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Invited

Quantum Mechanical and Non-Steady-State Transport Phenomena in Nanostructured Silicon Inversion Layers

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This paper discusses the quantum mechanical effects that are expected or have already been observed in ultra-small Si MOSFETs. These fall into three categories: effects related to lateral carrier confinement perpendicular to the direction of transport; effects that result from carrier propagation across very small distances where the wave nature of the carrier cannot be ignored; and effects arising from non-stationary transport, also across very small distances where electrons do not spend enough time so that a quasi-steady-state energy distribution can be established.

1. Introduction

It has been predicted that the continued growth of the semiconductor and electronic-systems industries relies on the discovery of alternatives to transistor-based microelectronics[1]. This prediction was based on the observation that integrated circuits are becoming increasingly limited by problems of scaling and interconnect. It was implied that our ability to reliably produce small structures on a wafer will outstrip our ability to utilize them in an evolutionary way where the primitive function is transistor switching. However, the ability to produce structures of small lateral dimensions opens the possibility that new phenomena based on the wave nature of the electron (or hole) will become accessible. This could lead to a variety of new "device" concepts implementing higher-order primitive functions that would be capable of complex logic operations at high speeds with minimum interconnect. At present we do not know what these "devices" will look like. Some clues are offered by such quantum mechanical phenomena as carrier confinement in quantum (zero-dimensional) wells, resonant tunneling between quantum wells, lateral superlattices, etc.

To date, the majority of studies of quantum effects in carrier transport in semiconductors resulting from small-scale structures has been limited to one dimension, namely, perpendicular to the semiconductor surface. This reflects the fact that the scale of reproducible features, such as spatially-modulated doping or bandgap, has only been possible by means of low temperature epitaxial deposition techniques (MBE and MOCVD). However, today we are able to realize lateral device features in the deep-submicron regime, and thus we are at the threshold of seeing associated quantum mechanical effects.

For the purposes of this article, the term "quantum mechanical" is used to designate any effects that arise from (a) quantization of carrier energy due to carrier confinement, or (b) modification of carrier energy and momentum distributions, both of which require that device features be comparable to carrier scattering lengths. Also, the discussion is limited to effects that manifest themselves in the electrical conductivity of devices.

2. Energy Quantization

It is well-known that the application of boundary conditions to Schroedinger's Equation leads to a quantization of electronic states and energies. This means that confinement of electrons to a finite region in space results in a spectrum of discrete energies for motion in the direction of confinement. The sharpness, and therefore the observability, of phenomena resulting from confinement depends on several factors including scattering, which broadens quantum states by $\hbar/\tau$, and temperature, which results in an effective broadening of about k_BT. Here $\hbar$ is Planck's constant divided by 2π, τ is the momentum relaxation time, and k_B is Boltzmann's constant.

Simple analysis based on Schroedinger's Equation yields a direct relation between confinement length, ℓ, and ΔE_n, the separation between the n^{th} and $(n+1)^{th}$ energy levels. Assuming that the potential is uniform within the confinement region (square-well approximation),

$$\Delta E_n = \frac{\hbar^2 \pi^2}{2m^*} \frac{(2n + 1)}{\ell^2} , \tag{1}$$

where m^* is the carrier effective mass in the semiconductor of interest. Taking both scattering and temperature broadening into account, the criteria for observability of energy level separation due to carrier confinement to a length ℓ, in terms of carrier mobility and temperature are summarized in Fig. 1. Here the mobility, μ, is connected to energy resolution through the scattering time τ, as $\mu = q\tau/m^*$, where q is the electron charge magnitude. This yields the observability criterion

$$\mu \geq \frac{2q\ell^2}{3p^2\hbar} . \tag{2}$$

Similarly,

$$\frac{1}{T} \geq \frac{2m^* k_B}{3\hbar^2 \pi^2} \ell^2 . \tag{3}$$

As can be seen from Fig. 1, with a mobility greater than 6000 cm^2/Vsec one would expect to see manifestation of carrier confinement in silicon at $\ell \leq 75$ nm and below about 8 K.

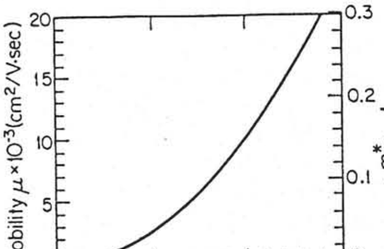

Figure 1. Criteria for observability of energy quantization due to carrier confinement. Carrier mobility, and inverse temperature times mass normalized to that in Si, must be above the graph curve.

An inversion layer in a MOSFET provides the easiest means of achieving carrier confinement because ℓ can be quite small, $\lesssim$10 nm. This kind of confinement has been studied extensively for years[1]. Quantum effects such as optically-stimulated transitions between energy states[2] and Landau level formation in a magnetic field[3] are observed at temperatures where $\Delta E < k_BT$. For example, in Si with an inversion layer thickness $\ell \approx 10$ nm, $\Delta E = 20$ meV, which means that at temperatures below 77 K (i.e. $k_BT \leq 6$ meV) occupation is restricted almost entirely to the lowest quantum level.

