Exploiting quantum coherence

In a lively dialogue, **Professor Kimberley C Hall** discusses what drew her to the field of quantum physics and provides an interesting overview of her latest research into ultrafast quantum control

Ctould you outline how you became interested in ultrafast quantum control?

I developed a keen interest in quantum physics during the early years of my undergraduate degree. I particularly like the intellectual challenge associated with the fact that the results are often counterintuitive. Pulses of coherent laser light make it possible to manipulate quantum states of matter deterministically and observe the resulting dynamic evolution in the laboratory. This direct connection between abstract mathematics and real-world experiments is very satisfying to witness in action – and this is the main reason for my interest in ultrafast quantum control experiments.

How do you define the term 'ultrafast'?

Ultrafast refers to the fact that the laser pulses used are very short in duration, approximately 100 femtoseconds. To put this timescale into perspective, comparing 100 femtoseconds to 1 second is like comparing 1 centimetre to the distance between the Earth and the Sun. Working with such short pulses, along with the specialised state-of-the-art lasers that produce them, is very challenging from a technical perspective. Overcoming this challenge is a satisfying and enjoyable part of carrying out these quantum control experiments.

Can you explain the importance of laser coherence in the control of quantum states?

For the kinds of applications we are interested in, the goal is to exploit quantum coherence to achieve a new functionality that would be inaccessible for devices based on classical physics. An easy way to prepare a coherent quantum state of matter – which could be a simple two-level quantum system, often called a quantum bit or qubit – is to use a coherent optical pulse. For the laser pulse, the word 'coherence' refers to the fact that light consists of oscillating electric and magnetic fields (a wave). This wave is coherent if the oscillations occur without any interruptions. Similarly, one can excite an oscillating quantum state of matter using a coherent light pulse, which has oscillations that persist without any interruption for a period of time. Not only can short coherent laser pulses be used to prepare that oscillating state, but also to manipulate it, detect loss of coherence and even reverse the effects of decoherence through a tailored train of pulses and repeated excitation.

What materials are you studying in your quantum control experiments?

Our focus over the past few years has been on semiconductor quantum dots. Semiconductors are currently used for many applications, including computers, compact laser sources and detectors. Adapting semiconductors for use as 'quantum hardware' would allow us to make use of the same advances in the

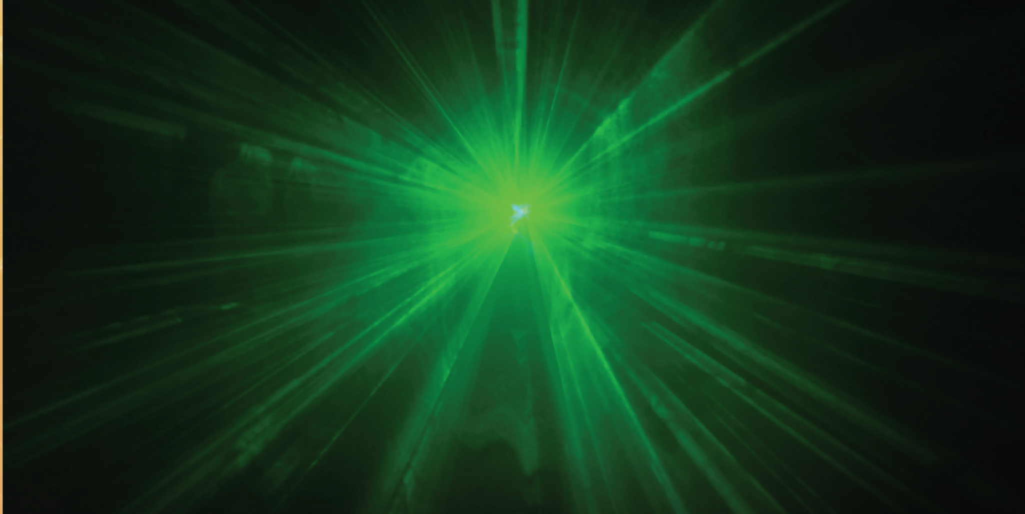
processing of these materials that have allowed these existing applications to be developed. For instance, the continual reduction in the minimum feature size in complementary metal-oxide semiconductor (CMOS) technology has fuelled the improvement in the speed and performance of traditional computers over the years. The solid-state chip-based approach to quantum hardware that semiconductors offer would also assist with the eventual integration of quantum devices with classical devices. This is what led to our focus on these promising materials.

