Like fish on waves: electrons go surfing

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Physicists at the RUB, working in collaboration with researchers from Grenoble and Tokyo, have succeeded in taking a decisive step towards the development of more powerful computers. They were able to define two little quantum dots (QDs), occupied with electrons, in a semiconductor and to select a single electron from one of them using a sound wave, and then to transport it to the neighbouring QD. A single electron "surfs" thus from one quantum dot to the next like a fish on a wave. Such manipulation of a single electron will in the future also enable the combination of considerably more complex quantum bits instead of classical bits ("0" and "1" states). The researchers have reported their results in *Nature*, one of the highest-impact-factor international scientific journals.

Electrons can move as freely as fish in water in electric conductors (metals) and semiconductors such as silicon (Si) or gallium arsenide (GaAs), albeit not "swimming" of their own but moving owing to differences in voltage. Inside a metal, they are present as a huge number of fish that fill nearly the entire volume of water. In semiconductors, this "fish density" is not as high and so the distance between the electrons (fish) is much larger. The electrons can be concentrated in a thin layer near the surface by the application of an external voltage. The new method that the international team of researchers has developed now fulfils this "fisherman's dream" for semiconductor physicists. The electron "fish" are all in one layer close to the surface and easily, individually accessible from the surface.

Prof. Andreas Wieck, physicist at the RUB, points out that there are, however no, "big fish," all electrons being similar and even always identical, undistinguishable objects. The method that the researchers from Germany, France and Japan used, nevertheless enables the "emission" of individual electrons from the QD, moving them over a specific distance and then detecting them at the neighbouring QD. A distance of four micrometres (µm) was used in the experiment – this is twenty times larger than a highly integrated transistor. Targeted transport of individual electrons is possible in the following way: First, a QD is defined between the tips of four electrodes to form this zero-dimensional object, containing some hundred electrons. The scientists subsequently send a sound wave along the semiconductor surface using interdigital (like two combs fitted together without touching each other) electrodes to which they apply a radio frequency voltage. This method functions in the opposite way as the electrical discharge of a piezo ignition system in which a crystal is deformed to attain a voltage. The researchers applied voltage to the crystal and thus deform it, and the alternating voltage leads to the formation of a sound wave.

In a sample, this wave moves, for example, from left to right through the quantum dot at the velocity of sound – inside the crystal at three kilometres per second. Its height is adjusted so that it extracts exactly one "fish" from it. The latter subsequently surfs on the wave in a one-dimensional channel. The "fish" arrives at the neighbouring quantum dot 4 µm to the right thereof. The researchers were able to attain good statistics by repetition of the waves and measurements and thus capable of determining the reliability of the method. During the first experiments, the probability of emission and detection of a single electron with the wave was 96 and 92%, respectively.

It is not possible to differentiate between the electrons "fish", but they can be differently aligned because they rotate like little spinning tops. This is called the "spin" of the electron. For example one can align a fish with "its head upwards," let it be transported with the wave, and then detect it again at the target quantum dot still having "its head upwards." The time for the spin to change is longer than the surfing time on the wave, so the probability of this occurring is very high. The quantum bits of the future will also consist of such spin-polarized electrons. The researchers attained their results with samples prepared by so-called molecular beam epitaxy at the chair of Applied Solid State Physics at the Ruhr University Bochum. They were structured in Tokyo and subsequently measured in Grenoble. But not only the samples, also a further development of this concept originates from Bochum: Prof. Wieck already published his vision of an electron directional coupler with two parallel one-dimensional channels, in which the electrons can skip from one to the other channel, 21 years ago. The research team has in the meantime realized this vision based on the results presented here. A further publication is therefore to follow shortly.

More information: Sylvain Hermelin, Shintaro Takada, Michihisa Yamamoto, Seigo Tarucha, Andreas D. Wieck, Laurent Saminadayar, Christopher Bäuerle and Tristan Meunier: Electrons surfing on a sound wave as a platform for quantum optics with flying electrons. DOI: 10.1038/nature10416

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