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Computing with a single atom

Background information about the 'single-atom writer' invention published in Nature

A research team led by Australian engineers has created the first working quantum bit based on a single atom in silicon, opening the way to ultra-powerful quantum computers of the future. Their work was published online by Nature on Thursday 20 September.

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Quantum vision: Computing with a single electron in silicon

A research team led by Australian engineers has created the first working quantum bit based on a single atom in silicon, opening the way to ultra-powerful quantum computers of the future.

In a landmark paper published today in the journal *Nature*, the team describes how it was able to both read and write information using the spin, or magnetic orientation, of an electron bound to a single phosphorus atom embedded in a silicon chip.

“For the first time, we have demonstrated the ability to represent and manipulate data on the spin to form a quantum bit, or ‘qubit’, the basic unit of data for a quantum computer,” says Scientia Professor Andrew Dzurak. “This really is the key advance towards realising a silicon quantum computer based on single atoms.”

Dr Andrea Morello and Professor Dzurak from the UNSW School of Electrical Engineering and Telecommunications lead the team. It includes researchers from the University of Melbourne and University College, London.

“This is a remarkable scientific achievement – governing nature at its most fundamental level – and has profound implications for quantum computing,” says Dzurak.

Dr Morello says that quantum computers promise to solve complex problems that are currently impossible on even the world’s largest supercomputers: “These include data-intensive problems, such as cracking modern encryption codes, searching databases, and modelling biological molecules and drugs.”

Project leaders Andrea Morello (left) and Andrew Dzurak (right), with PhD student Jarryd Pla (centre).

The benefits of quantum computing

A functional quantum computer will provide much faster computation in three key areas: searching large databases, cracking most forms of modern encryption, and modelling atomic systems such as biological molecules and drugs. This means they’ll be enormously useful for finance and healthcare industries, and for government, security and defence organisations. Functional quantum computers will also open the door for new types of computational applications and solutions that are, at this stage, difficult to conceive or comprehend.

How quantum computers work

In current computing, information is represented by classical bits, which are always either a zero or a one – the equivalent to a transistor device being switched on or off. For quantum computing you need an equivalent: and in the UNSW design the data will be encoded on the spin – or magnetic orientation - of individual electrons, bound to single phosphorus atoms. These are known as quantum bits, or qubits.

A clockwise (or "up") spin would represent a 1 and a counter-clockwise (or downward) spin would represent a 0 – but in the quantum realm, particles have a unique ability to exist in two different states at the same time, an effect known as quantum superposition. This gives rise to the unique ability envisioned for quantum computers to rapidly solve complex, data-intensive problems.

Multiple, coupled qubits can exist in states that have no classical analog, and they can be in many of such states at the same time. These special states are called "entangled states" because the information they contain tells you something about the correlations between the particles, but not the individual state of each particle. Using two qubits, the operation could be performed using four values, for three qubits on eight values, and so on. As you add more qubits, the capacity of the computers to perform operations increases exponentially. In fact, with just 300 qubits it is possible to store as many different numbers as there are atoms in the universe.

The silicon approach: UNSW leading the way

In recent years, scientists around the world have been developing completely new systems based on exotic materials or light to build a quantum computer. At UNSW, however, the approach has been to use silicon – the material currently used in all modern-day microprocessors, or computer chips. Silicon offers several advantages: the material is cost-effective, already used in almost all commercial electronics, and its properties are very well understood – the result of trillions of dollars of investment into R&D by the computer and electronics industry. Silicon electron "spins" also have very long "coherence times" – this means the quantum data encoded on the spin can remain there for longer periods than it would in most materials, before it is scrambled and lost. This is important for performing successful calculations.

In 1998, former UNSW researcher Bruce Kane first proposed the idea of using silicon as a base material for quantum computing. In a paper in *Nature* he outlined the concept for a silicon-based quantum computer, in which single phosphorus atoms in an otherwise ultra-pure silicon chip define the qubits.

His visionary work spawned an international effort to develop a quantum computer in silicon, and this latest result represents the biggest achievement en route to realising that dream – a result, researchers say, that could perhaps one day be seen as comparable to the invention of the transistors used in conventional computers.

A functional quantum bit – or qubit

In order to employ the electron spin, a quantum computer needs both a way of setting the spin state (writing information) and of measuring the result (reading information). These two capabilities together form a quantum bit or qubit – the equivalent of the bit in a conventional computer.

