Electrons in Silicon Microstructures

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Silicon microstructures only a few hundred atoms wide can be fabricated and used to study electron transport in narrow channels. Spatially localized voltage probes as close together as 0.1 micrometer can be used to investigate a variety of physical phenomena, including velocity saturation due to phonon emission, the local potentials caused by scattering from a single trapped electron, and quantum tunneling or hopping among very few electron states.

The production of integrated circuits involves some of the most sophisticated and precise manufacturing techniques ever developed and uses raw materials with an unmatched degree of purity and perfection. For example, single-crystal silicon wafers 15 cm or more in diameter can be obtained with concentrations of undesired dopants at less than one part in 10 billion and with only about one defect per square centimeter. Dimensional tolerances for film thicknesses used in this technology are routinely held to an accuracy of a few nanometers, and feature sizes in commercial circuits are already as small as 1 μm and will shortly be even smaller. The physics and chemistry of silicon, as well as its surfaces and interfaces with many materials, are exceptionally well understood. The electronic band structure and transport properties have also been extensively studied in an effort to gain greater insight into the behavior of this important material and devices made from it.

This combination of chemical and crystal perfection, coupled with a thorough understanding of the basic material and devices, makes silicon transistors attractive model systems for investigating a variety of fundamental problems, particularly electron transport in solids. New patterning techniques now exist for making devices with features nearly 100 times smaller than those used in commercial integrated circuits (*1, 2*). These techniques can be combined with the well-characterized semiconductor technology to manufacture devices that make it possible to study transport physics in microstructures only a few hundred atoms across.

The device used for these studies is the metal-oxide-semiconductor field-effect transistor (MOSFET), the cornerstone of much of the conventional silicon integrated-circuit technology. In this article, we describe these transistors and how they can be used to make a variety of fundamental measurements. These include studying the velocity-field relation for electrons, the scattering effects of one charged defect, and the characteristics of quantum mechanical hopping between individual electron states.

MOS Transistors

In the large MOSFET's common in commercial microchips, the current is through an electron layer that behaves like a quantum mechanically two-dimensional gas (*3*). For nearly two decades, the special properties of this two-dimensional electron system have been investigated, leading to such discoveries as the quantum Hall effect (*4*).

Figure 1 shows the schematic structure of a single MOS transistor designed for use in the physics experiments described below (*5*). It differs from typical MOSFET's only in the shape of the metal gate (G). This gate is separated from the silicon substrate by an insulating layer of silicon dioxide. Nearby, metal leads [source (S) and drain (D)] make contact with electron-rich n-type regions of the silicon (n^+). The rest of the silicon is p type (conduction by holes), so that electrical conduction between contacts is blocked by p-n diodes. When a positive charge is applied to the metal gate, however, a thin layer of electrons from the contacts is attracted into a potential well held tightly against the oxide-silicon interface. This two-dimensional electron gas (inversion layer) has the same shape as the gate above it and can be used to complete a circuit between the n-type contacts. Once the threshold voltage for formation of an inversion layer is reached, the system is essentially a parallel-plate capacitor, with the charge density in the inversion layer being equal and opposite to the additional charge density on the gate. Thus the gate controls the electron density, and hence the conductivity, of the inversion layer between the contacts. The inversion layer is so tightly bound against the interface that only the lowest quantized state of motion perpendicular to the interface is energetically favorable, and the occupied electron states differ only in their motion in the plane of the interface (*3*). Hence, the motion is strictly two dimensional.

Narrow inversion layers. Advances in microfabrication (*1, 2*) have made possible the fabrication of MOS transistors with narrow gate segments that control narrow conducting channels in the underlying silicon. This is shown in Fig. 1 where the central section of the gate has a segment of width W and length L with the electron current in the inversion layer directed from the wide segment near the source to the corresponding segment near the drain. Such devices, with W much less than 1 μm, allow study of the special properties of conduction in electron systems with an increasingly "one-dimensional" character (*6–18*). The geometry is particularly appropriate for transport experiments, since even a short segment of a narrow channel can contribute an appreciable fraction of the electrical resistance between the contacts.

A New Experimental Approach

What has been described so far is a conventional n-channel MOSFET, but with a gate made narrow so as to approach a one-dimensional conduction path. In this section, we describe new experiments with MOSFET's having gates of increased geometrical complexity in which spatially localized voltage measurements along narrow channels are made on length scales of 100 nm. These devices are otherwise similar to those described earlier (*6–9*). Figure 2A is a micrograph of a 50-μm square region on a silicon wafer containing

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eight different implanted contacts and their associated metal leads. The bright pattern toward the center is metal on top of an *n*-type polysilicon gate electrode defined by electron-beam lithography and reactive ion etching (*1, 2*). A 20-nm oxide layer separates this gate electrode from the underlying inversion layer of the same shape. The pattern converges in the center of the micrograph to microstructures so small that they are impossible to image in an optical microscope.

