Coupled Quantum Dots as Artificial Molecules

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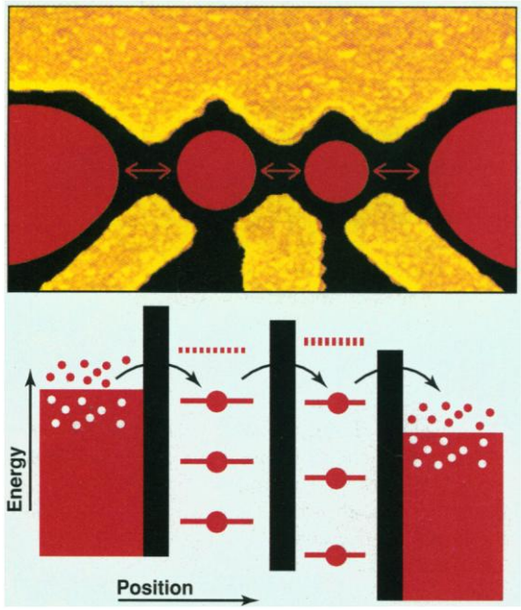
Over the last decade, as semiconductor devices have become smaller, physicists have increasingly turned to quantum mechanics to understand them. In particular, some very simple ideas about atoms and molecules appear to explain the seemingly exotic properties of artificially fabricated semiconductor devices. One such device is the quantum dot. This structure is essentially a tiny box that contains a small, adjustable number of electrons. Because of its small size and low occupancy, such an electron box can exhibit atomic properties. For instance, changing the number of electrons on a quantum dot by one costs a finite, measurable energy, which is analogous to the ionization energy of an atom. When the number of electrons on the dot is kept constant, the spectrum of electron energies is discrete just like the energy levels in an atom. The excitation energies arise from transitions of electrons between discrete, single-particle orbitals, like those that house atomic electrons. With such a strong correspondence between single quantum dots and atoms, physicists have recently been wondering whether the analogy can go farther: Can coupled quantum dots act like the coupled atoms in a molecule? Recent experiments (*1*–*4*) indicate that this might be the case.

Quantum dots are, in fact, tiny transistors, and they are made with transistor fabrication techniques in semiconducting materials. However, their specific design and their small size give dots atomic-like properties. Also similar to transistors, many dot devices are fabricated with a third terminal, the gate, which allows control over the number of electrons on the dot. This is like having a knob that tunes an atom to different elements of the periodic table. Measurements of current versus voltage directly reveal the discrete excitation spectrum. This is manifested by steps in the current that occur every time the applied voltage supplies enough energy to make a new excited state available for transport.

Attaching current and voltage leads, besides providing spectroscopic information, also points to a fundamental problem in measuring quantum devices. The coupling to large classical, dissipative systems (the measuring device) is destructive for the quantum effects of a small object like the quantum dot. The stronger the coupling to the dissipative system, the shorter the time an electron spends in a particular quantum state and, by the Heisenberg uncertainty relation, the greater the broadening of that discrete energy state. In addition to this uncertainty, smearing is a contribution that is attributable to the finite temperature of the electrons in the leads. This thermal smearing is usually suppressed by making measurements at very low temperatures, typically in the millikelvin range.



Connect the dots. (**Top**) The two–quantum dot device used in (*3*). The red parts schematically indicate the regions where the electrons are located. Voltages applied to the yellow gates allow tuning of the sizes of the red dot regions, and also the coupling (indicated by the arrows) to the leads on the left and right and between the two dots. (**Bottom**) Coupled-dot energy diagram. Electrons can only occupy discrete energy states in the two quantum dots (the dashed states are unoccupied). Because the energy states are continuous in the two leads, temperature causes a smearing of the occupation probability around the Fermi energy, as indicated by the occupied red dots and unoccupied white dots. Current can only flow when the energy states are aligned, which is indicated by the arrows.

