# Ultra-fast calculations using diamond

*TU Delft researchers have managed to use a piece of diamond to hold four quantum bits that can be spun, flipped and entangled with each other. This is an important step towards a working quantum computer.*

Tomas van Dijk

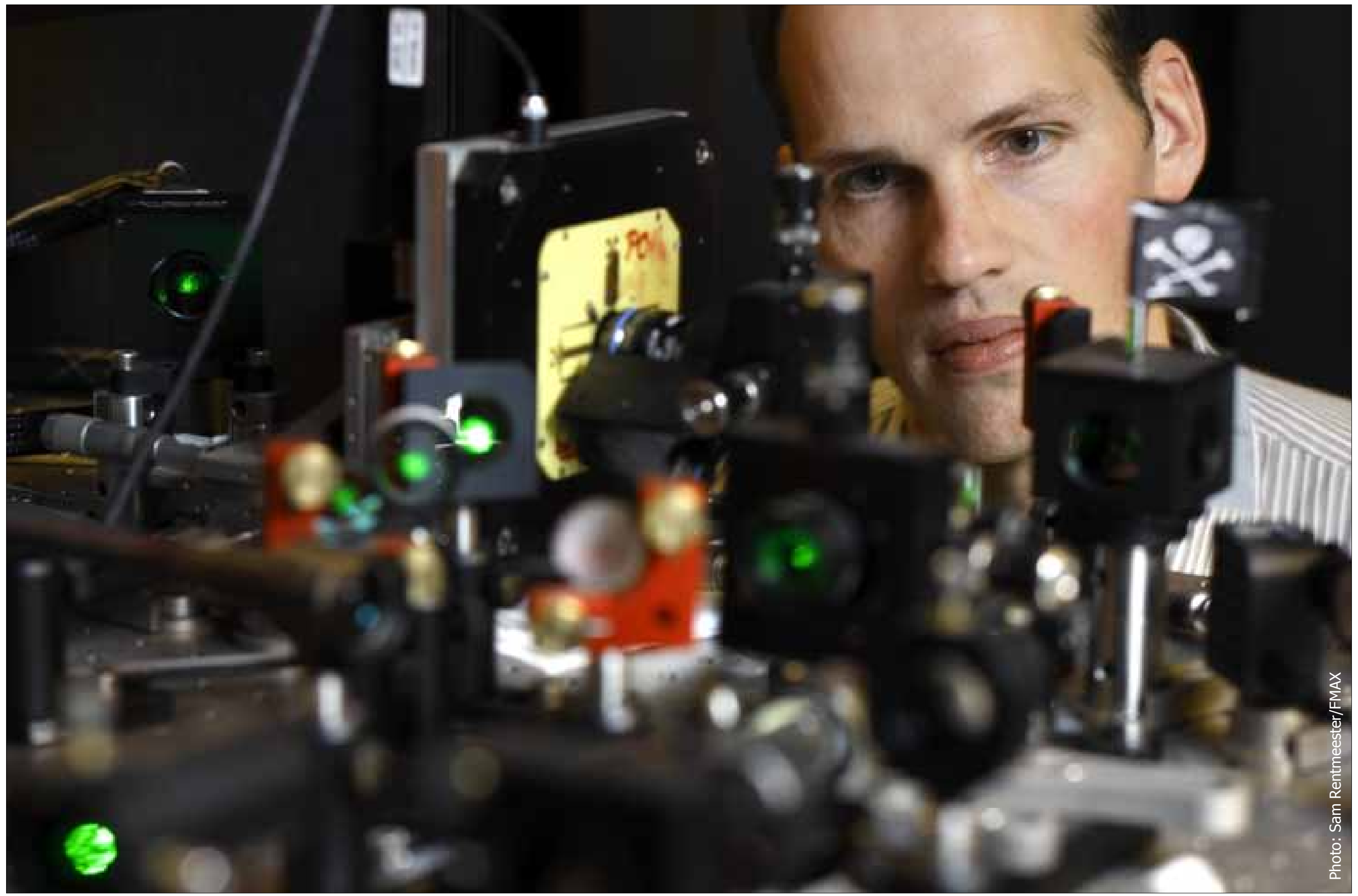
Photo: Sam Rentmeester/FMAX

Ronald Hanson: "When we get quantum error correction to work, our work on the quantum computer will be finished."

Atoms trapped by a laser beam, superconducting rings, carbon nanotubes: a whole range of possible elements for building future ultra-fast quantum computers has been proposed over the years.

Because of their adjustable quantum states, such as spin, charge, current direction and polarisation, these particles can be used to represent information in the form of bits with special properties. A quantum bit or qubit is not limited to just two states, like the transistors of today's computers, which can only be 1 or 0. A qubit can have several states simultaneously.

> 'From a microsecond to a millisecond is a huge difference'

In the wonderful world of quantum mechanics, electrons can, for example, have a left and a right spin at the same time. The possible combinations are unlimited, for example some right spin and a lot of left spin, or vice versa. Theoretically, this means that certain types of calculations can be performed extremely quickly.

Progress however is only being made a step at a time; for example, first researchers succeeded in keeping a quantum computer's switch in a stable position for a millisecond rather than just a microsecond, and later they managed to read out the quantum-mechanical state indirectly, without disturbing it.