Figure 2B shows an electron micrograph of the central region at 100 times higher magnification. In this case, the pattern consists of a narrow conducting channel with side branches. An external power supply is connected between the source side (S) and the drain side (D) of the transistor, forcing electrons to flow through the conducting channel under the gate. High-impedance voltmeters can be attached to each of the non–current-carrying side branches to measure the local potential along the channel.

Figure 2C presents a perspective view of the same structure, showing that the relatively thin metal gate and side branches have been used as protective masks against reactive ion etching of the polysilicon, silicon dioxide, and the underlying silicon substrate. This process leaves behind a vertical-walled structure containing the inversion layer. Because oxide and silicon on either side have been removed, the inversion layer at the oxide-silicon interface is physically constrained to have the same shape as the gate above.

The ability to make spatially localized voltage measurements on the 0.1-μm scale by means of these devices can be useful in probing many different aspects of conduction by electrons in inversion layers. Although the density of electrons in an inversion layer is much less than that in a metal, the physics can be quite similar.

At the conventional textbook level, conduction in metals is limited at high temperatures by interactions between electrodes and quantized lattice vibrations (phonons). At low temperatures these are less frequent, and the resistance decreases until collisions with other electrons and with impurity atoms predominate. The residual impurity scattering is essentially temperature independent, and for years that was the end of the story. Recently, however, it has been realized that localization and many-body aspects of the quantum mechanical conduction result in previously unanticipated resistance increases at low temperatures (below about 4 K), particularly in disordered systems with reduced dimensionality (*19*).

All the effects described above are observable in MOSFET inversion layers, and spatially localized measurements can shed additional light on each.

Experimental Applications of Microstructures

Phonon-limited drift velocity. For the first of three experimental applications of these devices, let us consider the interactions of electrons with phonons, the dominant scattering mechanism at room temperature. As the electric field driving the current increases, electrons acquire a drift velocity superimposed on their usual motions. Also, the average electron energy increases, and the electrons become capable of emitting more phonons. This phonon emission eventually tends to limit the drift velocity of electrons in silicon inversion layers to values of order 10^7 cm sec^{-1}. This effect has previously been studied by time-of-flight measurements over distances of order 60 μm (*20*) and has been inferred from the operating characteristics of conventional transistors.

With spatially localized probes, in situ measurement of velocity saturation due to phonon scattering is easily accomplished. The electric field is simply the voltage drop between adjacent probes divided by their spacing, and the drift velocity is defined as the current per unit width divided by the local charge density. As the current and field are increased, a voltage drop builds up along the conducting channel, and the positively biased end of the channel rises closer to the gate voltage, so that the electron density is smaller. By measuring the local channel potential, the charge density can be calculated with the use of few assumptions.

Figure 3 shows the electron drift velocity as a function of electric field for a narrow conducting channel 0.12 μm wide, with voltage probes spaced 0.25 μm apart. The tendency of the drift velocity to

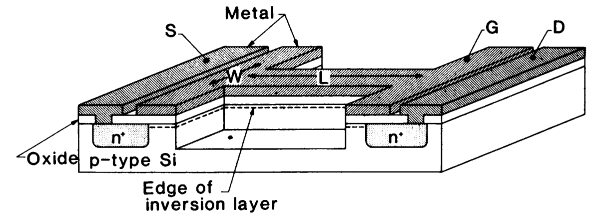

Fig. 1. Schematic diagram of a metal-oxide-semiconductor field-effect transistor (MOSFET). Conduction between the source (S) and drain (D) must pass through the thin electron inversion layer controlled by the gate (G). If the width W of the gate is narrow enough (of order 0.1 μm), conduction through the inversion layer displays an increasingly "one-dimensional" character.

