A farewell to wire?

Pulses of radiation could do anything, and more, that can be done with voltages and wires, according to researchers in Australia and Germany. *Wire Industry* spoke to the three men whose work may one day threaten large sectors of the wire and cable industry

When the pioneers of electrical devices began to build their circuits and devices, it must have seemed that electricity would always need wires. Even integrated circuits contain wires of a sort: guiding channels for the electrons. In some form, electrical current always needs a positive voltage at one end, a negative one at the other, and a well-defined electron channel in between. Or does it?

The assumption may not be valid for long. Physicists and engineers are now implementing a revolution in getting an electron current from A to B. There's no need to apply a voltage; these researchers use remote control. They shine radiation onto their circuits, and the electrons whizz away.

Axel Lorke, of Ludwig-Maximilians University in Munich, has already been approached by Siemens, which is interested in his work. Lorke is an expert in fabricating 'quantum dots': tiny areas, within a sheet of semiconductor, that can confine electrons. Lorke has now made sheets with an array of triangular 'anti-dots': areas which keep electrons out.

He irradiates this sheet using infrared radiation, and produces a dc current. And Lorke believes he may eventually be able to produce a new type of device for the electronics industry.

"It would certainly make some things easier, if one day people can fabricate large sheets of 'rectifying material'," he told *Wire Industry*. Cutting pieces from the sheet, and orienting them cleverly, it may be possible to build systems like transistors from a jigsaw of pieces. Once assembled, they can be operated using a pulse of radiation.

The trick works because all the triangular anti-dots on the sheet have their apex pointing in the same direction. The infrared radiation excites the electrons, sloshing them randomly around the material. But when they hit the anti-dots they are always deflected towards the apex.

"No matter which way you switch the current, you will always have a given output voltage," Lorke says. Out of random movement comes a strong, directed current.

Making the arrays is not complicated, and could be trivial compared to the complications of the electronics industry. "With a p-n junction or a Schottky diode, you run the electron across an interface. Here, we don't change the material at all: everything is done by shape," Lorke says.

From this, he believes, many innovations are possible. "You can imagine shooting electrons in certain directions, making electronic switchboards without wiring, or guiding them around to build transistors and rectifiers."

Axel Lorke

> **"You can imagine shooting electrons . . . making electronic switchboards without wiring, or guiding them around to build transistors and rectifiers."**

It is one thing to assemble a jigsaw of pieces to guide electrons around a predetermined path, but Peter Hanggi of Augsburg University in Germany wants to take things a step further. There may be no need, he told *Wire Industry*, to use physical obstacles to deflect electrons when they can be steered by the applied radiation itself.

Hanggi is thinking of what he calls the 'quantum ratchet'. Just as with ordinary ratchets, the quantum ratchet produces movement in one direction from a force that may be acting at random.

For a ratchet screwdriver, that means one way turns from a back-and-forth motion. For electrons, it means taking the backward and forward oscillations of electromagnetic radiation and producing one-way electron movement: ac signal becomes dc current.

The electrons can even move against an applied voltage. "Nature wouldn't normally allow this 'uphill' motion, but by ▶

having this external control they go where they wouldn't normally go," Hanggi told *Wire Industry*.

He explained that the process mimics the asymmetric 'sawtooth' of the traditional ratchet with an asymmetric electric potential inside a quantum dot. The electrical barrier has the same height at each end, but one barrier is steeper than the other.

Electrons follow the laws of quantum mechanics, which allow them to act like a particle or a wave, depending on their surroundings. So, while Axel Lorke's electrons are behaving like bouncing balls on a pinball table, Hanggi's electrons are more like waves.

Held in the quantum dot, the tails of these waves can 'leak' out through the barrier, allowing the electrons to do the same. This 'tunnelling' can occur in both directions, but it happens more easily when the barrier is thin.

Since the two barriers are different, applying an ac signal affects the thickness of the barriers in different ways on different halves of the cycle. Hanggi did the maths, and predicted that an ac signal will produce an intermittent dc current.

There are also interference effects, where the electron 'waves' within the quantum dot combine to form a whole mess of peaks and troughs within the space. Sometimes those large peaks will sit at one edge of the dot, allowing electrons to escape over that side.

Heiner Linke of the University of Sydney, Australia has brought Hanggi's ideas into reality using strings of connected quantum dots about a micrometre long.

He has seen both the tunnelling and the interference behaviours, with some added strange effects. With the interference, for instance, changing the level of the applied signal could reverse the current: a slight change in the conditions can shift the peaks enough to allow electrons to escape on the other side instead.

It is so sensitive, in fact, that Linke cannot predict exactly what will happen. "It's sort of a drawback that you don't have full control, but it's an advantage that you can control it very sensitively once you have it," he told *Wire Industry*.

With the tunnelling, Linke saw the current reverse when the temperature was changed. This happens because a change in temperature changes the number of electrons available to tunnel through a barrier.