A different approach to suppress the finite temperature of the leads, utilized recently (*3*), is to put two quantum dots in series, as shown in the figure. In this configuration, one dot basically acts as a low-temperature–pass filter for the other, such that only cold electrons contribute to current. When the energy states in the dots are separated by more than the thermal energy, the electrons cannot be thermally excited to higher states. This effectively leaves the dot at zero temperature. The energy diagram shows that current only flows when the energy states of the two dots are aligned. Upon increasing the voltage, the energy states in one dot move with respect to the states in the other. Alignment of two states results in a maximum in the current. Upon further increasing the voltage, the current decreases when the states are misaligned. This implies a negative differential resistance. These effects are demonstrated in the experiments by van der Vaart *et al.* (*3*) and Dixon *et al.* (*4*). Although the actual temperature of the current and voltage probes in the measurements of van der Vaart *et al.* is about 0.1 K, a detailed analysis of this data shows that the effective temperature was indeed suppressed to at least below 0.03 K. The residual smearing was mostly due to the uncertainty coupling to the leads. This experiment shows that a quantum dot can effectively cool another quantum dot. Such a cooling effect was also advocated in a proposal in which quantum dot devices, in a somewhat different configuration, served as on-chip refrigerators (*5*).

How do these coupled-dot experiments point to analogies with ionic or covalent molecules? In ionic molecules, binding occurs because a static redistribution of electrons between atoms leads to attractive Coulomb forces. The experiments show that coupled quantum dots can indeed be thought of as ionic molecules. The coupled-dot devices show a significant binding energy (*1*–*4*), which is usually understood in terms of the capacitance between the dots. However, a more detailed understanding of the experiment of Waugh *et al.* (*1*) requires an interesting modification of the concept of capacitance because of tunneling of the charge between the dots. The important transport properties of ionically coupled dots are the negative differential resistance and the refrigeration effects discussed above.

Some evidence has been given by Blick *et al.* (*2*) for the analog of covalent molecules in which two electron states are quantum mechanically coupled. The main requirement for covalent binding is that an electron can tunnel many times between the two dots with conservation of phase. This means that the electron cannot be thought of as a particle that sits in one

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particular dot but rather as a coherent wave that is delocalized over the two dots. The new state of the molecule as a whole is lower in energy than the states of the individual dots. This energy lowering is the binding force between the two dots. The experimental realization of two coherently coupled quantum dots would be very interesting because it has properties similar to those of a tunnel junction between two superconductors. In such two-level systems, radiation effects are very interesting. For instance, if the states in the two dots are not completely aligned, the energy difference may be overcome by the absorption and emission of photons from microwave radiation. This is expected to lead to new effects that are analogous to the ammonia molecule maser (6) or the alternating-current Josephson effect (7).

References

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Revisiting the Fluid Mosaic Model of Membranes