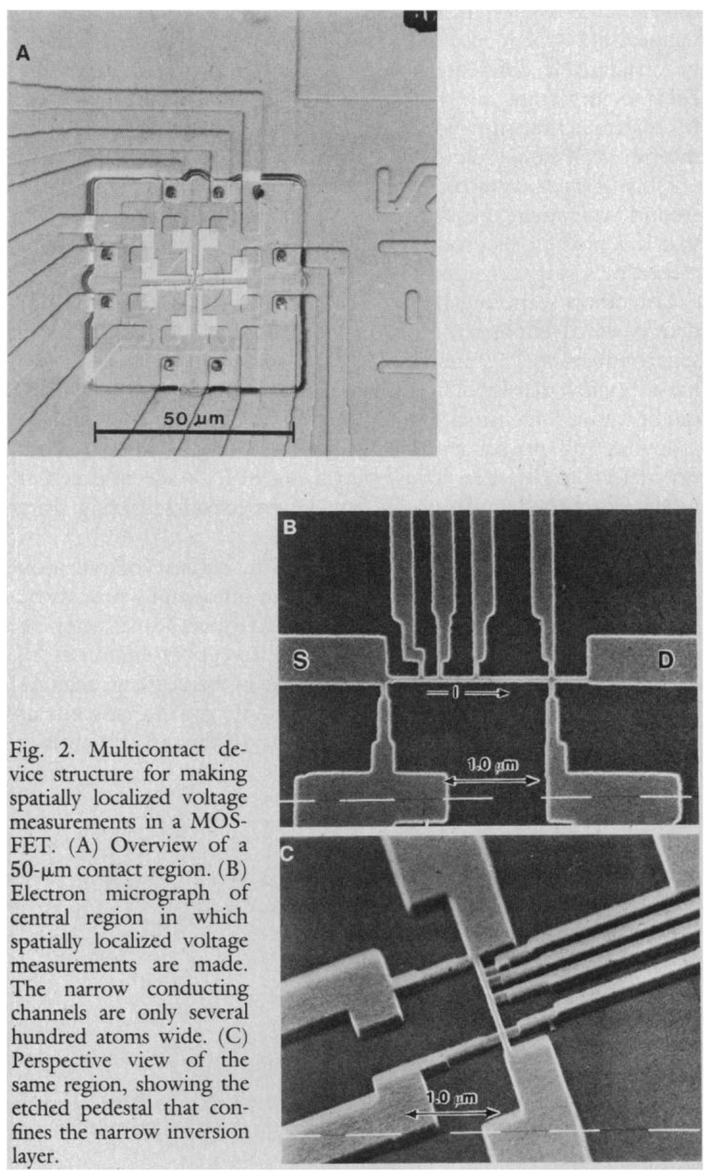

Fig. 2. Multicontact device structure for making spatially localized voltage measurements in a MOSFET. (A) Overview of a 50-μm contact region. (B) Electron micrograph of central region in which spatially localized voltage measurements are made. The narrow conducting channels are only several hundred atoms wide. (C) Perspective view of the same region, showing the etched pedestal that confines the narrow inversion layer.

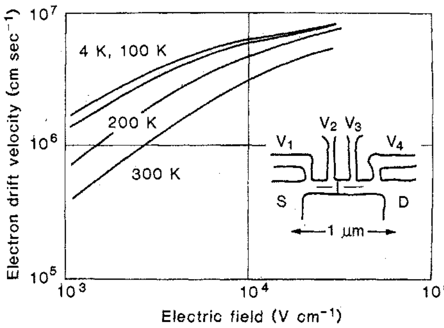

Fig. 3. In situ measurement of electron drift velocity as a function of electric field at various temperatures with voltage probes 3 and 4 (drain end). The channel current (I) is from source (S) to drain (D). The tendency toward velocity saturation because of phonon emission at high fields is easily observed.

saturate at 10^7 cm sec^{-1} is apparent. At low electric fields, the velocity is temperature dependent because the phonon scattering freezes out at low temperatures. At large electric fields, however, the electron temperature, which is directly related to electron energy, is so high that there are few restrictions on phonon emission regardless of the lattice temperature. Thus the curves tend to approach each other at the highest fields available in this experiment, and the temperature dependence of high- and low-field transport is seen to be qualitatively different. At even higher fields impact ionization becomes important, and a completely different behavior is observed. More detailed quantitative investigations are obviously possible by means of this new experimental approach.

Effects of single scatterers. In this section, we turn our attention to a second experiment that focuses on "impurity" scattering, showing that it is possible to probe spatially the local voltage perturbations caused by a single charged scatterer.

Couloumb scattering by fixed charges (caused by impurities or defects) is an important limit on the conductivity of electrons in semiconductors. The interface between silicon and silicon dioxide has a very low density of fixed charges and defects at which electrons can be trapped. Densities of interface trap states, for example, can be as low as 10^{10} per square centimeter, corresponding to only about one defect in 10^5 sites. Thus, silicon MOSFET's are an excellent model system for studying the details of electron scattering from defects.

