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LETTER TO THE EDITOR

Coupling between localized states in resonant tunnelling

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Abstract. Using novel silicon MOSFETs with two or three gate layers, which allow the effective size of the transitor to be tuned electrostatically, we have investigated resonant structure appearing below threshold in the low temperature conductance. The experimental results indicate that only few localized states contribute to the peak conductance and the evolution of the structure with gate bias suggests finite interactions between the states.

The irregular dependence of the low temperature conductance (g) on gate voltage (V_G) often seen in small field effect transistors close to threshold has been studied by several groups in recent years (Fowler *et al* 1986, Kopley *et al* 1988, Kwasnick *et al* 1984, McEuen *et al* 1990, Webb *et al* 1985). In an earlier publication (Stroh and Pepper 1989), we studied these fluctuations which result from hopping conduction in a mesoscopic system. In these experiments, we used 10 μm long MOSFETs whose conducting channel could be shifted controllably in both energy and position *perpendicular to the current direction* by the application of appropriate voltages to p^+ implants extending along both sides of the gate. Here, we investigate fluctuations in the conductance of a novel type of device which allows the control of the length and the position of the effective channel *in the direction* of current flow.

In addition to the hopping conduction fluctuations around threshold, isolated resonances appearing well below threshold could be observed in the present experiments, owing to the smaller sample size and the lower temperatures than were employed previously. The regime investigated is characterized from the microscopic point of view by the small number—often only one or two—of localized states through which the electrons can hop from source to drain. Normal resonant tunnelling involves only one intermediate state and is a classic quantum mechanical tunnelling problem. A conductance peak arises at a gate voltage for which the energy of one particular localized state, located nearly halfway between source and drain, coincides with the Fermi energy (E_F). Resonance broadening arises from the thermal smearing of the source and drain Fermi distributions as well as from the finite lifetime of the state. In the limit of a very short device, direct tunnelling from source to drain is expected to show up as a finite background conductance which should have a smooth dependence on the gate voltage. Hopping conduction in macroscopic samples, on the other hand, is a percolative transport mechanism and involves the additional physical process of thermal activation which

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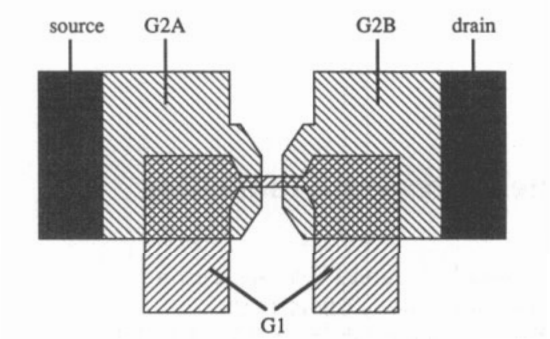

Figure 1. Schematic layout of the transistor used in the experiment.

enables the electrons to hop along a series of localized states having different energies (Mott and Davis 1979).

The mean hopping distance increases with decreasing temperature owing to the balance between the thermal activation rate and the quantum mechanical transmission coefficient, the latter decreasing exponentially with distance. Hence, to observe resonant tunnelling through a localized state, not only a small density of states (DOS) at E_F is required but also a sufficiently short device and very low temperature. Roughly speaking, resonant tunnelling is unimportant until the Mott hopping length becomes greater than half the sample length (Stone and Lee 1985).

The transistors used in the present experiments have been detailed elsewhere (Stroh *et al* 1991) and are only briefly described here. The layout is depicted schematically in figure 1. It includes two gate layers with different geometries which may be independently biased. The lower gate G1 is defined in n^+ doped polycrystalline Silicon ('poly') on a standard (100) p-type silicon wafer and a thermally grown oxide of thickness d_{ox} = 200 Å. The resistance of the inversion layer is dominated by the central narrow bridge connecting the two larger areas, this bridge having a length of 6 μm. On top of this structure, 1000 Å of oxide is grown, followed by the deposition and definition of a second poly layer, forming the upper gate G2. The source and drain contacts are made by phosphorus implantation. Gate G2 consists of two independently contacted parts, G2A and G2B, the gap between which is 3 μm wide and is centred above the narrow bridge of G1. Gate G2 overlaps G1 in such a way that the source and drain implants make contact to the inversion layer underneath G2 rather than to the one underneath G1, as shown in figure 1.

The central bridge of G1 is made very narrow, of the order of 0.5 μm, by what we call 'double exposure technique'. The pattern of gate G1 is defined on a light-field photolithographic mask to have a width of about 1.5 μm. The resist-coated wafer is exposed twice, the mask alignment being shifted by 1 μm perpendicular to the bridge before the second exposure. Using this technique, we have fabricated lines with widths as low as 0.2 μm.

