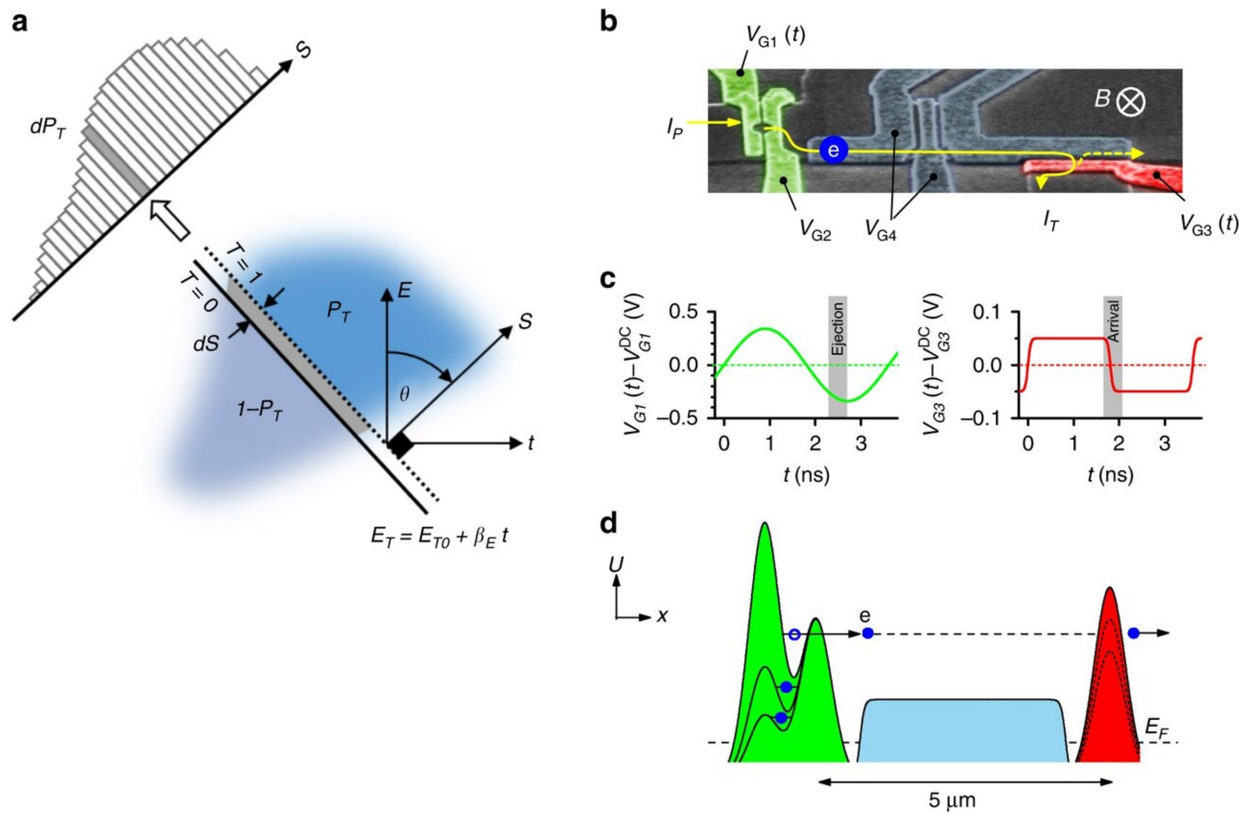
Scientists develop tomographic method to visualize state of 'solitary' electrons

December 4 2019



Electron tomography scheme using a modulated barrier. a An unknown Wigner distribution W(E,t) of a periodic electron source electron can be filtered using a linear-in-time threshold energy barrier set at height ET. The transmitted and reflected part, labelled PT and 1−PT result in a proportionate transmitted and reflected currents. A marginal projection of this distribution in the energy, time plane can be measured by fixing the ramp rate of the barrier βE, which sets ET, then moving the threshold boundary along the axis S in increments dS, while measuring the resulting changes in transmitted current. Repeating the experiment at different ramp rates (which sets the angle θ) gives enough information for a numerical reconstruction of the distribution. b False-colour scanning electron micrograph of device identical to that measured (see methods for details). The electron pump (left, highlighted green) injects pump current Ip. The barrier (right, highlighted red) selectively blocks electrons giving transmitted current IT≤IP. The path between these is indicated with a line. The gates along the path (controlled by VG4) depletes the underlying electron gas but do not block the high energy electrons. c Typical time-dependent control voltages for pump VG1 and probe barrier VG3 (each has a DC offset—see methods). d Electron potential U(x) along the electron path between source and probe barrier at three representative stages for pumping (left) and blocking (right). Credit: *Nature Communications*

Scientists at the National Physical Laboratory (NPL), working with the University of Latvia, the University of Berlin, Cambridge University and University College London, have developed a tomographic method to visualize the state of solitary electrons emitted from electron pumps.

