterogeneous over nm length scales. We have also analyzed two-state fluctuations localized at these interfacial traps, exhibiting bias-dependent rates and amplitudes. We learn from this that these traps modify both the carrier density as well as scattering cross section. When measured as an ensemble, these observed defects have a 1/f power spectral trend at low frequencies [3]. Low-frequency noise due to two level fluctuations inhibits the reliability and performance of nanoscale semiconductor devices, and challenges the scaling of emerging spin based quantum sensors and computers. The presented method and insights provide a more detailed understanding of the origins of 1/f noise in silicon-based classical and quantum devices, and could be used to develop processing techniques to reduce two-state fluctuations associated with defects.

References:
[1] M. Cowie, et al., Phys. Rev. Materials **6**, 104002 (2022)
[2] M. Cowie, et al., Phys. Rev. Lett. **132**, 256202 (2024)
[3] M. Cowie, et al., Proc. Natl. Acad. Sci. USA **121** (44) e2404456121 (2024)



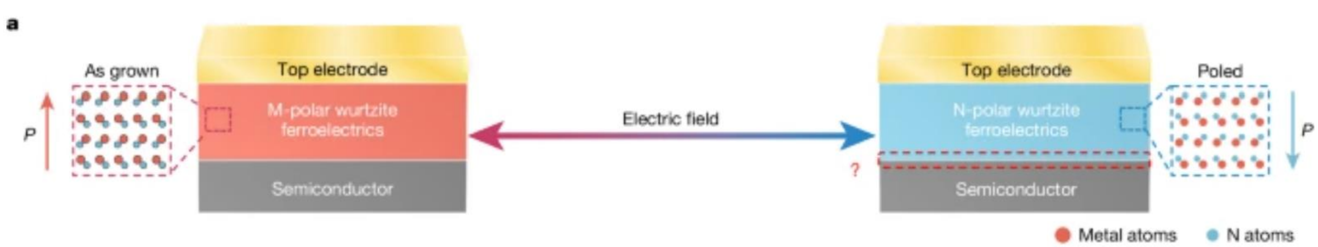
Each ring in this electrostatic force microscope image is defect at the Si-SiO2 interface.

Notice the ‘striped’, noisy defects (three examples circled in red). These are two-state fluctuations localized at these interfacial traps. This is the first time ever that a specific trap at the Si-SiOx interface has been characterized with spatial resolution.

Guo

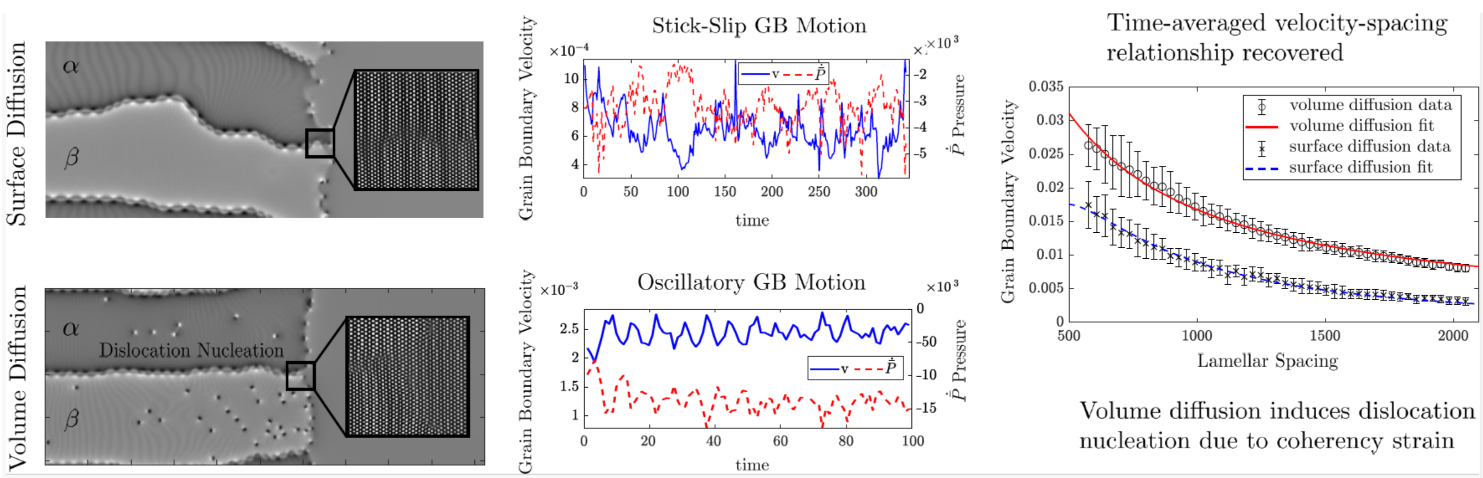
Wurtzite ferroelectrics have transformative potential for next-generation microelectronics. A comprehensive understanding of their ferroelectric properties and domain energetics is crucial for tailoring their ferroelectric characteristics and exploiting their functional properties in practical devices. We have been involved in a collaboration with experimental groups to determine the exact configurations and electronic structures of domain walls in wurtzite ferroelectrics. By both DFT calculations and experimental measurements, we explained the atomic configurations and electronic properties of electric-field-induced domain walls in ferroelectric ScGaN. A charged domain wall with a buckled two-dimensional hexagonal phase is revealed. The findings showcase the potential for ultrascaled device applications, and published in the journal Nature (**https://doi.org/10.1038/s41586-025-08812-7**)