We now discuss the operation of this transistor. As a positive bias is applied to G1 and both parts of G2, the substrate is inverted underneath the whole gate structure, so that only a bridge about 0.5 μm wide and 3 μm long connects the two large conducting areas. When the voltages V_{G2A} and V_{G2B}, applied to the two parts of G2 are then varied, the geometry of the central constriction in the inversion layer is changed because of the fringing electric fields in the gap between G2A and G2B. Specifically, making the bias applied to both G2A and G2B more positive shortens the constriction. In the experiments reported here, V_{G2A} and V_{G2B} were swept in opposite directions while their sum $V_{G2A} + V_{G2B}$ was kept constant. This is expected to result in a shift of the electrostatic constriction along the current direction. (For calculations on this effect see Stroh and Pepper (1989) and Glazman and Larkin (1991)).

We have also made devices with an additional aluminium gate covering only the central part of the device where gate G1 is very narrow, allowing further control of the electrostatic environment. The structure observed in the conductance was found to change when a bias was applied to this extra gate and must hence arise from this central part. The small effective sample size meant that 'universal conductance fluctuations' (Skocpol *et al* 1986) could be observed in the gate voltage range $V_{G2A} = V_{G2B} = 5V$ and $0.5V \leqslant V_{G1} \leqslant 2V$ at base temperature of the dilution refrigerator used. The RMS amplitude of these fluctuations was about $0.13\, e^2/h$.

The experiments reported here were also performed at base temperature of a dilution refrigerator. Whereas the mixing-chamber temperature was about 30 mK, the conductance became temperature dependent only above 100 mK. No difference in the lineshape of the resonances was observed between measurements performed at source–drain biases (V_{SD}) of 1 μV and 10 μV, corresponding to temperatures up to which the electrons could get heated, $T = eV_{SD}/k_B$, of 12 mK and 120 mK respectively, where e is the electronic charge and k_B the Boltzmann constant. We conclude that the effective electron temperature in the sample was about 100 mK and $V_{SD} = 10\ \mu$V was therefore an acceptable bias. Standard low frequency lock-in techniques were employed.

In order to determine whether the resonances are lifetime or thermally broadened, we analysed a well isolated peak which was observed in a measurement of the conductance g as a function of V_{G1} (at $V_{G2} = 5$ V). Fits to the experimental data of a Lorentzian and of $f(1-f)$ respectively, $f = 1/(1 + \exp((E - E_F)/k_BT))$ being the Fermi function, were of comparable quality when $g(V_{G1})$ was plotted on a linear scale. Here, the energy E is proportional to the gate voltage as elucidated below. In a semilogarithmic plot, however, the function $f(1-f)$ has linear slopes whereas the Lorentzian has not. Using this criterion, the peak was determined to be thermally broadened. Even in the hopping regime, where more than one localized state participates in the conduction process, thermal broadening causes the sides of the peaks to have constant slopes of $1/k_BT$ in a semilogarithmic plot of the conductance versus gate voltage, when the gate voltage scale is converted into the appropriate energy scale (Lee 1984, Azbel and DiVincenzo 1984). The conversion factor for our device with $d_{ox} = 200$ Å underneath gate G1 is

$$dE_F/dV_{G1} = R \times 6.8\,\text{meV V}^{-1} \qquad (1)$$

where R is the factor by which the DOS at E_F is reduced below the full value of a two-dimensional electron gas. A value of $R = 2.7 \pm 0.4$ was derived from peak slopes in a semilogarithmic plot where the temperature was assumed to be $T = 100$ mK. Fitting the function $f(1-f)$ to the above mentioned peak gave the different value of $R = 4.1 \pm 0.5$, demonstrating the difficulty of extracting a consistent value for R, even assuming the temperature to be known precisely. Using a value of $R = 3.5$, equation (1) becomes

$$dE_F/dV_{G1} \approx 24\,\text{meV V}^{-1}. \qquad (2)$$

There are then approximately eight electronic states in an energy interval of $2k_BT$ and per square micron at this temperature. Mesoscopic effects may hence be expected to