Could you describe a quantum dot and how it is produced?

Semiconductor quantum dots are nanometre-sized regions of one type of semiconductor inside another type of semiconductor, where the surrounding material is characterised by a larger potential energy. These tiny regions (the dots) may be used to trap individual electrons, or composite excitations called excitons that may be generated inside the dot using an optical pulse. Quantum dots may be produced in a variety of ways. The dots we have been studying were grown using a technique called molecular beam epitaxy by one of our collaborators, Dr Dennis Deppe at the University of Central Florida, USA. They are called self-assembled quantum dots because they are created by the spontaneous formation of isolated islands during the growth process.

Are collaborations important to the advancement of your research?

Collaborations are essential for our work because all of the materials we study are supplied by leading-edge researchers at other universities around the world. These materials must be grown by molecular beam epitaxy, which requires a dedicated facility and focused research effort. We have ongoing collaborations with researchers at the National Research Council of Canada, Eindhoven University of Technology in The Netherlands, University of Central Florida and University of Notre Dame, USA. Our research group is very fortunate to have ties to these excellent research teams in semiconductor growth.



Innovative optical **techniques**

The Ultrafast Quantum Control research group at Dalhousie University, Canada, is conducting leading studies into rapid processes in materials that could be used for next-generation computing technologies

WITH SIGNIFICANT ADVANCES in the study of quantum mechanics, the world could be on the threshold of a computing revolution. The creation of quantum-enabled technologies and quantum computing heralds the potential transformation of technologies and processes such as high-power computing, cryptography and database searching. In the digital age, these areas are vital to the functioning of society – and as a result, dramatically increasing computing power through enabling technologies that exploit quantum physics could bring significant benefits to humankind.

> Hall and her team have demonstrated that pulse shaping can be used to optimise both the speed and fidelity of a controlled-rotation gate and that this technique allows parallel quantum processing

Professor Kimberley C Hall, based in the Department of Physics and Atmospheric Science at Dalhousie University in Nova Scotia, Canada, is leading innovative research into ultrafast optical techniques that could facilitate the development of next-generation computing technologies that exploit quantum mechanical effects. As the Canada Research Chair in Ultrafast Science and Principal Investigator of the Ultrafast Quantum Control research group at Dalhousie, Hall's main research interests include electron spin coherence and relaxation, quantum information, photonic and spintronics devices, magnetic semiconductors and ultrafast dynamics in semiconductor nanostructures.

GROUNDBREAKING RESEARCH

Hall and her group are using ultrafast optical techniques to study the rapid processes in materials they believe could be used for novel computing technologies, including advanced electronic and optoelectronic devices. They are using cutting-edge technology – such as special lasers that produce short pulses of light with a duration of approximately 100 femtoseconds – to analyse incredibly rapid events, such as the motion of electrons in solids. Crucially, because this technology makes these laser pulses coherent, Hall can use them to initialise and manipulate quantum mechanical states of matter. Indeed, the exploitation of quantum coherence is the factor that sets apart the potential electronic applications of the future from present-day traditional computers. To date, the team has predominantly focused on quantum state manipulation in two areas: the manipulation of qubits in semiconductor quantum dots using pulse engineering and the pursuit of rapid optical manipulation of magnetic behaviour in diluted magnetic semiconductors.

PULSE SHAPING

The Ultrafast Quantum Control researchers have provided important insights into the use of optical pulse shaping as a method for optimising the performance of quantum gates for quantum computing. In this context, pulse shaping can be defined as a technology that enables the manipulation of the phase – or temporal profile – of the optical control pulse: "In turn, this leads to the manipulation of the quantum control Hamiltonian governing the coupling of light with the quantum dot," discloses Hall. "This is a very flexible approach to tailoring the quantum state of the qubit initialised by the laser pulse."

ADVANCING MATERIALS FOR QUANTUM TECHNOLOGIES

OBJECTIVE

To explore the use of optical pulse shaping as a strategy for optimising the performance of quantum gates for quantum computing.

