'Molecular spintronics': New technology offers hope for quantum computing

October 23 2019, by Deepak Venkateshvaran

Molecular films for spintronics deposited inside a nitrogen glovebox. Credit: Olga Zadvorna and Deepak Venkateshvaran, Author provided

Quantum computers, which work according to the strange rules of quantum mechanics, may one day revolutionize the world. Once we have managed to build a powerful working machine, it will be able to solve some problems that take today's computers millions of years to compute.

Computers use bits (zero or one) to encode information. Quantum computers use "qubits"—which can take any value between zero and one—giving them huge processing power. But quantum systems are notoriously fragile, and although progress has been made to build working machines for some proposed applications, the task remains difficult. But a new approach, dubbed molecular spintronics, offers fresh hope.

In 1997, theoretical physicists Daniel Loss and David DiVincenzo laid down the general rules necessary for creating a quantum computer. While normal electronic devices use electric charge to represent information as zeros and ones, quantum computers often use electron "spin" states to represent qubits.

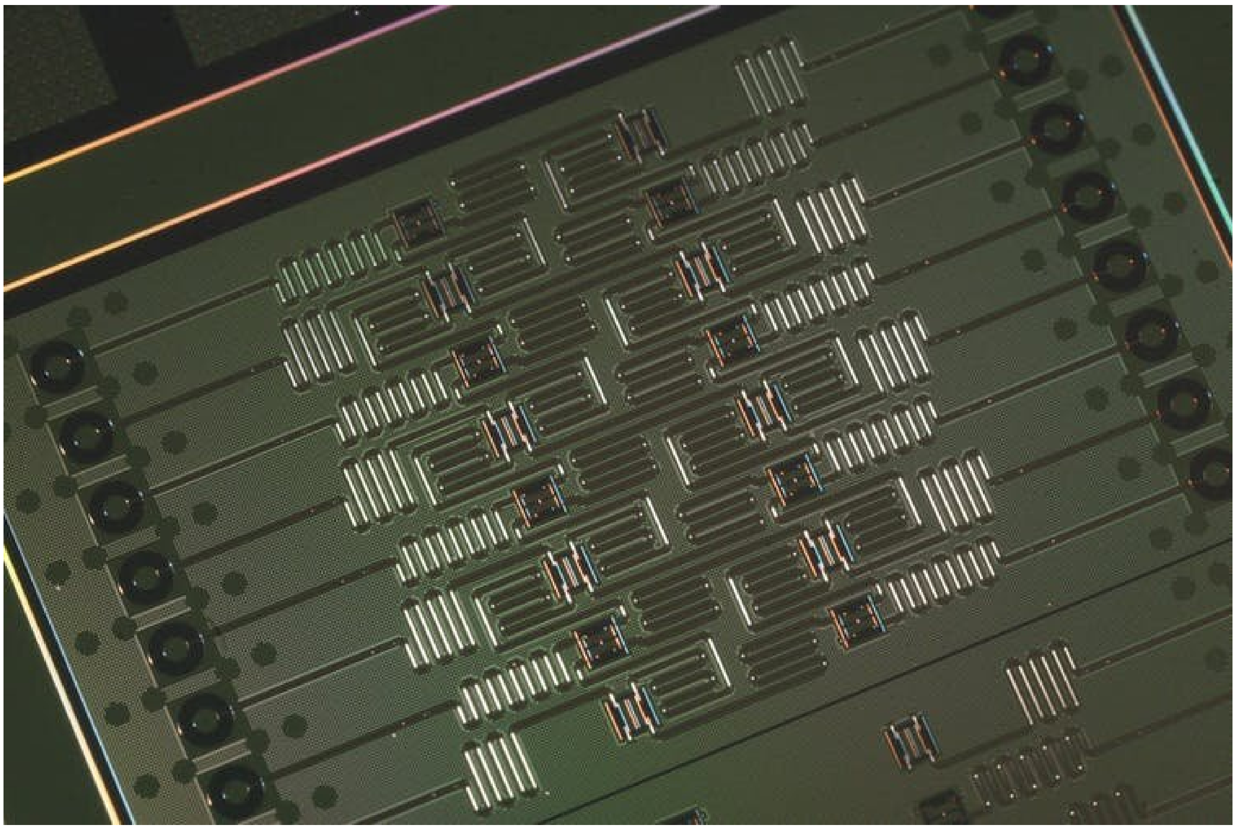
Spin is a fundamental quantity we've learned about through quantum mechanics. Unfortunately, it lacks an accurate counterpart in everyday experience, even though an analogy of a planet spinning on its own axis is sometimes used.

We do know that electrons spin in two different directions or "states" (dubbed up and down). According to quantum mechanics, each electron in a material spins in a combination (superposition) of these states—a certain bit up and a certain bit down. That's how you can get so many values rather than just zero or one.

Among the five requirements for building a quantum computer developed by Loss and DiVincenzo included the possibility of scaling up the system. More qubits mean more power. Another was making information survive for reasonable amounts of time once encoded, while others concerned the initialization, manipulation and read-out of the physical system.

