PERSPECTIVES: SUPERCONDUCTIVITY

Toward Tunable Superconducting Electronics

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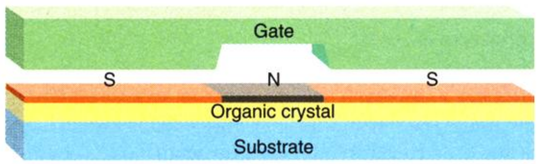
Recent years have seen remarkable progress in experimental studies of submicrometer electronic devices. Observations of discrete electronic modes and wave interference effects have demonstrated that individual quantum states can be accessed and manipulated in solid state systems. Devices in which ordinary conducting materials are integrated with superconductors are particularly interesting candidates for fundamental studies and applications. On page 252 of this issue, Schön *et al.* (*1*) report a method for creating tunable superconductor–normal metal electronic circuits at the turn of a knob. This may enable the creation of quantum switching networks with a potentially vast range of applications.

In a superconductor, the conducting electrons are condensed into a single macroscopic quantum state. The condensate consists of correlated electron pairs called Cooper pairs, which have a common wave function. When conducting materials are embedded in a superconducting environment, special correlations are induced among the "normal" conducting electrons. This proximity effect modifies the transport and other properties of the conductor substantially. The most spectacular manifestation is the Josephson effect—the possibility for a nondissipative current, a supercurrent, to flow through the conductor. The Josephson effect (*2*) was first observed in superconductor-insulator-superconductor (SIS) tunnel junctions. Since then, it has also been seen in various structures (weak links) in which the nonsuperconducting region was not a tunnel barrier but rather a region with high conductivity. A typical example of a weak link is a superconductor–normal metal–superconductor (SNS) junction.

An SNS junction can be viewed as a quantum potential well between superconducting electrodes, enabling electrons to be trapped in the normal region. The density of the localized states depends on the distance to the superconductor, the transparency of the NS interfaces, and the difference between the phases of the condensate wave functions in the electrodes. In such a junction, the transport properties of the normal conductor may be controlled through varying the superconducting phase difference.

There is a remarkable difference between the properties of the localized states in proximity wells and in normal attractive potential wells (like those that bind atomic electrons). The localized states in normal quantum wells cannot carry current, whereas proximity wells are transparent for the supercurrent. This unique property of the proximity conductor which underlies the Josephson effect is related to the electron correlations created by a process known as Andreev reflection (*3*). In this mechanism, a low-energy electron approaching a perfect NS interface from the side of the normal conductor cannot penetrate on its own into the superconductor, where electrons can only exist in Cooper pairs. On the other hand, the electron cannot be reflected because of the weak potential barrier formed by the NS interface. The problem is solved by converting the electron into a hole that retraces the electron trajectory and simultaneously creating a Cooper pair in the superconductor. Each Andreev reflection event is therefore accompanied by the transfer of a charge of 2e through the NS interface.



Field-effect SNS junction. The electrostatic gate induces nonhomogeneous electron or hole doping in a monolayer-thick organic film. The superconducting regions have a larger charge carrier concentration than the central region, which behaves like a normal conductor. The size of the central region and the magnitude of the superconducting gap are controlled by the gate voltage.

The quantum wavelength of correlated electrons in proximity structures is much larger than the wavelength of normal electrons. This is because the former is related to the superconducting coherence length (often ~0.1 to 1 micrometer). This enhances all quantum effects in proximity conductors considerably, even in materials with high electron concentrations. Together with the controllability of quantum effects, this makes proximity conductors very attractive for potential applications in quantum electronics.

During the last decade, submicrometer-scale proximity effects have been thoroughly investigated and are now rather well understood. Many quantum interference phenomena have been observed experimentally (*4–6*). As in many other areas of solid state physics, the driving force was the progress in the development of new materials and devices. The recent explosion of experimental activity on the proximity effect became possible because of successes in the fabrication of mesoscopic metallic SNS junctions with submicrometer separation of superconducting electrodes. Another novel device that can also show the proximity effect is the Josephson field-effect transistor (JOFET) (*7*). A JOFET is usually fabricated by connecting a two-dimensional electron gas (2DEG) to superconducting bulk electrodes, forming an S-2DEG-S structure. To achieve the proximity effect in such a structure, the strong potential barrier, called the Schottky barrier, between the superconductor and the 2DEG, which commonly exists because of the bending of the potential at the metal-semiconductor interface, must be suppressed. This problem has been solved for InAs-based devices, where control of the Josephson current and the current-voltage characteristics in JOFET is achieved by changing the geometry and resistance of the proximity region through a capacitive gate that influences the electron density in the 2DEG region. In contrast to metallic junctions with typically strong structural disorder in the normal regions, ballistic transport has been demonstrated in JOFETs. Such devices have produced many interesting and important results, but they also have several limitations, such as a low critical Josephson current, interface disorder, and problems with attaining few-mode quantum transport regimes.

In several recent papers, Batlogg and co-workers at Bell Labs have developed a technique for doping organic crystalline films by field effect. In this method, the electric field from the gate electrode (see the figure) is used to attract free charges to the surface and create a dilute 2D gas of charge carriers. Recently, the group has demonstrated that these metallic 2D regions can be superconducting in a number of organic films (*8*), with a record critical temperature T_c of 54 K in hole-doped C_{60} (*9*). The same group has now taken a decisive step toward a practical device by im-

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plementing a field-effect gate-induced Josephson junction (*1*). In this device, the electrodes are field-effect–doped such that the system becomes superconducting below a critical temperature determined by the gate voltage. By lithographically profiling the gate (see the figure), Schön *et al.* were able to induce a planar junction with an interface region with lower charge carrier density. In this structure, the electrodes become superconducting, whereas the area between them remains normal, creating an SNS-type junction within a single material. The SNS junction produced by Schön *et al.* (*1*) shows appreciable current at low applied voltage, indicating a strong proximity effect. A highly important result is the large I_cR_N product of critical current I_c and normal resistance R_N, which indicates that the same conducting modes contribute to both normal and superconducting transport.

