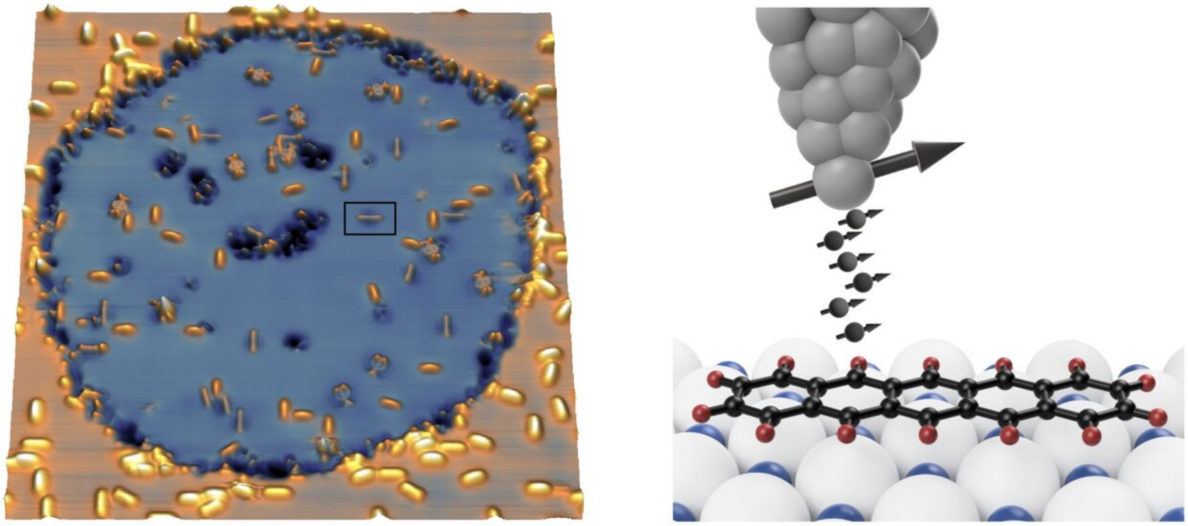
An alternative way to manipulate quantum states

June 20 2024, by Oliver Morsch



Left: Single pentacene molecules (yellow) on the insulating layer (blue). Right: Electrons with spins aligned in parallel (small arrows) tunnel from the tungsten tip (top) to the molecule (bottom). Credit: ETH Zürich / Aishwarya Vishwakarma und Stepan Kovarik

Researchers at ETH Zurich have shown that quantum states of single electron spins can be controlled by currents of electrons whose spins are evenly aligned. In the future, this method could be used in electronic circuit elements.

Electrons have an intrinsic angular momentum, the so-called spin, which means that they can align themselves along a magnetic field, much like a compass needle. In addition to the electric charge of electrons, which determines their behavior in electronic circuits, their spin is increasingly used for storing and processing data.

Already, one can buy MRAM memory elements (magnetic random access memories), in which information is stored in very small but still classical magnets—that is, containing very many electron spins. The MRAMs are based on currents of electrons with spins aligned in parallel that can change the magnetization at a particular point in a material.

Pietro Gambardella and his collaborators at ETH Zurich now show that such spin-polarized currents can also be used to control the quantum states of single electron spins. Their results, which have just been published in the journal *Science*, could be used in different technologies in the future, for instance in the control of quantum states of quantum bits (qubits).

Tunnel currents in single molecules

"Traditionally, electron spins are manipulated using electromagnetic fields such as radio-frequency waves or microwaves," says Sebastian Stepanow, a Senior Scientist in Gambardella's laboratory. This technique, also known as electron paramagnetic resonance, was developed in the mid-1940s and has since been used in different fields such as materials research, chemistry and biophysics.

"A few years ago, it was demonstrated that one can induce electron paramagnetic resonance in single atoms; however, so far the exact mechanism for this has been unclear," says Stepanow.

To study the quantum mechanical processes behind this mechanism more closely, the researchers prepared molecules of pentacene (an aromatic hydrocarbon) on a silver substrate. A thin insulating layer of magnesium oxide had previously been deposited on the substrate. This layer ensures that the electrons in the molecule behave more or less as they would in free space.

Using a scanning tunneling microscope, the researchers first characterized the electron clouds in the molecule. This involves measuring the current that is created when the electrons tunnel quantum mechanically from the tip of a tungsten needle to the molecule. According to the laws of classical physics, the electrons should not be able to hop across the gap between the tip of the needle and the molecule because they lack the necessary energy. Quantum mechanics, however, allows the electrons to "tunnel" through the gap in spite of that lack, which leads to a measurable current.

PhD student Stepan Kovarik in front of the vacuum chamber in which the samples for the experiment are produced. Credit: D-MATL / Kilian Dietrich, Maria Feofilova and Hasan Baysal

Miniature magnet on the tip of a needle

This tunnel current can be spin-polarized by first using the tungsten tip to pick up a few iron atoms, which are also on the insulating layer. On the tip, the iron atoms create a kind of miniature magnet. When a tunnel current flows through this magnet, the spins of the electrons in the current all align parallel to its magnetization.

The researchers applied a constant voltage as well as a fast-oscillating voltage to the magnetized tungsten tip, and they measured the resulting tunnel current. By varying the strength of both voltages and the frequency of the oscillating voltage, they were able to observe characteristic resonances in the tunnel current. The exact shape of these resonances allowed them to draw conclusions about the processes that occurred between the tunneling electrons and those of the molecule.

Direct spin control by polarized currents

From the data, Stepanow and his colleagues were able to glean two insights. On the one hand, the electron spins in the pentacene molecule reacted to the electromagnetic field created by the alternating voltage in the same way as in ordinary electron paramagnetic resonance. On the other hand, the shape of the resonances suggested that there was an additional process that also influenced the spins of the electrons in the molecule.

"That process is the so-called spin transfer torque, for which the pentacene molecule is an ideal model system," says Ph.D. student Stepan Kovarik. Spin transfer torque is an effect in which the spin of the molecule is changed under the influence of a spin-polarized current without the direct action of an electromagnetic field. The ETH researchers demonstrated that it is also possible to create quantum mechanical superposition states of the molecular spin in this way. Such superposition states are used, for instance, in quantum technologies.

"This spin control by spin-polarized currents at the quantum level opens up various possible applications," says Kovarik. In contrast to electromagnetic fields, spin-polarized currents act very locally and can be steered with a precision of less than a nanometer. Such currents could be used to address electronic circuit elements in quantum devices very precisely and thus, for instance, control the quantum states of magnetic qubits.

More information: Stepan Kovarik et al, Spin torque–driven electron paramagnetic resonance of a single spin in a pentacene molecule, *Science* (2024). DOI: 10.1126/science.adh4753

Provided by ETH Zurich

Citation: An alternative way to manipulate quantum states (2024, June 20) retrieved 24 June 2024 from https://phys.org/news/2024-06-alternative-quantum-states.html