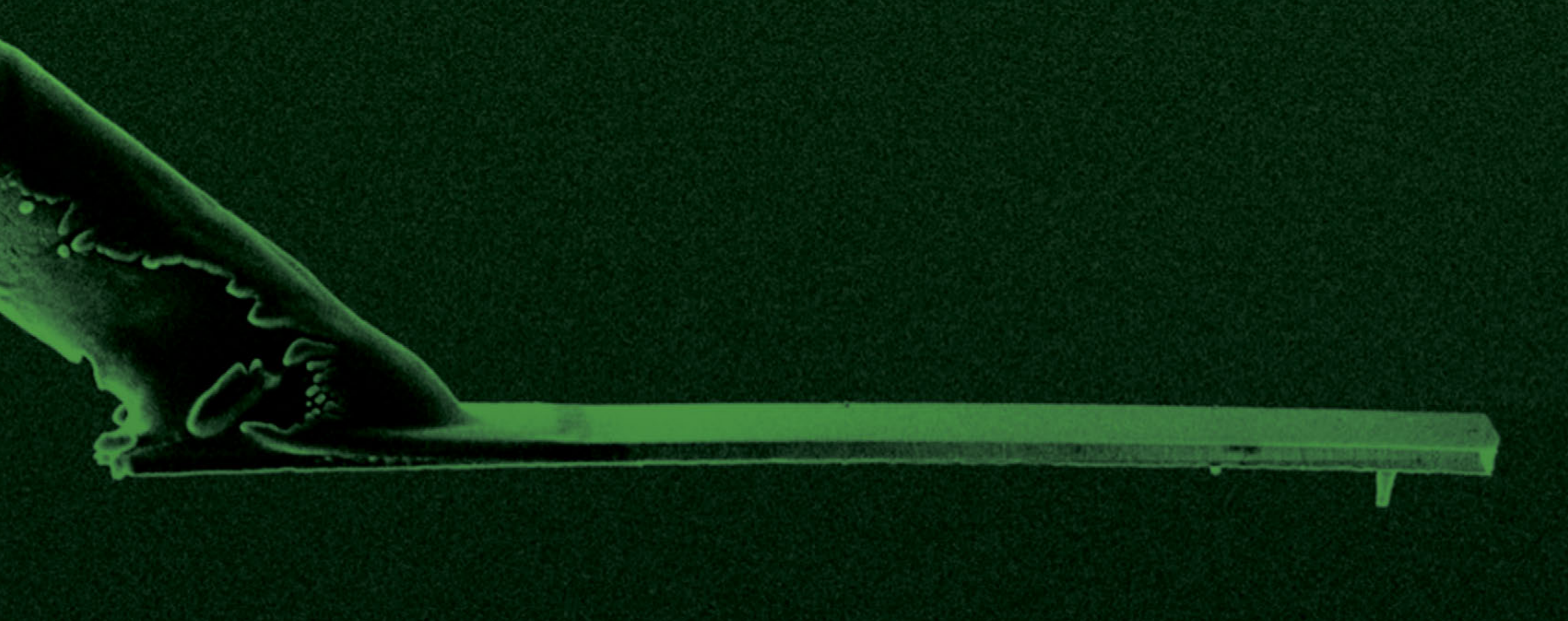

FEATURED

Condensed Matter Physics

by Michael Grinolds PhD '14, Sean Hart PhD '15, Shannon Harvey PhD '17, and Prof. Amir Yacoby

Back in the 1980s, when Richard Feynman proposed the idea of a computer that could take advantage of the laws of quantum mechanics, it was a technological impossibility, and most people thought it would always remain purely theoretical. But experimental breakthroughs in the 1990s and beyond have paved the way for a proliferation of platforms from which researchers are attempting to build a quantum computer today.

Above: SEM image of a single crystalline diamond nanopillar probe with a single NV centre at its tip, able to scan within tens of nanometres of a sample surface. The nanopillar is used as the tip of an atomic force microscope, enabling magnetometry measurements of unprecedented sensitivity and spatial resolution.

Meanwhile, a number of algorithms that could be run efficiently on quantum computers, but not on classical computers have been discovered, thereby increasing demand. The challenges are high: computers will need thousands of qubits (the quantum analog of a bit) and computational error rates of at most about one percent to perform effective quantum algorithms—a scaling of several orders of magnitude above current systems.

While much of the excitement about quantum computing research is derived from the potential applications, this research has also unveiled new physics due to qubits' ability to function as sensors. To perform quantum operations, qubits must be exquisitely sensitive to the fields that drive them, which also makes them unparalleled sensors. They can be adapted to measure other systems, working, for instance, as a magnetometer that can sense biological molecules. Additionally, qubits can be used to study their own environment, which yields information on their noise bath—knowledge that can be used to improve qubits. The search for a long-lived qubit has also motivated the field of topological quantum computing, where emergent new particles would store quantum information in a way that is protected from environmental perturbations.

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SEMICONDUCTOR SPIN QUBITS

One of the Yacoby Lab's projects uses spins in semiconductor quantum dots as qubits. Electrons can be confined within quantum dots, also known as "artificial atoms," to a space small enough that their energy levels become quantized. At tens of millikelvin, where the experiment is run, electrons occupy the orbital ground state of the dot, and noise in the system is reduced significantly enough that quantum superpositions of electron spin states are long-lived. Using the spin state of electrons in quantum dots as the basis for the qubit takes advantage of a spin's isolation from its environment to achieve long coherence times essential for low error rates, while still allowing for rapid control techniques available for quantum dots.