3. Ultra-Narrow MOSFETs

The initial attempts to observe quantum effects resulting from lateral confinement were made using MOSFET ultra-narrow channel devices[4-7]. In such devices the lateral confinement in addition to the normal vertical confinement is expected to result in quasi-one-dimensional (Q1D) conduction in the third direction. Since the lateral distance to which electrons can be confined is generally larger (at present about 50 nm) than the inversion layer thickness, lower temperatures are required to observe the quantum nature of this system. Figure 2 shows the effective density of states at several temperatures in a Si Q1D MOSFET with W = 50 nm.

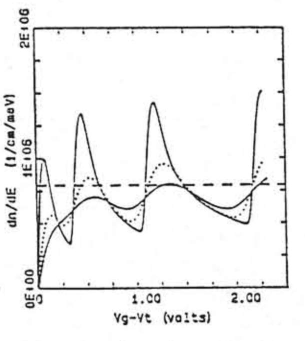

Figure 2. Effective density of states vs gate voltage in a Q1D channel, 50 nm wide, at various temperatures. Dashed line is the equivalent 2D approximation for the same channel width.

To observe transport modulation by quantum levels in a Q1D system, a variation of conductivity, σ, with the density of states must exist. Since the gate capacitance has been shown to be constant[8] with n, this must occur through modulation of τ as is the case in Shubnikov deHaas oscillation. Since τ is sensitive to all states within $\hbar/2\tau$ of the Fermi level, the resulting broadening leads to relatively weak oscillation of the conductance with gate voltage (transconductance). Unfortunately, the transconductance of narrow channels has consistently revealed "structure" which does not correlate with the expected Q1D density of states. It now appears that the transconductance fluctuations observed in these single-channel devices are directly related to random spatial fluctuations in the lateral confining potential, and this obscures the Q1D spectrum[4]. It is worth noting that the weak localization effect that is believed to give rise to the irregular transconductance fluctuations is in itself interesting and thus under investigation by several research groups[6]. In an attempt to reduce noise and to observe the primary quantum effects directly, our group at MIT developed the grating-gate FET (GGFET) shown in Fig. 3a. In this structure, the lateral confining field is produced by appropriately balancing the potentials on the upper gate and the grating gate. Due to the grating, this yields ~250 isolated, ultra-narrow channels in parallel. It is expected that N parallel channels should increase the signal-to-noise ratio by $\sqrt{N}$, (approximately 15 in our case), with respect to a single channel device. Initial measurements at 1.2 K yielded the conductance modulation shown in Fig. 3b, which we believe indicates formation of a true Q1D conductor. This observation is also consistent with channel widths of ~50 nm predicted by computer simulation, and with the measured mobility of ~7000 cm^2/Vsec at liquid He temperatures.

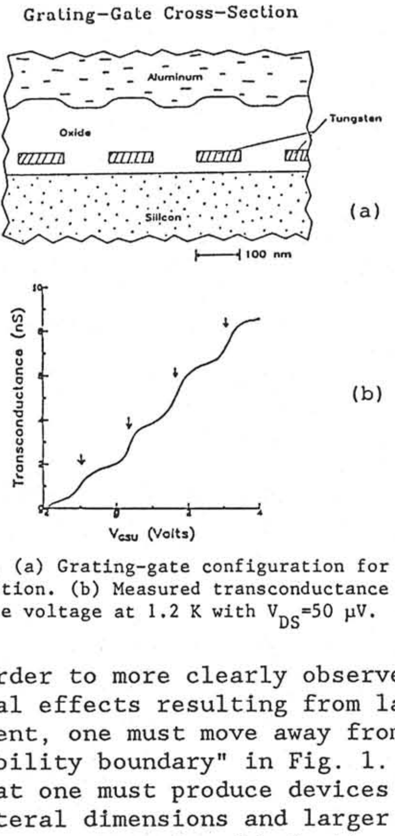

Figure 3. (a) Grating-gate configuration for Q1D channel formation. (b) Measured transconductance vs upper-gate voltage at 1.2 K with V_{DS}=50 μV.

In order to more clearly observe quantum mechanical effects resulting from lateral confinement, one must move away from the "observability boundary" in Fig. 1. This means that one must produce devices with both finer lateral dimensions and larger mobilities. At present, microfabrication techniques can produce structures with dimensions of a few tens of nanometers, but devices must be developed which can actually utilize such dimensions and produce observable carrier confinement. In addition, while improved processing may result in devices with mobilities of 20,000 or greater in silicon at low temperatures, the use of materials with high electron mobility and low electron mass such as GaAs offer great promise. Devices in these materials could conceivably result in observable quantum effects at liquid N_2 temperatures.