The research team, led by engineers from UNSW, have now completed both stages. Their new result follows on from a 2010 study also published in *Nature*, in which the same group demonstrated the ability to read the state - or "direction" - of an electron's spin. Now, with the ability to write the spin state, they have completed the two-stage process required to operate a quantum bit.

The new result was achieved by gaining unprecedented control over an electron bound to a single phosphorous atom, implanted next to a specially-designed silicon transistor.

Professor David Jamieson from the University of Melbourne’s School of Physics led the team that implanted the phosphorous atom into the silicon device.

“Our team has the unique expertise to implant a single phosphorus atom into the correct location of a nanoscale quantum device”, says Professor Jamieson.

Next to the single phosphorous atom is a silicon transistor so small that electrons have to travel along it one after the other. The engineers designed their circuit so that the current would only flow if the electron from the phosphorus atom moved to an ‘island’ at the centre of the transistor. They also set up their device so the electron could only make this jump if it had a particular spin state. If the electron spin was up, then it could jump into the transistor, but if it was down then it couldn’t move. This meant the researchers could tell whether the electron’s spin was up or down simply by measuring the current through the transistor.

The latest finding shows they can now ‘write’ information onto the spin of the electron that is bound to the phosphorus atom in their qubit device. What this means is that they can manipulate the spin state of the electron, pointing it in any direction they choose, which gives them full control of the quantum bit. This result, like their work on the spin reader, has now been published in *Nature*.

The researchers will now work to combine pairs of these devices to create a two-bit logic gate – the basic processing unit of a quantum computer. While building a full-scale quantum computer remains a daunting and ambitious engineering challenge, the main scientific hurdle of demonstrating a functioning quantum bit in silicon has now been realised.

Further information

Timeline of the development of silicon quantum computing in Australia

1994: **Peter Shor** from Bell Labs (USA) shows that a quantum computer would be able to decrypt Public Key Encrypted codes (at the heart of modern secure communications) exponentially faster than today's supercomputers. This triggers massive interest in quantum computing worldwide.

1994-1998: Various schemes proposed for making a quantum computer using different systems including photons, ion traps, superconductors, semiconductor quantum dots.

1998: **Dr Bruce Kane**, then a postdoctoral researcher at **UNSW** (now a researcher at the US Laboratory for Physical Sciences in Maryland), publishes a paper in *Nature* [Nature **393**: p 133 (1998)] outlining the concept for a silicon-based quantum computer, in which the qubits are defined by single phosphorus atoms in an otherwise ultra-pure silicon chip.

The quantum information is encoded in either the **spin of the electron** or the spin of the P nucleus. This is the first such scheme in silicon – the material used for all modern day microprocessors.

Kane's paper attracts great interest because: (i) Silicon is "industrially relevant"; (ii) Silicon electron "spins" have very long "coherence times" (hence, low error rates). This paper has now generated over 2000 citations.

Despite the great potential for a silicon quantum computer, the task of building devices at the single atom level is considered almost science fiction back in 1998.

2000: **Prof Bob Clark** establishes the ARC Special Research Centre for Quantum Computer Technology, headquartered at UNSW, to attempt to build a quantum computer.

The Centre has now expanded to become an ARC Centre of Excellence – with more than 150 researchers in Australia, and major collaborations world-wide.

The Centre now generates about 100 research publications a year.

Bob Clark retired from CQCT in 2008 to take up the role of Australian Chief Defence Scientist from 2008-2011. He now researches energy policy at UNSW.

Prof Andrew Dzurak (UNSW) and **Prof David Jamieson** (University of Melbourne) were founding chief investigators in CQCT and were charged with using **ion implantation** to build a silicon quantum computer.

Ion implantation is a technology for injecting "dopant" atoms (such as phosphorus) into modern silicon integrated circuits. As a **"mass production" technology** ion implantation is very attractive if we are ever to build a commercially viable large-scale silicon quantum computer processor chip.

2000-2009: Various researchers at CQCT contribute to ground-breaking **single atom nanotechnologies** – generating hundreds of papers.

Two main approaches:

- "Top-down" approach - using ion-implantation [led by Dzurak and Jamieson]
- "Bottom-up" approach – using scanning-probe lithography [led by Michelle Simmons]

Despite the amazing progress in single atom nanotechnologies over the past decade, until now there has been no demonstration of a single electron spin quantum bit based on phosphorus donors, as first envisaged by Kane back in 1998.