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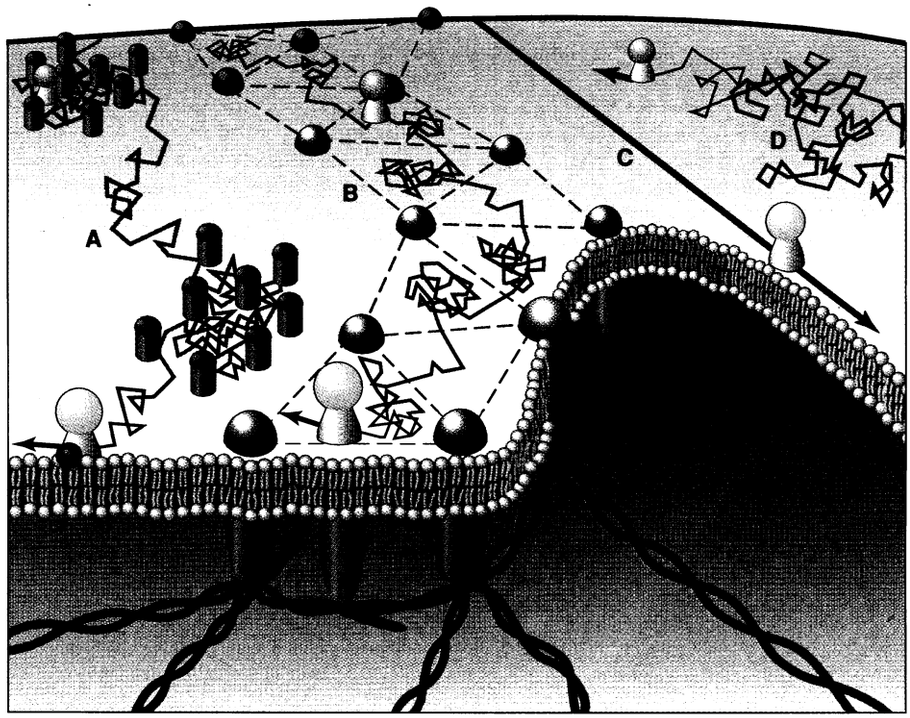
The fluid mosaic model, described over 20 years ago, characterized the cell membrane as "a two-dimensional oriented solution of integral proteins . . . in the viscous phospholipid bilayer" (*1*). This concept continues as the framework for thinking about the dynamic structure of biomembranes, but certain aspects now need revision. Most membrane proteins do not enjoy the continuous, unrestricted lateral diffusion characteristic of a random, two-dimensional fluid. Instead, proteins diffuse in a more complicated way that indicates considerable lateral heterogeneity in membrane structure, at least on a nanometer scale. Certain proteins are transiently confined to small domains in seemingly undifferentiated membrane regions. Another surprise is that a few membrane proteins undergo rapid, forward-directed transport toward the cell edge, perhaps propelled by cytoskeletal motors.

This more detailed view of the life of a membrane protein has emerged as a result of one old and two newer methods. For the past two decades, fluorescence recovery after photobleaching (FRAP) has been the major tool for measuring the lateral mobility of membrane components labeled directly with fluorophores or with fluorescent antibodies. In this method, a short pulse of intense laser light irreversibly destroys (photobleaches) the fluorophores in a micrometer-sized spot. The fluorescence gradually returns as fluorophores from the surrounding region diffuse into the irradiated area. FRAP experiments can reveal the fraction of labeled membrane proteins or lipids that can move, the rate of this movement (characterized by the lateral diffusion coefficient), and the fraction of proteins that cannot move on the time scale of the experiment. These apparently nondiffusing proteins are called the immobile fraction; a quantity that is frequently large and usually of unknown origin.

A second method, single-particle tracking (SPT), directly complements the information that is obtained from averaging the movement of hundreds to thousands of molecules in a FRAP experiment. In SPT, a membrane component is specifically labeled with an antibody-coated submicrometer colloidal gold or fluorescent particle, and the trajectory of the labeled molecule is followed with nanometer precision with digital imaging microscopy (*2*, *3*). Visualization of individual protein motions can reveal submicroscopic membrane structures as the protein encounters obstacles in its path, although careful data analysis is required to distinguish between nonrandom and random movements (*4*).

The third method, recently applied to membranes, is the optical laser trap, allowing further characterization of the obstacles a membrane protein encounters. Proteins are labeled with submicrometer beads and manipulated in the plane of the membrane with laser light. Optical trapping occurs when a near-infrared laser beam with a bell-shaped intensity profile is focused on the bead attached to the protein. Optical forces on the bead, which are directed toward the highest intensity of the beam, trap the particle (*5*). By moving the laser beam or the microscope stage, the labeled protein can



Lateral transport modes on the cell surface. (**A**) Transient confinement by obstacle clusters (**B**) or by the cytoskeleton, (**C**) directed motion, and (**D**) free random diffusion.

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