A surface-gated InSb quantum well single electron transistor

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Abstract. Single electron charging effects in a surface-gated InSb/AlInSb QW structure are reported. This material, due to its large $g$-factor and light effective mass, offers considerable advantages over more commonly used materials, such as GaAs, for quantum information processing devices. However, differences in material and device technology result in significant processing challenges. Simple Coulomb blockade and quantized confinement models are considered to explain the observation of conductance oscillations in these structures. The charging energy ($e^2/C$) is found to be comparable with the energy spectrum for single particle states ($\Delta E$).

The single electron transistor (SET) relies on the discrete nature of charge to modulate the conductance of a small, isolated volume of conducting material. Within this nanoscale region, known as a quantum dot, the confinement in all three dimensions is sufficiently strong that the electrons may only exist at well-defined quantized energies. The confining potential may be created either by the physical dimensions of the dot (using for example a small metallic grain [1] or material constriction [2, 3]), or by inducing an electrostatic potential at the surface of a semiconducting heterostructure [4]. The latter method is desirable for many applications, particularly quantum information devices, as it allows greater control over the geometry of the confinement potentials, may be realistically scaled up to incorporate more than one dot, and is also compatible with existing planar transistor fabrication techniques.

The conduction properties of the SET are defined by the geometry and potential of the dot region and the conducting leads. In contrast to conventional transistors, where conductance can be continuously reduced by increasing the magnitude of the gate bias, the SET conductance...
oscillates as a result of the addition or removal of single electrons. As the population of electrons is incrementally decreased by depleting the small semiconducting region, their number may be reduced down to a single electron before device pinch off. The use of the spin quantum number of a single confined electron has been demonstrated as a ‘quantum bit’ in such semiconductor systems [5]. Though widely studied in the GaAs material systems [6]–[8], electrostatically defined SETs in InSb quantum well-based structures are unreported. The recent demonstration of acceptably low leakage Schottky gates patterned on to InSb/AlInSb heterostructure material [9, 10] allows us to demonstrate an electrostatically defined SET in an InSb-based material. Of all the III–V semiconductors InSb offers the smallest electron effective mass, the highest mobility and the largest $g$-factor ($\sim 51$). The large $g$-factor has important implications for potential spin-to-charge readouts of quantum bits [11] and also offers the possibility of localised qubit addressing [12].

The InSb/AlInSb heterostructure material was grown by solid-source molecular beam epitaxy (MBE) on a semi-insulating GaAs substrate. The structure, which is illustrated in figure 1, consists of an accommodation layer, a $3 \mu$m $\text{Al}_{1-x}\text{In}_{x}\text{Sb}$ buffer ($x = 0.15$), a 20 nm InSb quantum well, followed by a 50 nm $\text{Al}_{1-x}\text{In}_{x}\text{Sb}$ ($x = 0.20$) cap with Te modulation $\delta$-doping ($\sim 1 \times 10^{12} \text{cm}^{-2}$) located 5 nm above the quantum well. This forms a type I heterostructure, providing confinement for both electrons and holes in the quantum well channel. Hall measurements for this material have determined the mobility to be $35 000 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ (RT)/$55 000 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ (77 K) with a carrier concentration of $4.6 \times 10^{11} \text{cm}^{-2}$ (RT)/$2.7 \times 10^{11} \text{cm}^{-2}$ (77 K). The SET confinement potential was created using a ‘fork-gate’ arrangement similar to that reported by Meirav et al [13] and indicated in figure 1. The devices were fabricated using optical lithography to define the source and drain contacts using Ti/Au layers deposited by e-beam evaporation. E-beam lithography was used to define Ti/Au Schottky fork-gate structures on to mesas of width 3, 6 or 12 $\mu$m. These gate contacts are approximately 750 nm across in total and separated by 100 nm at the constrictions at each end rising to a 300 nm gap in the central (quantum dot) region. The devices were then isolated by wet chemical etching. The gates are fed in from either side and are air-bridged between the mesa edge and the feed metal to minimise current leakage due to material or surface conduction. Details of related InSb/AlInSb quantum well FETs with room temperature ac and dc performance can be found in [14], and details of Schottky barriers on this material can be

Figure 1. Schematic of an InSb/AlInSb quantum well heterostructure showing the layer structure and gate layout.
Figure 2. Conductance peaks observed in a typical InSb/AlInSb heterostructure quantum dot at 4.5 K.

found in [10, 15]. The devices created by this process are intentionally depletion mode, and consequently are designed to operate under negative gate biases.