4. Ultra-Short MOSFETs

It has been predicted that when carrier transport occurs over distances comparable to the carrier scattering length transport would no longer be governed by "classical" quasi-stationary statistical distributions of energy and momentum but rather that "transient" effects would lead to strong modification of these distributions. The resulting transient transport effects have been described as ballistic, to denote motion largely unimpeded by collisions[9)], and as velocity overshoot to denote brief attainment of carrier (ensemble) average velocities in excess of saturation[10)]. Both of these effects are expected to take place over a limited distance from the carrier injector of most any device, for example, the source of a MOSFET. However, for the effects to be observable in terms of the device conductance the length of the device channel must be at least comparable to distance over which steady state energy and momentum distributions are established. It has been pointed out that, at room temperature, the critical distance for ballistic transport in Si is about 10 nm [11)], which makes the observation of this effect very difficult. However, more recent calculations based on computer simulation have yielded predictions of observable velocity overshoot in Si MOSFETs at room temperature provided $L \leq 100$ nm, and the low field mobility, μ_0, is greater than 500 cm^2/Vsec [12)]. Although ultra-short MOSFETs with $L \gtrsim 100$ nm have been reported[13)], velocity overshoot was not observed, presumably because μ_0 did not satisfy the above criterion.

The first observation of electron velocity overshoot in a Si device was reported by Chou et al.[14)]. The devices were MOSFETs with L = 75 nm, and the observation was carried out at 4.2 K. More recently, Shahidi et al.[15)] has reported observation of electron velocity overshoot in MOSFETs with channel lengths below 130 nm at 77 K, and below 90 nm at room temperature. Figure 4 shows the calculated average electron velocity at several temperatures as a function of L. Also shown in the figure are electron

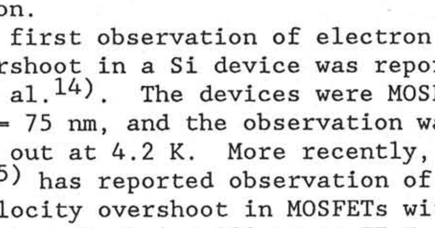

Figure 4. Calculated average carrier velocity vs channel length in short-channel MOSFETs at room temperature and 77 K, indicating velocity overshoot at channel lengths below 0.09 μm at both temperatures.

saturation velocities in bulk Si. These observations are consistent with the increase in low-field mobility[13] in the more recent devices (450 cm^2/Vsec), compared to 300 cm^2/Vsec in the devices of Chou.

Considerably more work is required at present before it can be concluded whether practical MOSFETs can be fabricated that will take advantage of transient transport effects. In addition to refinements of the criteria for attainment of these effects, other criteria such as reliability of devices operating in this transport regime and sensitivity of device parameters to fabrication tolerances will have to be established and, of course, satisfied.

5. New Device Concepts

It is tempting to close this article with some reflections on device concepts made possible by present microfabrication techniques. A new MOSFET structure, akin to the ultra-short-channel MOSFET, has been recently demonstrated for the study of surface-superlattice (SSL) formation[16]. The structure is shown in Fig. 5a. The combination of the lower grating gate electrode with the upper uniform gate allows the formation of a controllable surface potential modulation in the direction of electron transport. This results in modification of the energy-momentum relation for transport in the direction of the potential modulation (SSL). The structure can be thought of as a series of strongly-coupled Q1D channels. With appropriate bias, strong variations of the transconductance were observed at 1.2 K, as shown in Fig. 5b. From these results it has been concluded that the criterion for observability of SSL phenomena is that the SSL period must be less than or comparable to the energy relaxation length, as opposed to the shorter momentum relaxation length[16].

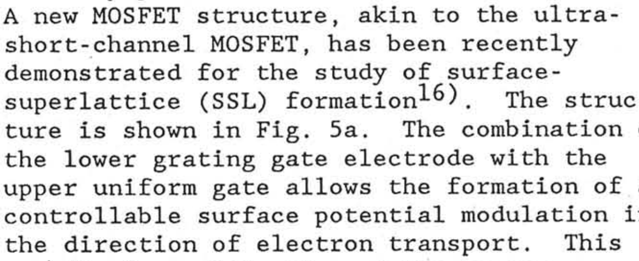

Figure 5. (a) Cross section of surface superlattice device. Grating periodicity is 200 nm. (b) Measured transconductance vs drain current at 1.2 K, V_{DS}=50 μV.

The SSL device is the first step towards a family of surface resonant tunneling devices which may have practical potential for implementing the kinds of functions mentioned at the Introduction. One can imagine these devices as a series of weakly-coupled 1D or 0D potential wells. With appropriate height and width of the potential barrier transport between successive wells will occur only when energy states line up, resulting in abrupt change of conductivity and very rapid carrier transport. Resonant tunneling between 2D wells (planar structures) has already been demonstrated in III-V heterostructures[17]. Whether it will be possible in a Si MOS configuration remains to be seen.

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