An advantage of the present technology is that the SNS structure consists of a single material, thus avoiding problems with interface barriers and disorder. Furthermore, the technology of the Bell Labs group opens up the possibility of fabricating flexible proximity circuits in which several parameters of the normal and the superconducting regions can be tuned, such as the critical temperature and the geometry. By extending their approach in an obvious way through splitting and adding gates, it should be possible to design superconducting switching networks with interesting properties. Such devices could be used to develop tunable ballistic proximity dots and constrictions in which a small number of discrete quantum electronic modes are selected by split gates and Andreev reflections. Localized Andreev states in such structures may serve as qubits and logic gates for quantum computation.

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PERSPECTIVES: NEUROBIOLOGY

Function Following Form

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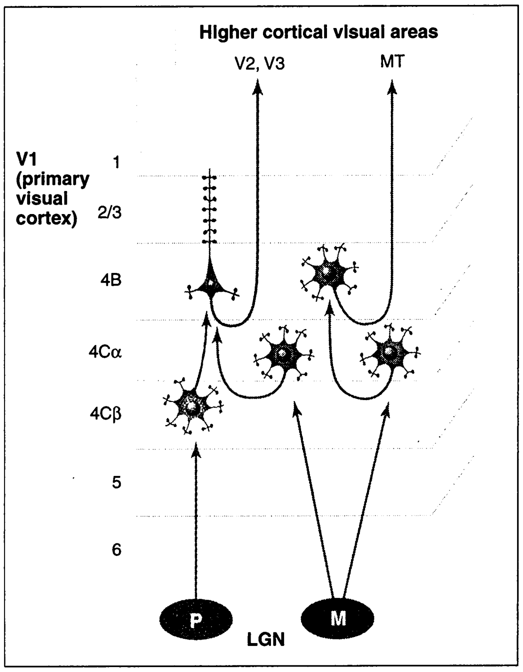
Does the morphology of a neuron and its many processes (axons and dendrites) tell us what it does for a living? If so, anatomical information could serve to classify neurons into distinct functional classes. This issue has been of interest to neurobiologists ever since Cajal used a silver stain to demonstrate the dazzling complexity and diversity of neuronal forms throughout the central nervous system. In certain neurons, such as retinal ganglion cells, there is a strong correlation between the structure of their dendrites (slender extensions emanating from the neuronal cell body), the pattern of incoming electrical signals (inputs) they receive from other neurons, and their function. But elsewhere in the brain, for example in the cerebral cortex, we have only hints as to these relationships (*1, 2*). On page 297 of this issue, Yabuta *et al.* (*3*) report a striking correlation in the primary visual cortex (area V1) of the monkey. They show that two different morphological classes of V1 neurons, spiny stellate cells and pyramidal cells, receive different signals from two major streams of visual information from the retina and then direct this information to higher cortical visual areas.

The visual system relays different types of visual information in parallel through the magnocellular (M) and parvocellular (P) pathways of the retina. The M and P pathways transmit this information to separate divisions of the visual thalamus and themselves terminate in separate layers of V1 (layers 4Cα and 4Cβ, respectively). Layer 4C neurons project to other layers of the visual cortex, which provide outputs to higher cortical areas (V2, V3, MT) that are thought to mediate distinct visual abilities, such as seeing color or motion (see the figure). The different activities of these areas might reflect differential contributions from the P and M pathways. Layer 4B, one of the targets of relays from layer 4C, contains many direction-selective neurons that respond better to stimulus motion in one direction than in the opposite direction. Layer 4B neurons receive a prominent M input, and provide a substantial output to visual cortical areas such as area MT (V5) known to be important in motion perception. Convergence of M and P signals onto single cells in layer 4B has previously been demonstrated (*4*), but Yabuta *et al.* now show that this convergence occurs only on certain cells in this layer. Using an elegant combination of anatomical and electrophysiological techniques in monkey brain slices from cortical area V1, Yabuta *et al.* determined the locations of neurons providing excitatory inputs to neurons in layer 4B. They then labeled the cells whose activity they had recorded. Their results show that different morphological classes of cells within layer 4B receive distinct patterns of input from layer 4C. Spiny stellate neurons receive strong input from layer 4Cα but none from 4Cβ, whereas pyramidal neurons receive strong input from both layers 4Cα and 4Cβ (see the figure).

These results are important beyond simply classifying cells on the basis of morphology. Because stellate and pyramidal cells of lay-



Information relays in the visual cortex. Distinct types of visual signals (M and P) are relayed from the retina through separate divisions of the lateral geniculate nucleus of the thalamus (LGN) to different portions of primary input layer 4C of the primary visual cortex (V1). A further relay conveys these signals to layer 4B, which provides a major output from V1 to higher visual areas (V2, V3, MT). Spiny stellate cells in layer 4B (orange), which project to area MT (V5), receive a strong M input but no P input. Pyramidal cells (purple), which project to areas V2 and V3, receive both M and P inputs.

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