

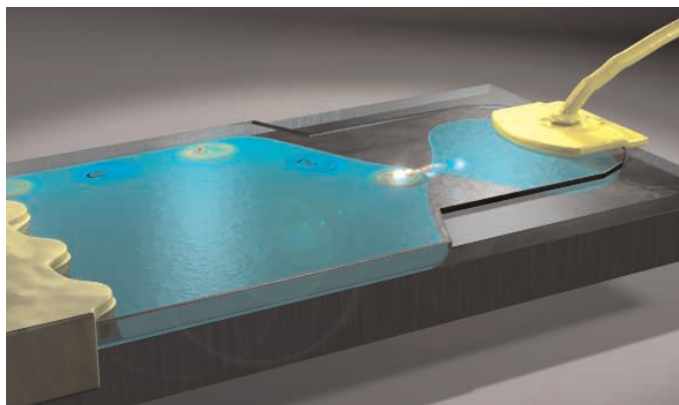
One Electron Makes Current Flow

Stephen Giblin

Even the smallest components in a modern desktop computer use tens of thousands of electrons at a time to implement classical logic (the conventional 1s and 0s of binary computation). A computer that operated on single electrons, however, could in principle implement quantum logic functions (quantum bits or “qubits” that could perform computational tasks that are beyond the ability of classical computers). One proposed architecture for a single-electron computer could be realized in a two-dimensional electron gas (2DEG), a special kind of reservoir in which electrons can travel without dissipation (1). On page 1169 of this issue, Fève *et al.* (2) report on an important step toward this vision: a device that can emit single electrons into a 2DEG and absorb them again on nanosecond time scales. With such a controllable electron source, researchers will now be able to set up one or more electrons in well-defined quantum states, which are crucial for any future quantum computer.

A macroscopic electric current, as measured by an ammeter, is the result of the movement of many discrete charges around a circuit. But this discreteness manifests itself as “shot noise”—one of the sources of random fluctuation in the current that engineers need to understand in order to design working components and circuits. Shot noise was first observed by Schottky in 1914, but it was not until the late 1980s that advances in nanofabrication technology first enabled control over the movement of individual electrons, giving birth to the field of single electronics (3).

The key requirement of a single-electron device is that a small (typically <100 nm) conducting island should be isolated from the rest of the electrical circuit by tunnel barriers, thin regions of insulator through which electrons can “tunnel” according to the laws of quantum mechanics. If the island is small enough, the number of electrons it holds can be changed



One at a time. A quantum dot (blue region at right) can emit single electrons through a tunnel barrier into a 2DEG (blue region at left) in response to changing the voltage on a nearby control electrode (gold contact at right). If an ac voltage is applied to the control electrode, an ac current will flow through the device. Fève *et al.* have calculated this current by considering the dot and barrier as a quantum RC circuit. (The image is greatly exaggerated in size.)

precisely by adjusting external voltages. Suitable islands and tunnel barriers have been made with metals and metal oxides (4), and also with the versatile gallium arsenide 2DEG system (5), which has the additional advantage that the height of the tunnel barriers can be changed easily with a control voltage, making it more or less likely for electrons to pass through. Islands formed in a 2DEG are usually referred to as “quantum dots” or “artificial atoms,” because the electrons trapped inside them occupy quantum energy levels similar to those in a real atom.

By combining tunnel barriers with one or more islands, researchers can make charge detectors with subelectron resolution, called single-electron transistors, as well as devices, known as turnstiles or pumps, that can transfer electrons one at a time from a source to a drain electrode (6). Pumps and turnstiles continue to be of great interest to the electrical metrology community because they offer a new way of generating an accurately known dc current—a primary standard—based on only the electronic charge e and frequency f . Pumps based on metal-oxide technology (7, 8) and on gallium arsenide 2DEGs (9) are being extensively studied.

The device studied by Fève *et al.*, illustrated schematically in the figure, is much simpler than a pump or turnstile. It consists of just one quantum dot and a tunnel barrier through which electrons can enter and leave

A single electron pumped in and out of a quantum dot could be useful as a calibration standard for electronics or as the basic unit of a quantum computer.

the dot. Changing the voltage applied to the control electrode alters the spacing of the dot energy levels, and thus the number of electrons in the dot. Another voltage changes the height of the tunnel barrier. Because of the gap between the control electrode and the dot, no dc current will flow through the device. The authors measure, and calculate, the ac current I_{ac} in response to an ac voltage V_{ac} applied to the electrode.

To calculate I_{ac} , it is necessary to know the impedance of the device (that is, the extent of its opposition to current flow). The tunnel barrier behaves like a variable resistor R , and the dot forms a capacitance C with the electrode.

Hence, the device impedance is due to the sum of C and R in series. One would imagine it should be possible to calculate R from the properties of the tunnel barrier, and C from the properties of the quantum dot and the geometry of the electrode, thus determining the impedance. However, in the 2DEG, where electrons can propagate for some distance without interacting with other electrons, R and C cannot be treated as separate entities.

The main achievement of Fève *et al.* is their calculation of the impedance by theoretically treating the device as a quantum RC circuit. Starting from an equation describing the microscopic quantum-mechanical motion of electrons through the tunnel barrier and into the capacitor, they are able to work out the macroscopic parameters R and C . The quantum RC circuit has some bizarre properties. For example, changing the height of the tunnel barrier changes C but not R , exactly the reverse of what one would expect.