Even allowing for a higher trap density because of radiation damage incurred during the electron beam lithography process by the high energy incident electrons, we would expect a small segment of a device with probes (Fig. 2B) to have only hundreds of scatterers. Thus if the charge of a single trap in this segment changes because of the capture of an electron, the scattering in that segment will change significantly (of order 1 percent). If the defect is initially

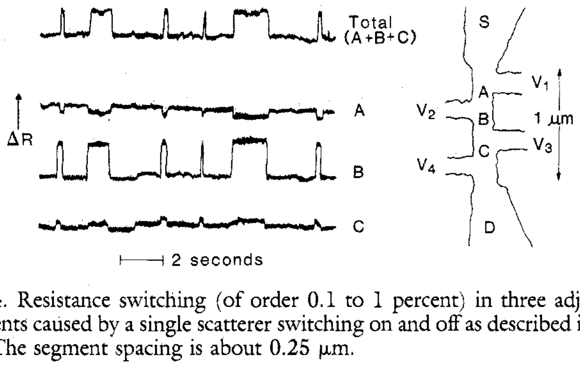

Fig. 4. Resistance switching (of order 0.1 to 1 percent) in three adjacent segments caused by a single scatterer switching on and off as described in the text. The segment spacing is about 0.25 μm.

neutral, it will become negatively charged and will contribute additional scattering. If the defect initially has a positive charge, the capture of an electron will neutralize it and reduce the scattering in the channel segment. We have discovered that these effects are directly observable in our small devices (*21–23*). It is the extremely small size of these devices that allows us to observe the individual character of these traps. Larger transistors would exhibit a superposition of many such events and, therefore, some averaged behavior.

We have measured the conductivity of a variety of narrow, submicrometer-sized MOSFET's, looking closely at time-dependent conductivity fluctuations. Ranges of temperature (typically 1 to 100 K) and gate voltage exist in which random switching between two values of the conductivity can be observed on time scales of order 0.01 to 10 seconds (limited by the experimenter's patience and the response time of the measuring instrument). The switching rate is a strong function of temperature, and the duty cycle of the switching depends strongly on gate voltage. A given trap will fluctuate in occupancy at an observable rate only if it is close enough to the silicon–silicon dioxide interface and has an energy within several times the thermal energy, kT, of the Fermi level (k, Boltzmann's constant; T, temperature of the electrons). In our small devices, individual traps have sufficiently different parameters that, at any given gate voltage and temperature, at most one trap is likely to switch at an observable rate. Thus we can readily observe the conductance switching from a single trap.

If probes are added to a narrow channel device, as was done in the measurements on electron velocity discussed above, information can be obtained about the spatial position of a trap and the range of its scattering effects. Figure 4 shows a schematic of a device with four probes along the channel. Next to the schematic is a plot of the voltage drop along each segment as a function of time. If a trap state is located in the middle segment, B, then when the charge of the state changes because of electron capture or emission, this segment will show a change in scattering while segment C may be unaffected. If the range of influence is large enough, however, the scattering may affect the potential in adjacent segments.

The trap shown in Fig. 4 is clearly near segment B where the largest voltage change occurs. Segment C shows a matching, but greatly reduced, voltage change, while segment A shows switching of the opposite sign. This effect is described qualitatively in Fig. 5. The upper part of this figure shows the voltage along the channel as electrons flow from left to right in the device. The average effect of all the other scatterers is to produce a voltage that changes nearly linearly with distance in this low-field regime. When one scatterer is added in segment B, the local distribution of current is disturbed (*24, 25*). Backward-scattered electrons form a reflected current, I_R, and conservation of charge is maintained by a diffusion current, I_D, from the other side. The reflected current from scattered electrons travels to the left, dissipating exponentially with a characteristic scattering length. This current creates a disturbance in the charge distribution around the scattering center, causing an increased voltage drop in the segment containing it but a decrease in the segment "upstream" from it. Since these probes are 0.25 μm apart, this scattering length appears to be of order 0.1 μm. With the use of samples with a variety of probe spacings, it will be possible to obtain detailed information about this scattering process.