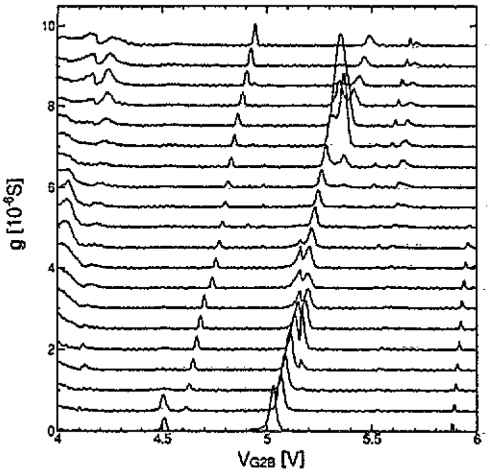

Figure 2. Resonances in the sub-threshold conductance which appeared as the resistance-dominating region of the device was shifted parallel to the direction of current flow. The curves, all of which apart from the lowest are offset for clarity, correspond to fixed biases V_{G1}, the lowest being $V_{G1} = 320$ mV and increasing in 0.5 mV steps for successive ones. The average bias on the two parts of gate G2 was $V_{G2} \equiv (V_{G2A} + V_{G2B})/2 = 5$ V.

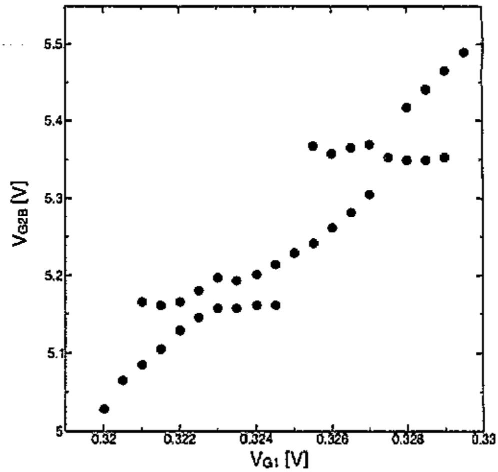

Figure 3. The resonance positions for one group of peaks in figure 2. The errors are of similar magnitude to the symbol size.

show up. Figure 2 shows the results of an experiment in which V_{G2A} and V_{G2B} were varied simultaneously while $V_{G2} \equiv (V_{G2A} + V_{G2B})/2$ was kept constant at 5 V. This was repeated for several values of V_{G1}. A systematic shift of the structure appears between successive sweeps, which is likely to be due to a slight asymmetry of the sample; that is, the gap in the second gate is probably not exactly in the middle of the narrow bridge of the first gate, which probably has some width variations. This is corroborated by SEM micrographs taken of other devices on the same wafer.

The resonant structure follows a characteristic pattern of development as V_{G1} is changed. We concentrate on the group of peaks appearing at $V_{G2B} = 5.05$ V in the lowest trace and at $V_{G2B} = 5.5$ V in the uppermost trace of figure 2. This group consists of one peak in some curves and two peaks in others. The peak positions are plotted in figure 3. A fairly clear anti-crossing appears at $V_{G2B} = 5.2$ V during which the heights of the two peaks (see figure 2) and their separation in the V_{G2B} coordinate (figure 3) remain roughly constant. We propose the following explanation of this behaviour. Two localized states are near the centre of the device and at an energy close to E_F for a certain range of electrostatic conditions, represented by the parameters V_{G1} and V_{G2B}. The states are sufficiently close to each other to interact electrostatically and therefore form one quantum mechanical system and a level splitting, corresponding to the coupling constant, results. In this scenario, two resonances with a well defined separation are expected to show up. The resonance positions would be independent in absence of an interaction. Since the width of a thermally broadened resonance is about $4k_BT$ and the separation of the considered peaks in figure 2 is approximately equal to their width, the interaction strength between the two resonant states is of the order of a few $k_BT|_{100\,mK}$.

An alternative explanation is that the pair of peaks are caused by a time-integrated 'random telegraph signal' (Kirton and Uren 1989): there is only one current carrying resonant state but its energy switches between two discrete values, possibly depending on the occupancy of a nearby electron trap or an atomic reconfiguration. In such a situation, two peaks may be observable owing to the long signal integration times required experimentally. Even though we have observed a conductance peak with an apparently discretely varying position in a different experiment, there are no additional observations which could support this picture.

The crossing at $V_{G2B} = 5.35$ V shows dramatically different behaviour. The peaks seem rather to be attracted towards one another and the crossing is associated with a strong increase in the total integrated transmission. This could be due to a serial combination of two resonant states, which form a 'mini-hopping-path' under favourable bias conditions. Such a path may carry a much larger current than a single resonant state. This concept is similar to the theory of 'necklace states' (Pendry 1987).

In conclusion, we have used a novel MOSFET design to investigate the low temperature conduction regime where current flows by resonant tunnelling through localized states. The resonant structure could be changed by a modulation of the electrostatic conditions, and there was evidence for both attractive and repulsive types of interaction between localized states.

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