Building a silicon quantum computer chip atom by atom

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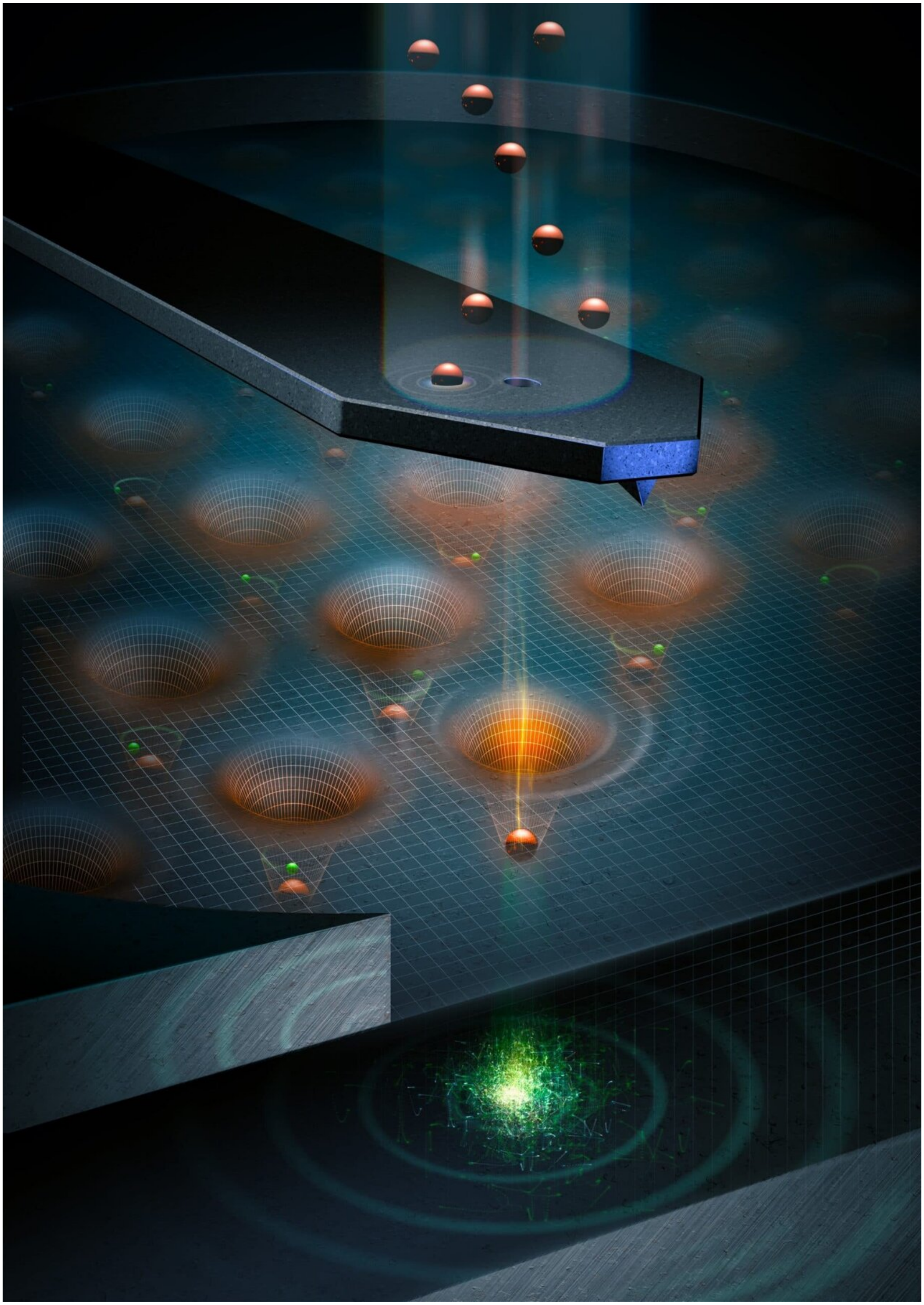

A University of Melbourne led team have perfected a technique for embedding single atoms in a silicon wafer one-by-one. Credit: University of Melbourne

A University of Melbourne-led team has perfected a technique for embedding single atoms in a silicon wafer one-by-one. Their technology offers the potential to make quantum computers using the same methods that have given us cheap and reliable conventional devices containing billions of transistors.

"We could 'hear' the electronic click as each atom dropped into one of 10,000 sites in our prototype device. Our vision is to use this technique to build a very, very large-scale quantum device," says Professor David Jamieson of The University of Melbourne, lead author of the Advanced Materials paper describing the process.

His co-authors are from UNSW Sydney, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Leibniz Institute of Surface Engineering (IOM), and RMIT Microscopy and Microanalysis Facility.

"We believe we ultimately could make large-scale machines based on single atom quantum bits by using our method and taking advantage of the manufacturing techniques that the semiconductor industry has perfected," he says.

Until now, implanting atoms in silicon has been a haphazard process, where a silicon chip gets showered with phosphorus which implant in a random pattern, like raindrops on a window.