Fig. 1: Atomic-scale evidence of polarity switching in ScGaN.



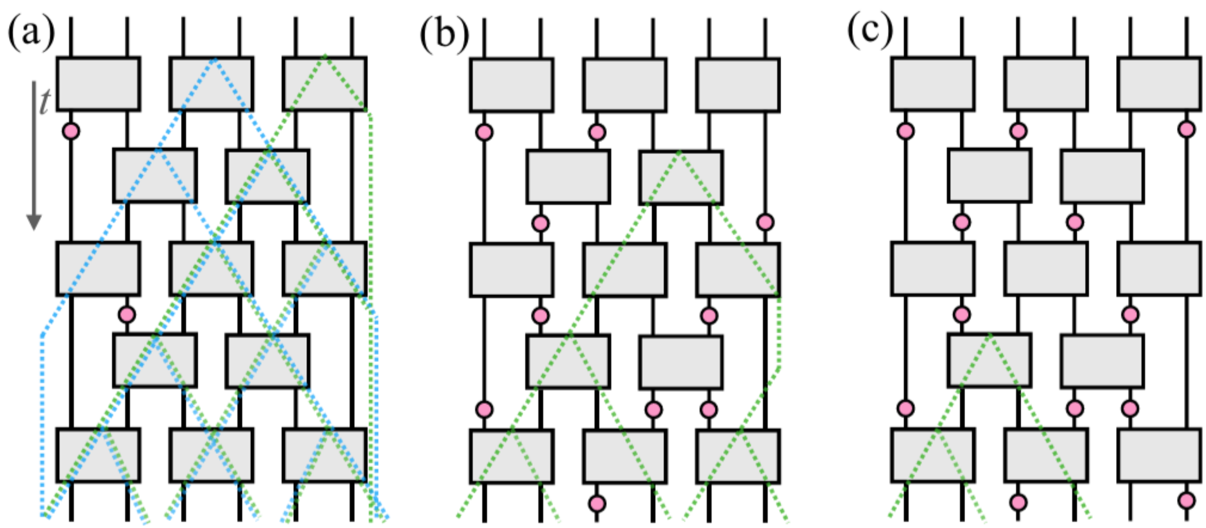
Provatas

In the reporting period, my group's research made contributions to two key areas of microstructure evolution that is directly relevant to material properties. The first was to elucidate some of the key mechanisms at play in a recently discovered experimental phenomenon where an ultra-rapidly cooled liquid evolves a tapestry of atomic-scale defects in the solid state that are traditionally associated with mechanical deformation. The second was to show how the competition between bulk and grain boundary diffusion can lead to an oscillatory flow of lamellar colony growth in a solid-state matrix, a process mediated by a dislocation stress relaxation mechanism (see picture attached). This work was produced by two excellent McGill Physics students (Sammohith Nittala and Alex Mamaev).