KEY COLLABORATORS

Dr Dennis Deppe, University of Central Florida, USA

Dr Robin Williams, National Research Council of Canada, Canada

Dr Paul Koenraad, Eindhoven University of Technology, The Netherlands

Dr Jacek Furdyna, University of Notre Dame, USA

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CONTACT

Dr Kimberley C Hall
Associate Professor
Canada Research Chair in Ultrafast Science

Department of Physics
and Atmospheric Science
Dalhousie University
Halifax, Nova Scotia
Canada

T +1 902 494 7109
E kimberley.hall@dal.ca

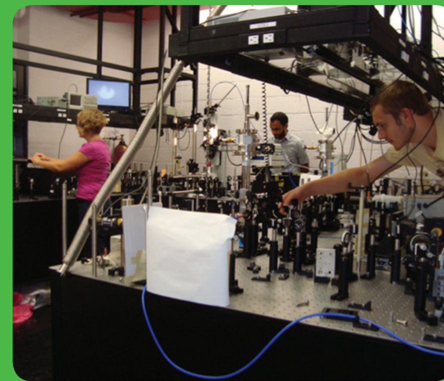
http://ultrafast.physics.dal.ca

KIMBERLEY C HALL received a BSc in Physics from the University of Western Ontario in 1995 and a PhD in Physics in 2002 from the University of Toronto. She completed her postdoctoral work at the University of Iowa in 2004, after which she joined Dalhousie University as Associate Professor and Canada Research Chair in Ultrafast Science. Her research interests cover electron spin coherence and relaxation, quantum information, photonic and spintronics devices, magnetic semiconductors and ultrafast dynamics in semiconductor nanostructures.

DALHOUSIE UNIVERSITY
Inspiring Minds

THE ULTRAFAST QUANTUM CONTROL GROUP

Based in Dalhousie University, Hall is the director of two ultrafast quantum control laboratories with an impressive array of cutting-edge ultrafast spectroscopy technologies. The students in the group obtain a detailed and specialised knowledge of semiconductor theory and nonlinear optics, as well as developing expertise in a variety of optical spectroscopy techniques. The researchers have a strong track record of research excellence and have had many papers published in leading scientific journals, including *Nano Letters* and *Applied Physics Letters*.



While pulse shaping has been used to optimise quantum gate performance involving atomic and molecular qubit systems, its application to solid-state quantum hardware has until now been underexplored. Excitingly, Hall and her team have demonstrated that pulse shaping can be used to optimise both the speed and fidelity of a controlled-rotation gate and that this technique allows parallel quantum processing. In one particularly notable recent achievement, they performed a 20-fold reduction in the speed of a single qubit gate through the application of advanced femtosecond pulse shaping techniques.

DILUTED MAGNETIC SEMICONDUCTORS

The researchers are exploring a range of different materials for advanced electronics, but are particularly interested in diluted magnetic semiconductors: "These materials consist of traditional (non-magnetic) semiconductors that have been doped with magnetic impurities such as manganese," Hall explains. "They exhibit an interesting form of ferromagnetism – a magnetic orientation of the material with two stable directions – that is easy to control with external parameters, such as light or electrical gates."

Indeed, the unique properties of diluted magnetic semiconductors could lead to their adoption as an alternative material for memory devices. This represents a step forward from existing technologies, which are made from metals and are therefore incompatible with regular semiconductors. It is hoped that diluted magnetic semiconductors could eventually lead to the logic and memory functions of computers being located on the same chip, completely transforming the way computers are built.

During the past few years, Hall and her research group have conducted many experiments on gallium manganese arsenide (GaMnAs), a prototypical diluted magnetic semiconductor. Promisingly, these experiments have shed new light on how manganese doping changes the band structure, and have even procured the first measurement of the manganese-hole spin-flip scattering time. These studies will ultimately help researchers to engineer the properties of these semiconductor materials and aid in identifying the appropriate model of ferromagnetism. Their more recent experiments on GaMnAs have opened up new insights into an ultrafast demagnetisation process with potential for obtaining optical read and write functionality for applications.

FUTURE DIRECTIONS

Although the world's first commercial quantum computer was sold in 2011 to the American global security company Lockheed Martin, current research on quantum computing is still very much in its infancy. This is predominantly due to the fact that a large number of material systems are being investigated for their potential suitability as quantum hardware. With understanding of these different material systems varying widely, it is essential that their respective benefits and drawbacks are further scrutinised and compared.

Looking ahead, Hall and her team are eager to continue their investigations into next-generation computing technologies, envisaging that this research area will become increasingly important over the course of the next decade. While demand for potential handheld quantum computers remains unknown, Hall believes that next-generation quantum technologies will certainly have a significant role to play in future: "There are other quantum technologies that are much more likely to realise widespread use, such as single and entangled photon sources for quantum cryptography, spin-sensitive electronic and optoelectronic devices, ultrafast coherent optical switching technologies and others we have not yet even envisioned".