Heiner Linke

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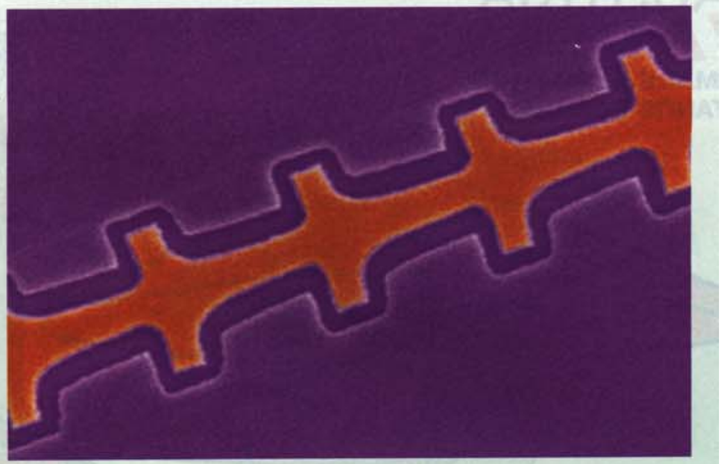


Scanning electron micrograph (SEM) image of a tunnelling ratchet. The device consists of a gallium arsenide chip that was patterned using electron beam lithography and wet etching. Electrons travelling along the orange channel formed by a string of funnel-shaped units (each about 1 μm in size) are confined at the narrowest sections, and therefore have a 'sawtooth' potential. When an ac voltage is applied a rectified current is generated, the direction of which can be tuned by the temperature of the wire.

All these effects are potentially useful in using simple ac signals to guide electrons around a material without the need for channels and wires: as long as there are structures on the material that introduce some asymmetry to the picture, applying the right kind of pulse could, in theory, cause electron movement in any direction.

Hanggi is even aiming to do away with the need for asymmetric structures.

He believes he can combine two ac signals to drive electrons around a surface in any direction. Altering the phase difference between these signals provides a simple steering mechanism, just like having two oars on a rowing boat.

Applying the right kind of pulse could, in theory, cause an electron movement in any direction

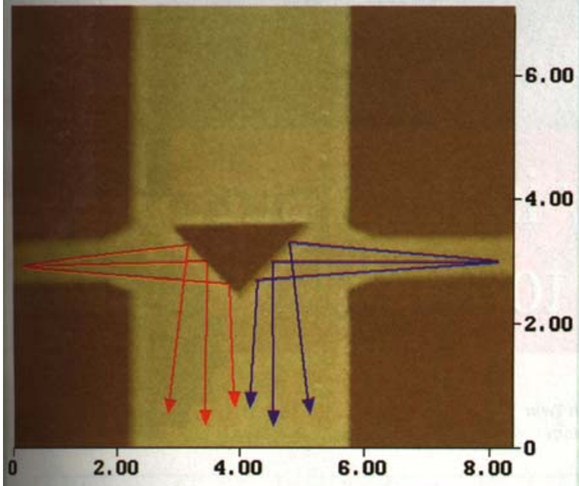
Hanggi is currently working with Axel Lorke to achieve this in a practical experiment. In the end, he thinks, pulses of radiation could do anything, and more, that can be done with voltages and wires.

There is one drawback with all these systems, however, and it is a problem that may keep the quantum ratchets from ever reaching the commercial world.

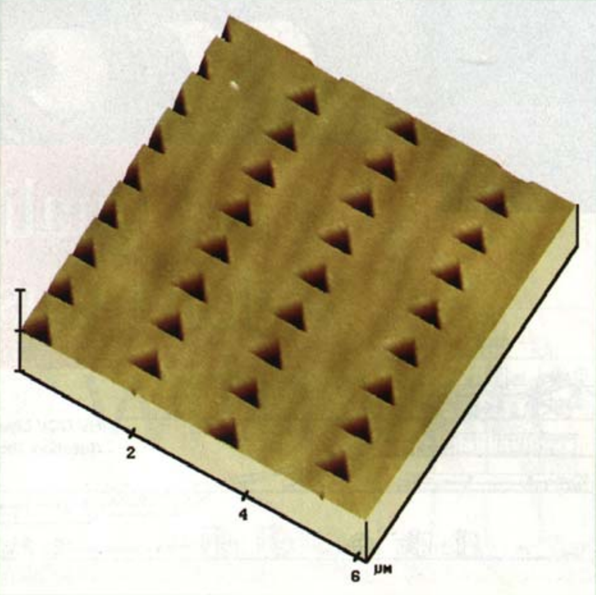
Quantum systems are extremely sensitive, and so can be disturbed by the thermal energy of even extremely low temperatures.

Linke's interference experiments have to run at 0.3 K (-272.7 °C), and even the less sensitive tunnelling effects start to blur out above four or five Kelvin.

Lorke's 'pinball' techniques have more chance of making it: ▶



Atomic force micrograph (AFM) image of a 'ballistic rectifier'. Parts of the sample were etched away (the darker parts of the image) to give the active area (the lighter parts) a particular shape which determines the function. This is fundamentally different to more 'usual' devices, with which materials' properties play the leading role. Electrons from the input leads (the narrow leads on the left and right of the picture) are injected into the junction. They bounce off the triangular anti-dot in the centre and are guided to a predetermined output lead, irrespective of the input current directions. Thus, the polarity of voltage measured between the output leads is independent of the polarity of the input current



Atomic force micrograph (AFM) of an array of 'anti-dots', tiny voids in the surface of the semiconductor. Electrons will bounce off these voids almost specularly. When the entire array is rocked (eg by the high frequency electric field of far-infrared radiation) the triangular shape of the scatterers will act on the electrons like a weir on fish, pushing them along to create a dc-current. The symmetry of the lattice has been optimised to observe a transverse signal (as in the ballistic rectifier)

they should work at up to 77 K, and may eventually even be operable at room temperature.

Clearly, no-one yet knows what will come of these ideas. "There are plenty of people out there who say that it will never work," says Heiner Linke. "On the other hand," he adds, "there are also plenty of people and funding agencies who think that it is worth a shot."

Peter Hanggi is willing to go much further: "I am convinced that the time will come when these new concepts will find their way into practical applications and devices," he told *Wire Industry*.

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Guiding electrons around without using some sort of wire is, he believes, "much too appealing" not to be developed for any number of real-life applications.

"Much too appealing" unless, of course, you happen to be involved in the wire industry. ■