Pereg-Barnea

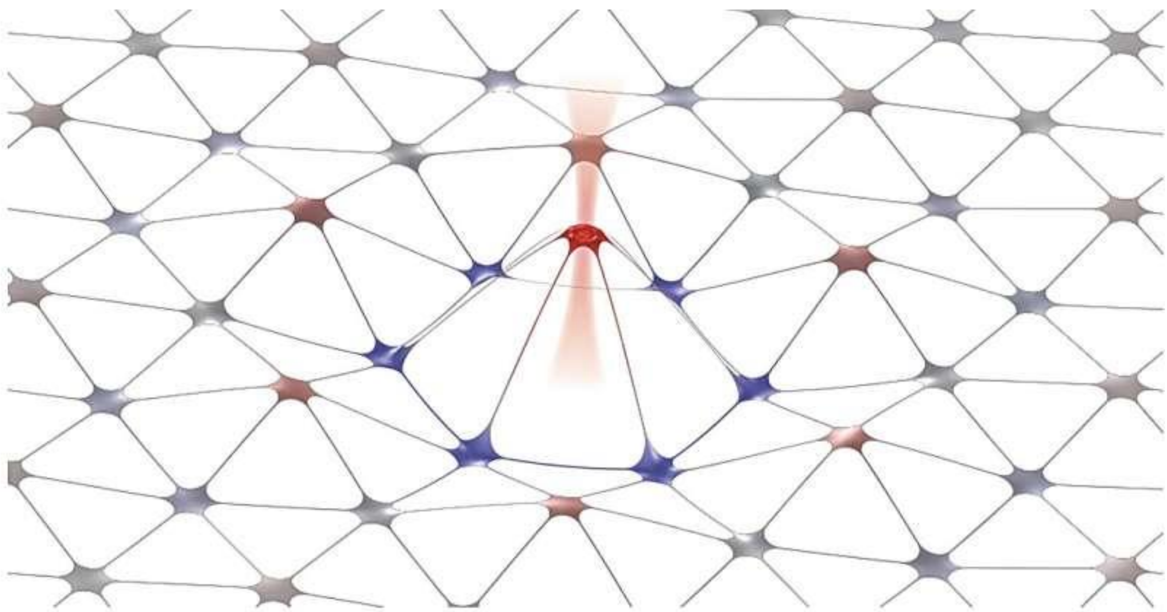
This year, among other projects, we learned about creating long range entanglement in quantum circuits. While non-monitored circuits produce entanglement only on short scales, performing random measurements changes the picture completely. Randomly monitored circuits are made of layers of quantum gates where at each point a qubit can be measured with some probability *p*. It has been shown that the entanglement between two parts of the circuit (bipartite entanglement) changes its behaviour as a function of *p* from area law to volume law entanglement. In our work we find that the measurements also cause long range entanglement between multiple partitions of the system which is peaked at some optimal *p.*



The figure shows 3 different p-values in brick-work circuits. The dashed lines represent the spread of entanglement.

Sankey

Our big result is using the mechanical properties of light to create an optically reconfigurable mechanical defect mode, notably tuning its inertial mass by a factor of 37. This was a PRL highlighted by editor suggestion, physics article, and phys.org article. In addition to unlocking things like optically programmable waveguides, dimers, superlattices, and more, the system exhibits a collectively enhanced response to light that offers a potential alternative pathway toward large scale quantum motion and associated searches for new physics. **(**we also found a new way to laser cool using thermal effects in our fiber mirrors, which is neat)



Community Activities

Weekly Seminars

The CPM in collaboration with INTRIQ has continued to offer weekly seminars hosting a variety of external and internal speakers. Each visitor spends a day or two at McGill meeting with researchers and giving a lecture. The list of speakers and their talk abstracts can be found here. This year seminars were organized by Tami Pereg-Barnea and Kirk Bevan.

RQMP Grande Conference May 2024

The conference, hosted by McGill and organized by the OC which includes Kai Wang of CPM was focused on Metamaterials and was a great success.

RQMP Axes Meetings

The RQMP is composed of 5 thematic axes each led by two RQMP members from different institutions. Four of the axes are led by CPM members – Cooke, Guo, Grutter and Pereg-Barnea. Each axis holds an annual workshop hosted by one of the RQMP institutions and organized by the axis leaders.

CPM student Committee

Five CPM students have volunteered to serve in the CPM student committee. The committee is organizing social and scientific events and has recently renovated the common seating area on the 4th floor of the Rutherford building.

Advanced Material Academy (AMA)

A group of RQMP researchers which includes many CPM members has obtained federal funding for a training program through the NSERC CREATE program. Starting in fall of 2025, CPM student members can enroll in the program at o cost and participate in a variety of training activities which include academic exchange and industrial internships.