In an earlier paper, they restricted the scope of the experiment and theory to small values of V_{ac} (10). In the present work, they expand both theory and experiment to encompass large-amplitude excitations—large enough to cause electrons to tunnel in and out of the dot. In all cases, the quantum RC circuit theory successfully predicts I_{ac} as a function of the two control parameters, V_{ac} and the height of the tunnel barrier. Over a particular range of these two parameters,

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something rather special happens: Exactly one electron is ejected from the dot and then reabsorbed during one cycle of V_{ac} . Then, I_{ac} has an exactly quantized value, analogous to the quantized dc currents generated by pumps and turnstiles.

The authors have used the macroscopic quantity I_{ac} as a probe of the circuit dynamics and have shown that electrons can be emitted into, and reabsorbed from, the 2DEG in a controllable manner on nanosecond time scales. This is an important first step toward a 2DEG quantum computer. The next step will be to show that two electrons can be made to

interact in a “coherent” manner, that is, without their delicate quantum states being disturbed by external influences. This will require advances in single-electron detectors, which do not currently operate fast enough to probe the dynamics of electrons in the 2DEG. There is much interesting work to be done and, in the future, scientists and engineers might think of single-electron behavior not just as a cause of noise but as a tool to solve problems.

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CHEMISTRY

The Direct Approach

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The formation of carbon-carbon bonds is central to organic synthesis because it provides the carbon skeleton that often defines the structure and function of an organic compound. Coupling one aromatic compound with another is one of the most useful types of carbon-carbon bond formation, allowing chemists to construct the carbon frameworks for a wide range of materials, electronic devices, and pharmaceutical agents (1). On page 1172 of this issue (2), Stuart and Fagnou report an innovative new approach for accomplishing this type of bond formation by metal-catalyzed oxidative coupling of the simplest of aromatic starting materials.

Most methods for coupling two aromatic compounds require both reaction partners to be converted into an intermediate before the reaction. In one reaction partner, a halogen or related electrophilic group is attached to the site where a bond is to be formed; the other reaction partner is similarly preactivated by placing a metal at the site of bond formation (see the figure, reaction type 1) (1, 3). Several transition metal catalysts have been developed to accomplish general, extremely efficient, high-yield reactions between such preactivated partners. However, although the approach is very powerful and extensively used, it produces metal and halide byproducts. Furthermore, preparation of the preactivated coupling partners often requires additional synthetic operations.

Over the past decade, impressive advances

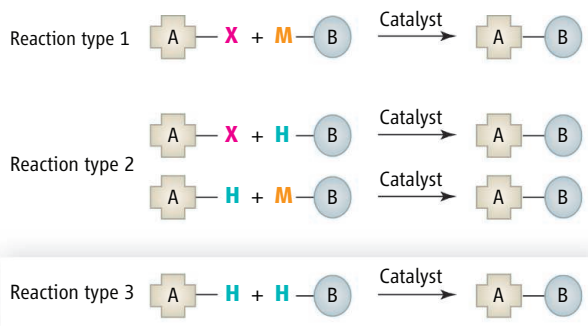
have been made in enhancing the efficiency of coupling aromatic compounds by direct arylation processes. In this approach, one of the preactivated starting materials is replaced with a simpler structure that does not incorporate the activating group (see the figure, reaction type 2) (4). This approach is no longer just of academic interest but is also being used increasingly for industrial applications (5), because only one preactivated partner needs to be prepared and waste byproducts can be reduced.

Stuart and Fagnou have now gone one step further by coupling two simple aromatic compounds, neither of which requires the attachment of activating groups (see the figure, reaction type 3). The authors have solved a number of potential problems, not the least of which is the selective coupling of the two aromatic compounds to produce the desired product without each compound also coupling with itself to produce undesired side products (6). The authors were able to avoid this type of side reaction by coupling two classes of aromatic compounds that have different electronic character and C-H acidity; one of these classes is the indole structure that is prevalent in drugs. The use of palladium trifluoroacetate as the catalyst and of 3-nitropyridine and cesium pivalate as additives were

Aromatic compounds can be coupled without having to preactivate the reactants. The method is more efficient and generates less waste than other approaches.

critical to the success of this coupling reaction. Excess copper acetate was also required as the terminal oxidant to enable catalyst turnover.

The approach demonstrated by Stuart and Fagnou could have immense practical importance for the synthesis of materials, electronic



How to couple two different aromatic compounds. In reaction type 1, both aromatic compounds are preactivated (compound A with a halide X and compound B with an electropositive metal M). In reaction type 2, only one of the aromatic compounds is preactivated. In reaction type 3, simple aromatic compounds are coupled, neither of which is preactivated. Stuart and Fagnou now show how reaction type 3 can be realized.

devices, and drugs. However, further advances will be required to enhance reaction efficiency, for example, by reducing catalyst and terminal oxidant loading levels. It also remains to be seen how many different combinations of aromatic compounds can effectively be coupled without the occurrence of undesired self-coupling side reactions.

An additional challenge of this aromatic coupling process is to ensure selective coupling at a specific site on each molecule when

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