Quantum conduction. For our final experimental application, let us consider the more explicitly quantum mechanical aspects of the conduction process. Electrons propagate as waves with wavelengths inversely proportional to their momentum. Two extreme cases come to mind. Electrons confined in a perfect box will occupy well-defined energy states corresponding to wavelengths that "fit" in the box. If the box is long and narrow, the energy cost of "fitting" additional oscillations of the wave function in the transverse direc-

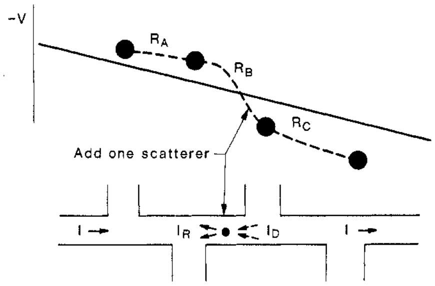

Fig. 5. Potential distribution along a MOSFET channel after adding one extra scatterer. R_A, R_B, and R_C are the resistances in the three channel segments near the scatterer. The lower schematic shows the channel with the scatterer between the middle probes. The applied current, I, the reflected current, I_R, and the diffusion current, I_D, associated with the scatterer are also shown.

tion is large, so that in order of increasing energy the states can be organized into distinct subbands, each with its own state of transverse motion. We refer to this as the "particle-in-a-box" case, where some disorder, such as scattering sites, will perturb the states and their energies; however, evidence of the subband structure might be expected to remain if the disorder is not too great. Conduction is limited by the type of elastic scattering described above.

Alternatively, the disorder can be so great that the electron waves are scattered many times, interfering with themselves to form localized states (*19, 26*). In this case, inelastic scattering events that raise or lower the electrons in energy are required to assist them in traversing the obstacles. Tunneling and thermally assisted hopping between states are mechanisms invoked to explain this process (*13, 27*).

Whatever the proper description of the states, they will be occupied in order of increasing energy as the electron density is increased by increasing the gate voltage, attracting more electrons into the inversion layer. The transition between fully occupied and completely empty states occurs in an energy range of several kT around the Fermi energy. In either the extended or the localized state pictures, conduction can be described primarily by scattering processes involving this range of partially occupied states.

Our silicon microstructures allow us to probe the conduction through tiny regions only 120 nm long by 40 nm wide. For electron states contained within this volume, it is straightforward to calculate that there are, on average, about eight states within 5 kT of the Fermi energy at temperatures of about 2 K. Thus, the conduction involves repeated transitions between a very small number of states. The larger the energy transitions required, the less frequent they will be and the larger the difference of voltage required to drive them. If we change the gate voltage by enough to increase the Fermi energy by many kT, a totally new set of states will be involved, and the conduction may be either greater or smaller.

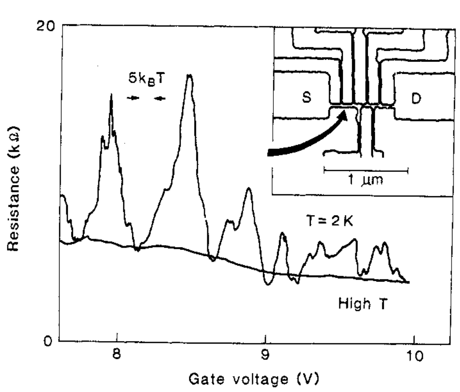

Fig. 6. Reproducible but irregular variation of the resistance of a short, narrow-channel segment as the gate voltage (Fermi level) is changed. In this range of temperatures and sizes, few electrons lie within 5 kT of the Fermi level, and thus conduction by quantum tunneling or hopping involves few electron states. The measurements were made on the segment indicated by the arrow in the inset, with the current directed from the source (S) to drain (D).

Figure 6 shows the resistance as a function of gate voltage at 2 K for such a small channel segment. Large variations (up to a factor of 3) are indeed observed, and their size rapidly increases as the temperature is lowered. Other segments also show large variations as a function of gate voltage, but these are completely uncorrelated with the resistance of adjacent segments. The latter fact helps us to ascertain that most states are localized within a given segment. On the other hand, for a short enough segment there are a number of gate voltages at which no temperature dependence is observed. This probably corresponds to conduction through a single state that spans the probes or to a few closely spaced states. From qualitative arguments such as these it is possible to learn about the typical extent of the localized states. Furthermore, by extending the measurements to lower temperatures it should be possible to make detailed measurements of conduction limited by a single "difficult hop" or tunneling transition between quantum energy states.

Conclusion

Silicon integrated-circuit technology combined with high-resolution lithography provides a tool for making microstructure devices with unmatched precision and control. In the three experiments described here, we have illustrated this new technique for studying the microscopic behavior of electrons in geometrically restricted conduction paths. These devices have been used to study the fundamental aspects of conduction in solids down to the level of observing the behavior of single electrons on specific sites. At a time when integrated-circuit technology is preparing to enter the submicrometer size range, extensions of this technology are being used to study devices 10 to 100 times smaller, exploring the physical limits of miniaturization.

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