Electron pumps are semiconductor devices that trap and emit single electrons 'on-demand.' The control of single electrons is a potentially useful technique for future quantum technology platforms, supporting precision electrical metrology, high-speed sensing, and quantum computation/communications.

The new method enables mapping of the shape of the electron in the energy-time plane and may reveal the quantum state of the electron. This would help development of quantum sensing schemes or enable encoding of quantum information onto the electron state.

Single electrons pumps: beyond charge transfer

It is often convenient to think of electricity as the flow of a continuous fluid and ignore its granularity. Even small electrical currents in the microampere range correspond to many trillions (1012) of electrons per second and the movement of individual electrons is often not apparent. Typically, the intrinsic "lumpiness" of electricity only reveals itself in the unwelcome form of background ("shot") noise in electronic components.

The development of nanometre-scale devices in highly-engineered metal/semiconductor structures have enabled scientists to take control of single electron effects for useful purposes. Single electron devices can be used as sensors of electric field, cryogenic thermometers, and as building blocks for certain kinds of "qubit."

The recent redefinition of the SI ampere enables single electron pumps to be used as primary current standards, creating a known current one electron at a time.

Another use of this "ultimate current source" is to inject single electrons into the waveguide that can exist along the edge of a semiconductor in a magnetic field. These electrons can travel for very long distances (tens of micrometers) without scattering. This effect provides a platform which is often loosely described as "electron quantum optics," by analogy with optical systems whose quantum behavior is well explored. The broad motivation for "swapping photons for electrons" is to develop solid-state quantum device infrastructures with possible advantages of scalability and ease of integration.

An early application could be the sensing of time dependent signals with a high effective bandwidth, using the fact that single ballistic electrons interact with circuit components on picosecond time scales. While this idea has been demonstrated by some of the same team in an earlier work, quantum versions of this effect are expected to have increased sensitivity. However, harnessing quantum effects and achieving high resolution sensing in the presence of potentially complicated interactions requires control and readout of the quantum state of single electrons. This question addressed in this new work is how to probe the state of electrons emitted from the pump.

Energy selective probes of electrons

In the devices used here, the electrons are emitted with relatively high energy, about 100 meV higher than any other electrons in the system, traveling through a channel where other electrons have been depleted.

The time delay between each electron (3.6 nanoseconds) is also larger than the arrival time distribution of each electron (only ~10 picoseconds long) so each electron is somewhat isolated from any other conduction electrons. One consequence of this solitary nature is that any probe that requires the presence of any other electrons, as other researchers have used for low energy electron sources, is not viable.

Instead this team used high speed control of a barrier placed in the path of the electrons. This is used to selectively block transmission, while measuring the transmission probability via the transmitted current.

This provides enough information for tomographic mapping of the electron energy, time distribution and a powerful visualization of the electronic shape in energy-time coordinates.

Approaching the quantum limit

The measured distributions were found to be concentrated into a small lens shape whose angle is set by electron ejection speed. This gives a way of shaping the distribution using experimental controls. The authors also considered how possible it is to get close to the intrinsic quantum fuzziness (imposed by the Heisenberg uncertainty principle) in these devices. Quantum-limited transmission of the electrons would enable the development of more sophisticated devices, like hot electron interferometers which could act as sensors. While the present experiments are operating just outside this regime, the imprinted dynamics of electron ejection are clear, and theoretical work suggests that information about the quantum state of the electron should come into focus in future experiments.

Jonathan Fletcher, Higher Research Scientist, National Physical Laboratory (NPL) says, "When you are working on current standards you can joke with people that your job is to count electrons. Now we are zooming-in on the quantum state of these electrons I guess it's more like we are feeling their shape somehow. This is important because it's what sets the resolution in sensing applications, and it tells us about the viability of using these electrons in more sophisticated circuits."

More information: J. D. Fletcher et al. Continuous-variable tomography of solitary electrons, *Nature Communications* (2019). DOI: 10.1038/s41467-019-13222-1

Provided by National Physical Laboratory