Timeline for the ion-implanted ("top-down") single-atom quantum bit

2006: Dr **Andrea Morello** joins the team at UNSW, in the quest to build silicon qubits using the "top-down" approach. Morello brings a background in quantum spin physics, which is essential to the team.

Morello and Dzurak form a close partnership – aimed at realising the dream of a silicon quantum bit.

2008: The "Top-Down" team at UNSW conceives a new scheme to read out the spin of an electron on an implanted phosphorus donor.

Paper published in Physical Review B in 2009 [A. Morello et al., Phys. Rev. B **80**, 081307 (2009)].

2009: Morello and Dzurak, and their experimental teams, see the first experimental evidence of the read out of the electron spin on a phosphorus atom in a qubit device.

2010: Paper published in *Nature*, describing the "*Single shot readout of an electron spin in silicon*" – the step of ***measuring*** a silicon qubit. [A. Morello et al., Nature **467**: p687 (2010)]

2012: Paper published in *Nature*, describing "*A single-atom electron spin qubit in silicon*" – the final crucial step of ***writing*** information on an electron, to fully ***operate*** a silicon qubit. [J. Pla et al., Nature (2012) in press]

Key research team members and their roles in the paper

Dr Andrea Morello (UNSW) – Project Co-leader (with Dzurak). Joint conceptual design of experiment. Leader of the Quantum Spin Control experimental program at CQC^2T and responsible for the quantum measurement infrastructure.

Prof Andrew Dzurak (UNSW) – Project Co-leader (with Morello). Joint conceptual design of experiment. Director of Australian National Fabrication Facility at UNSW and co-leader of "top-down" single-atom device engineering (with Jamieson) at CQC^2T.

Mr Jarryd Pla (UNSW) –PhD student at the UNSW School of Electrical Engineering & Telecommunications in Dr Morello's group, and lead-author on the Nature paper. Lead experimentalist.

Prof David Jamieson (University of Melbourne) – Co-leader of "top-down" single-atom device engineering (with Dzurak) at CQC^2T.

Other Authors

Dr Kuan Yen Tan, UNSW (now at Aalto University, Finland)

Mr Juan-Pablo Dehollain, UNSW

Dr Wee Han Lim, UNSW

Dr John Morton, University of Oxford (now at University College, London)

Key Stakeholders & Funding Bodies

1. **Centre of Excellence for Quantum Computation and Computer Technology (CQC2T):** Australian centre of research excellence, headquartered at UNSW, in which Dr Morello and Prof Dzurak are project leaders. Founded in January 2000.

2. **Australian National Fabrication Facility (ANFF):** Founded in 2006 under the Australian Government's *National Collaborative Research Infrastructure Scheme*. Provides infrastructure and technical support at UNSW for fabrication of the qubit devices.

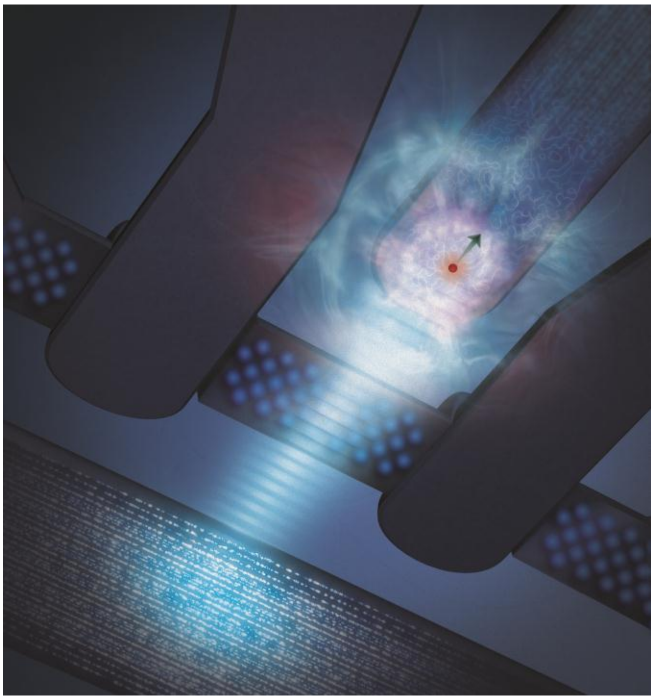
3. **Australian Research Council (ARC):** Major funder of CQC^{2}T via the ARC Centres of Excellence Scheme (a funder since 2000).