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The team has two major research directions: enhancing the coupling between qubits and improving the qubits' coherence times, both of which act to increase the number of coherent multi-qubit operations, a metric for the capabilities of the system. While semiconductor qubits can take advantage of miniaturization and mass production methods developed to manufacture classical computer chips, before adapting these technologies the group must develop a robust scheme for coupling large numbers of qubits. Quantum computers require entanglement, non-classical correlations between the states of multiple qubits, which can be generated in this system using electrostatic dipole interactions. Current work is directed toward extending the range of the interaction by putting metal gates that extend between the qubits onto the device, which could pave the way for large 2D arrays of qubits useful for error correction.

In order to improve coherence times, the team is pursuing research into noise that affects the qubit. Noise decoheres the delicate quantum superpositions necessary for quantum computing, and remains the major obstacle to effective quantum computers. To remedy this, the group is studying the rich magnetic and electric environment that interacts with these semiconductor qubits. As graduate student Shannon Harvey puts it, "doing so, you might discover the ultimate source of the noise and use that information to direct your material's growth or device processing to mitigate it. Or you can use your knowledge of the frequency spectrum of the noise to drive the qubit so that it's insensitive to noise." Graduate student Michael Shulman adds, "No one knows yet what the building block of the quantum computer will be, or what the essential advances that will render them practical are, but by employing a range of approaches and considering the successes and failures of other types of qubits, we can advance the field in a synergistic way."

NV CENTERS IN DIAMOND

Another team in the Yacoby Lab is working on improving qubits made with defects in diamond. Nitrogen-vacancy (NV) color centers are atomic defects in diamond where one carbon atom is replaced by a nitrogen atom that is adjacent to a carbon vacancy. These defects are essentially solid-state molecules: They have quantized energy levels that can be manipulated electromagnetically, and at the same time they are rigidly held in a diamond lattice so that their surroundings can be fabricated using micro- and nano-fabrication techniques. One hope is that, like early research efforts on trapped ions, several NV defects can be entangled together to process quantum information. There is also the expectation that the scalability of solid-state fabrication techniques will allow for building up to many-qubit systems.

In the Yacoby Lab, the research is focused on understanding how these defects interact with their solid-state environments. Postdoctoral fellow Marc Warner outlines the challenge: "With solid-state defects like NV centers, each defect has a different environment, and so unlike atomic or ionic systems, every quantum bit is unique." On the most basic level, he says, as NV defects are created by nitrogen-ion implantation — a stochastic process — their exact locations are unknown. Given that entanglement between the spins of defects is often achieved using distance-dependent magnetic dipole interactions, it is critical to be able to position the defects in three dimensions with atomic precision.

From Left to Right. Back Row: Toeno van der Sar, Amir Yacoby, Rainer Stöhr Front Row: Lan Luan, Andrei Levin, Yuliya Dovzhenko, Monica Allen, Shannon Harvey, Angela Kou, DiDi Wei, Ben Feldman, John Nichol

To this end, the Yacoby group NV team developed a new kind of microscope for nanoscale imaging of NV centers. Noting that NV centers have a paramagnetic ground state with unpaired spins, they built a spin microscope that uses magnetic resonance imaging (MRI) techniques to visualize these individual defects in three dimensions. The microscope combines the optical readout of NV centers and scanning nanomagnets with large magnetic field gradients. Graduate student Michael Grinolds describes the process this way: "By moving the nanomagnets in space and optically monitoring the NV electron spin resonances, we can map out their locations." As an added benefit, he notes, the magnetic field gradient also spectrally distinguishes different NV centers, which affords individual control over each potential quantum bit.

TOPOLOGICAL QUBITS

A different approach, called topological quantum computing, forms the third component of the Yacoby Lab's effort to harness the power of quantum information. Conventional approaches to building a quantum computer typically focus on localized nodes or particles —qubits in other words—that are coherently integrated into a larger computing network. A continuing challenge of this strategy is that the qubits need to be isolated from their environment for enough time to execute an interesting computation. The topological approach takes the view that if the quantum information can be stored nonlocally, then any type of local disturbance would be incapable of destroying coherence.

Obtaining such a nonlocal system may seem quite difficult, but the key lies in the interactions among the building blocks of the quantum computer. Rather than having a network of connected nodes, one might instead imagine a two-dimensional liquid of interacting electrons, so that the emergent behavior of the electron system can become intrinsically nonlocal. Under certain conditions, moreover, the electrons can conspire to create new emergent particles, where each pair of these new particles encodes a two-level quantum system. The only way to evolve between the two states would be to cause one of

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these special particles to completely encircle another. If one can localize the two particles far from one another, then the quantum information becomes spread out and more resistant to local environmental perturbations.

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DIVERSE PROJECTS

In addition to the three topics discussed here, the Yacoby Lab also studies the Quantum Hall Effect in graphene as well as graphene-based technologies. Although the Yacoby group studies a diverse set of projects, they share a number of fundamental ideas and experimental techniques, and students enjoy exchanging advice on everything from how to fabricate devices in the clean room to the ins and outs of running a dilution refrigerator. Many students like being surrounded by people doing research in a variety of fields. As graduate student Hechen Ren put it, "Sharing an office with people studying so many different systems keeps me informed about what's happening at the forefront of so many topics in condensed matter physics. It's a very exciting place to be."