Although originally conceived for a quantum computer based on electron spins in tiny particles of semiconductors, the proposal has now been implemented across many physical systems, including trapped ions, superconductors and diamonds.

But, unfortunately, these require a near perfect vacuum, extremely low temperatures and no disturbances to operate. They are also hard to scale up.



IBM 16 Qubit Processor. Credit: IBM Research/, CC BY-SA

Molecular spintronics

Spintronics is a form of electronics based on spin rather than charge.

Spin can be measured because it generates tiny magnetic fields. This technology, which often uses semiconductors for manipulating and measuring spin, has already had a huge impact on improving hard drive information storage.

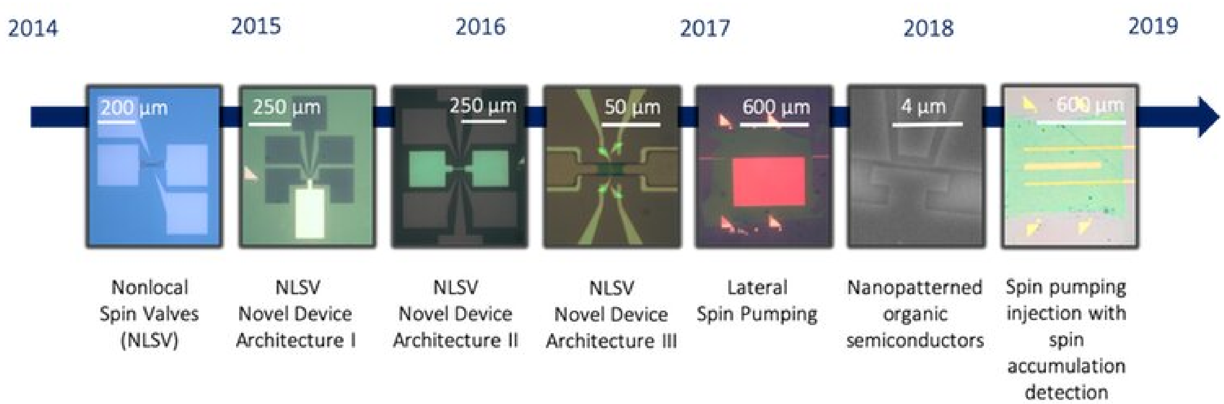
Now, scientists are realizing that spintronics can also be done in organic molecules containing rings of carbon atoms. And that connects it with a whole other research field called molecular electronics, which aims to build electronic devices from single molecules and films of molecules.

The combination has proven useful. By carefully controlling and manipulating an electron's spin within a molecule, it turns out we can actually do quantum computations. The preparation and readout of the electron's spin state on molecules is made by zapping them with electric or magnetic fields.

Carbon-based organic molecules and polymer semiconductors also address the criteria of being easy to scale up. They do this through an ability to form molecular frameworks, within which molecular qubits sit in close proximity with each other. The tiny size of a single molecule automatically favors packing large numbers of them together on a small chip.

In addition, organic materials disturb quantum spins less than other electronic materials do. That's because they are composed of relatively light elements such as carbon and hydrogen, resulting in weaker interactions with the spinning electrons. This avoids its spins from easily flipping state, causing them to be preserved for long periods of up to several microseconds.

In one propeller-shaped molecule, this duration can even be up to a millisecond. These relatively long times are sufficient for operations to be performed—another great advantage.



Exploratory organic spintronic devices built during the ERC SC2 Synergy Grant. Credit: Deepak Venkateshvaran

Remaining challenges

But we still have much left to learn. In addition to understanding what causes extended spin lifetimes on organic molecules, a grasp on how far these spins can travel within organic circuits is necessary for building efficient spin-based electronic circuits. The figure below shows some of our concepts for exploratory organic spintronic devices towards this goal.

There are also major challenges in getting such devices to work efficiently. The charged electrons that carry spins in an organic material constantly hop from molecule to molecule as they move. This hopping activity is unfortunately a source of electrical noise, making it difficult to electrically measure small spin current signatures using conventional architectures. That said, a relatively new technique known as spin pumping might prove suitable for generating spin currents with low noise in organic materials.

Another problem when trying to make organic molecules serious candidates within future quantum technologies is the ability to coherently control and measure spins on single molecules, or on a small number of molecules. This grand challenge is currently seeing tremendous progress. For example, a simple program for a quantum computer known as "Grover's search algorithm" was recently implemented on a single magnetic molecule. This algorithm is known to significantly reduce the time necessary to perform a search on an unsorted database.

In another report, an ensemble of molecules were successfully integrated into a hybrid superconducting device. It provided a proof-of-concept in combining molecular spin qubits with existing quantum architectures.

Much is left to be done, but in the current state of play, molecular spin systems are fast finding several new applications in quantum technologies. With the advantage of small size and long-lived spins, it is only a matter of time before they cement their spot in the roadmap for quantum technologies.

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