Over the past ten years, press release has followed press release. Each time it is announced that the quantum computer is now a step closer to feasibility. But will a quantum computer ever actually be built? Dr Ronald Hanson, of the Kavli Institute of Nanoscience, laughs when asked this question. After all, the field is developing rapidly. "Ten years ago, we weren't able to do anything," he says. "But now look at how we can spin and manipulate atoms and electrons. When I tell my friends about this, they're amazed." Dr Hanson is hopeful that future quantum computers will be made using diamond.

Quantum states are difficult to measure, partially because they are "drowned out" by noise from their surroundings, for example from neighbouring atoms that are also vibrating and spinning. Most research into quantum phenomena is therefore carried out at extremely low temperatures. However, a computer that only operates at temperatures just above absolute zero does not seem a very practical proposition.

## Room temperature

Qubits turn out to be very stable in a diamond. Hanson and his colleagues have been working for years on qubits in diamond chips. Some of their experiments are conducted at room temperature.

Recently, the researchers succeeded in very accurately reading out a "mini-quantum computer" – a computer consisting of four qubits. This was a breakthrough, and their research was published in Nature last September (first author: Lucio Robledo).

The TU Delft team is working with synthetic diamond in which a few nitrogen atoms are distributed. Wherever a nitrogen atom occurs, an open space or hole arises in the crystal structure of the diamond, with each hole containing an electron.

The trapped electron is one of the four quantum bits. The three other quantum bits are the nitrogen atom itself and two neighbouring 13C carbon isotopes.

The atomic nuclei form very stable quantum bits because they hardly interact with their surroundings. This is because most of the diamond consists of 12C isotopes, which do not have any spin. This makes diamond a material suitable for building a quantum computer that works at room temperature.

In order to read out the states of the atoms, the researchers had to open up a new bag of tricks. "Atoms are relatively unaffected by the magnetic noise of their surroundings, because they only have a small magnetic moment," explains Dr Hanson. "This makes them stable but also difficult to read out. Electrons have a much larger magnetic moment. To read out the state of atoms, equipment needs to be a thousand times more accurate than for reading out electrons. For this reason, we chose an indirect method by using the electron trapped in the hole."

The scientists thus use the trapped electron as an intermediary in making the measurement. First they perform a so-called quantum operation, in which the electron enters an entangled state with the atomic nuclei. This means that information is transferred from the nuclei to the electron. The researchers are then able to read out the state of the electron and deduce the original state of the nuclei.

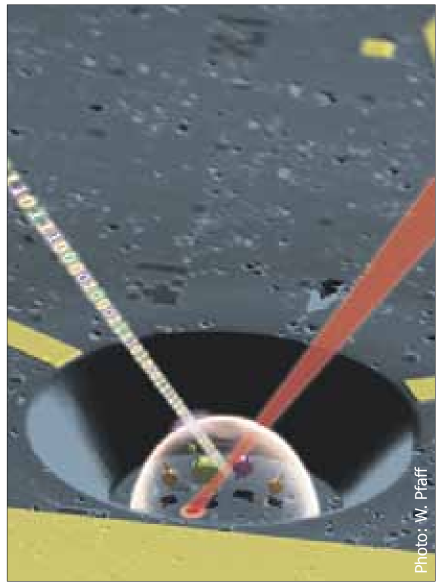
Photo: W. Pfaff

The four quantum bits of spins (the spheres with arrows) are read out by firing a red laser light at them. Information about the state of the spins returns with the light.

In order to read out the state of the electron, the researchers fire laser pulses with very precisely adjusted wavelengths at the electrons. They do this eight times, because the electron may have taken on eight different spin velocities, depending on the spin states of the nuclei of the atoms with which it has become entangled.

The electron will absorb a photon from only one of the eight pulses. When the electron does this, it subsequently emits a photon, and this event can be detected.

Dr Hanson: "In other words: eight times we ask the electron a question about its state, which it can answer with yes or no."

## Noise

The measuring technique is remarkable, because it does not alter the state of the atomic nuclei. This method is also suitable for setting up atomic nuclei for further calculations.

The researchers did not perform this particular experiment at room temperature, but rather at 10 kelvins. Unlike the atomic qubits, the electrons are very sensitive to noise.

"If we ask the electron, 'Are you in this particular state?', we do not receive a clear answer at room temperature," Dr Hanson explains. "We can probably solve this problem in the future by asking the question a hundred times and then averaging the answers we receive."

Dr Hanson is not concerned that this statistical trick will make the quantum computer slower: "Calculations can be performed so much more efficiently using quantum bits that it will always be faster than a conventional computer."

He adds that the great remaining challenge is to maintain the quantum bits indefinitely, using a sort of self-correcting mechanism in the chip.

A few years ago, Dr Hanson's team succeeded in maintaining quantum bits in a stable position for a millisecond rather than just a microsecond by exposing them to microwaves. This breakthrough was published in *Science*. "From a microsecond to a millisecond - this is a huge difference.

The 'holy grail' is to maintain the qubits indefinitely using quantum error correction," Dr Hanson continues. Using this technology, information that is actually carried by only a single quantum bit is encoded in the form of several bits. If one of the bits enters a different state during the calculation, this can be detected using a clever reading-out method, which does not require reading out the states of the bits (which would interfere with the calculation). A deviating bit can be set to the proper state using microwaves.

"When we get quantum error correction to work, our work on the quantum computer will be finished," Dr Hanson concludes. "After that, we will work on remote quantum entanglement, or teleportation."

**Lucio Robledo, Lilian Childress, Hannes Bernien, Bas Hensen, Paul Alkemade & Ronald Hanson. DOI 10.1038/nature10401**