4. **US Army Research Office:** Funder of the Silicon Quantum Computer Program at UNSW and the University of Melbourne since 1999.

5. **Australian Government Department of Innovation, Industry, Science, Research and Tertiary Education (DIISRTE):** Major funder of ANFF through the *National Collaborative Research Infrastructure Scheme* and *Super Science – Future Industries* programs.

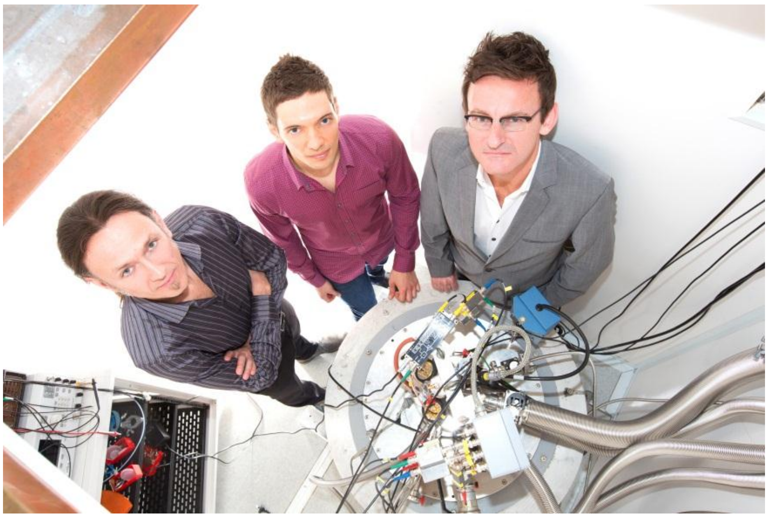
6. **NSW Government – Department of Trade & Investment, Office of Scientific Research**: Provides significant co-funding to CQC^{2}T (since 2003) and also to ANFF (since 2006).

Photographs and Captions



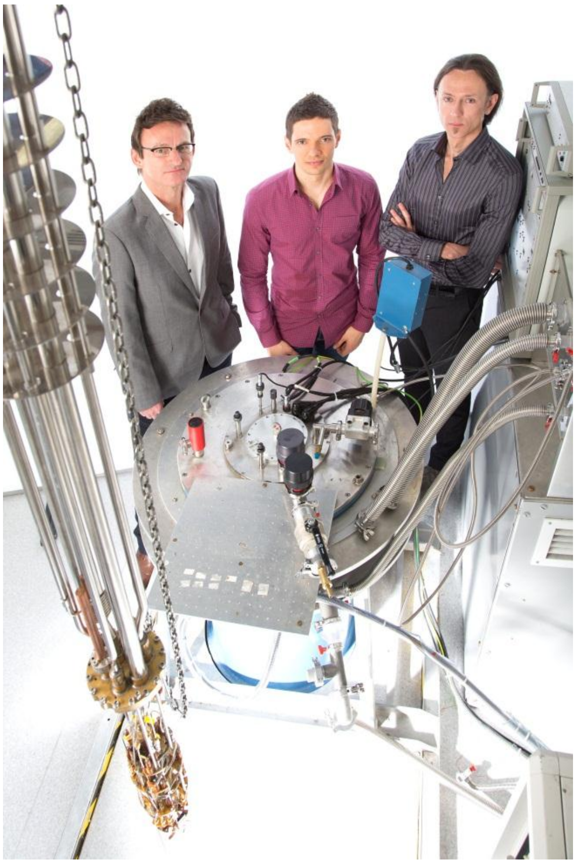
Artist's impression of a phosphorus atom (red sphere surrounded by electron "cloud", with arrow showing the spin direction) coupled to a silicon single-electron transistor. A burst of microwave radiation (light blue) is used to 'write' information on the electron spin.

Credit: Tony Melov



Project leaders Andrea Morello (left) and Andrew Dzurak (right), with PhD student and lead author Jarryd Pla (centre).

Credit: UNSW



Project leaders Andrew Dzurak (left) and Andrea Morello (right), with PhD student and lead author Jarryd Pla (centre).

Credit: UNSW