"We embedded phosphorus ions, precisely counting each one, in a silicon substrate creating a qubit 'chip," which can then be used in lab experiments to test designs for large scale devices."

"This will allow us to engineer the quantum logic operations between large arrays of individual atoms, retaining highly accurate operations across the whole processor," says UNSW's Scientia Professor Andrea Morello, a joint author of the paper. "Instead of implanting many atoms in random locations and selecting the ones that work best, they will now be placed in an orderly array, similar to the transistors in conventional semiconductors computer chips."

"We used advanced technology developed for sensitive X-ray detectors and a special atomic force microscope originally developed for the Rosetta space mission along with a comprehensive computer model for the trajectory of ions implanted into silicon, developed in collaboration with our colleagues in Germany," says Dr. Alexander (Melvin) Jakob, first author of the paper, also from the University of Melbourne.

This new technique can create large scale patterns of counted atoms that are controlled so their quantum states can be manipulated, coupled and read-out.

The technique developed by Professor Jamieson and his colleagues takes advantage of the precision of the atomic force microscope, which has a sharp cantilever that gently 'touches' the surface of a chip with a positioning accuracy of just half a nanometre, about the same as the spacing between atoms in a silicon crystal.

The team drilled a tiny hole in this cantilever, so that when it was showered with phosphorus atoms one would occasionally drop through the hole and embed in the silicon substrate.

The key, however, was knowing precisely when one atom—and no more than one—had become embedded in the substrate. Then the cantilever could move to the next precise position on the array.

The team discovered that the kinetic energy of the atom as it plows into the silicon crystal and dissipates its energy by friction can be exploited to make a tiny electronic 'click."

That is how they know an atom has embedded in the silicon and to move to the next precise position.

"One atom colliding with a piece of silicon makes a very faint click, but we have invented very sensitive electronics used to detect the click, it's much amplified and gives a loud signal, a loud and reliable signal," says Professor Jamieson.

"That allows us to be very confident of our method. We can say, "Oh, there was a click. An atom just arrived." Now we can move the cantilever to the next spot and wait for the next atom."

"With our Centre partners, we have already produced ground-breaking results on single atom qubits made with this technique, but the new discovery will accelerate our work on large-scale devices," he says.

What is quantum computing and why is it important?

Quantum computers perform calculations by using the varied states of single atoms in the way that conventional computers use bits—the most basic unit of digital information.

But whereas a bit has only two possible values—1 or 0, true or false—a quantum bit, or qubit, can be placed in a superposition of 0 and 1. Pairs of qubits can be placed in even more peculiar superposition states, such as "01 plus 10," called entangled states. Adding even more qubits creates an exponentially growing number of entangled states, which constitute a powerful computer code that does not exist in classical computers. This exponential density of information is what gives quantum processors their computational advantage.

This basic quantum mechanical oddness has great potential to create computers capable of solving certain computational problems that conventional computers would find impossible due to their complexity.

Practical applications include new ways of optimizing timetables and finances, unbreakable cryptography and computational drug design, maybe even the rapid development of new vaccines.

"If you wanted to calculate the structure of the caffeine molecule, a very important molecule for physics, you can't do it with a classical computer because there are too many electrons," says Professor Jamieson.

"All these electrons obey quantum physics and the Schrödinger equation. But if you're going to calculate the structure of that molecule, there are so many electron-electron interactions, even the most powerful supercomputers in the world today can't do it.

"A quantum computer could do that, but you need many qubits because you've got to correct random errors and run a very complicated computer code."

Silicon chips containing arrays of single dopant atoms can be the material of choice for classical and quantum devices that exploit single donor spins. For example, group-V donors implanted in isotopically purified Si crystals are attractive for large-scale quantum computers. Useful attributes include long nuclear and electron spin lifetimes of P, hyperfine clock transitions in Bi or electrically controllable Sb nuclear spins.

Promising architectures require the ability to fabricate arrays of individual near-surface dopant atoms with high yield. Here, an on-chip detector electrode system with 70 eV root-mean-square noise (≈20 electrons) is employed to demonstrate near-room-temperature implantation of single 14 keV P+ ions.

The physics model for the ion–solid interaction shows an unprecedented upper-bound single-ion-detection confidence of 99.85 ± 0.02% for near-surface implants. As a result, the practical controlled silicon doping yield is limited by materials engineering factors including surface gate oxides in which detected ions may stop.

For a device with 6 nm gate oxide and 14 keV P+ implants, a yield limit of 98.1% is demonstrated. Thinner gate oxides allow this limit to converge to the upper-bound. Deterministic single-ion implantation can therefore be a viable materials engineering strategy for scalable dopant architectures in silicon devices.

More information: Alexander M. Jakob et al, Deterministic Shallow Dopant Implantation in Silicon with Detection Confidence Upper-Bound to 99.85% by Ion–Solid Interactions, *Advanced Materials* (2021). DOI: 10.1002/adma.202103235

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