Processing technology in this new heterostructure material system is still immature for low-temperature mesoscopic devices. Due to the novel nature of the heterostructure and the complexity of highly-mismatched epitaxial growth, Schottky barrier conductivity is often prohibitively high for quantum device applications, which require extremely low gate transport currents. Yield of sufficiently low leakage gates for single-electron transistor devices is currently low, with suitable devices susceptible to irreversible gate failure. Gating and material technology are the subject of continual improvement, and the data presented here reflects the significant progress made recently in surface-gate control of InSb mesoscopic devices.

The addition energy spectrum of a SET can be accessed by sweeping the gate voltage so that the potential on the dot varies between pinch-off and some point at which the dot is no longer defined. These measurements were performed in a liquid helium bath cryostat at 4.5 K in the presence of a small dc source–drain bias (100 µV supplied from a HP4155B semiconductor parameter analyser). The gate voltage was swept between $-0.29$ and $-0.25$ V, and the conductance was deduced from measurements of the drain current. At voltages below $-0.29$ V the conductance peaks vanish, indicating that either the tunneling barriers are too large to allow further discernable charge transport or the dot is entirely depleted. The conductance of a typical SET device is plotted against the gate voltage in figure 2. Sharp reproducible periodic peaks are observed separated by regions of low conductance. The height of the peaks is significantly below the quantum limit of conductance, $2e^2/h$, which suggests that the tunneling barriers leading to and from the dot are large. A consequence of this observation is that it is not possible to state with certainty that the last peak represents the transition between zero and single electron occupancy.

Direct observation of the energy spectrum may also be provided by varying the drain voltage with a fixed gate voltage [8]. This allows the Fermi energy in the drain contact to
pass through the energy levels in the dot increasing the number of possible current channels incrementally. This can be seen in the output current of another similar InSb/AlInSb SET in figure 3, where there is some finite region of minimal conductance about zero drain voltage of the order of a few millivolts, followed on either side by stepwise increments in current. Unfortunately, due to device fragility, insufficient conductance data was collected to allow the usual diamond plot of conductance as a function of gate and drain biases. It is therefore difficult to draw any definite conclusions regarding electron occupancy and subband separation.

The Coulomb blockade model describes how electron–electron repulsion results in an energy gap between the \( N \) and \( N + 1 \) charging states (where \( N \) is the number of electrons on the dot) [16]. It is then predicted that in order to increase the electron population by one, the dot potential must be lowered by \( U \sim \frac{e^2}{C} \), and that periodically in gate voltage there exist values of the dot potential where the \( N \) and \( N + 1 \) states are degenerate and single electrons can flow on to and off the dot freely (resulting in a current of single electrons). As well as this semi-classical approach it is also necessary to consider the quantized single particle states resulting from such strong confinement. In semiconducting materials with small effective masses, such as InSb, this consideration is important since the energy separation between single particle states, \( \Delta E \), is inversely proportional to the square root of the effective mass, \( m^* \) [17]. Much work has been done in describing the charging model of GaAs quantum dots in terms of the energy quantisation and Coulomb blockade, resulting in a shell-filling structure analogous to that of atomic physics [17, 18]. Generally for GaAs devices the dominant feature is Coulomb blockade, however the InSb-based dots studied here have both a larger \( \Delta E \) and slightly smaller \( \frac{e^2}{C} \) (due to the large dot size) so that, in principle, one can easily achieve a situation where \( \Delta E \geq \frac{e^2}{C} > kT \), at temperatures up to a few tens of Kelvin. A two-dimensional calculation of the potential distribution in the quantum well of a 2DEG is shown in figure 4. This is generated...
Figure 4. Approximate confinement potential generated by a typical fork-gated InSb/AlInSb SET with some finite negative bias.

for fork-gates with the same nominal dimensions as those observed from SEM inspection of our devices. The electrostatic approximation is based on that of Davies and Larkin [19]. The heavy dashed line illustrates the contour above which the 2DEG is depleted, and consequently defines the boundary of the quantum dot. This value was obtained by examining the potential required to deplete the ground state in the quantum well (2DEG) of the heterostructure according to a self-consistent Schrödinger–Poisson model [15]. At high biases the potential within the dot may, to a good approximation, be characterised in the form of a circular simple harmonic oscillator potential with easily calculable single particle energy states $E_n \approx (n_1 + n_2 + 1) \hbar \omega$ (where $n_1$ and $n_2$ may be 0, 1, 2, ...), leading to a series of degenerate energy levels separated by $\hbar \omega$.

Deviation of the shape of the dot from a circular form will lead to a lifting of degeneracy in the confined states, and a more complicated energy spectrum which is not considered in this basic analysis. The circular confining potential was examined for a range of different gate biases, and the approximate Coulomb blockade charging energies and single particle states were calculated. It is found that the confining potential, defined by the parabola $V = 1/2kr^2$, (where $r^2 = (x^2 + y^2)$ and $k = m^* \omega^2$) was approximately constant over a large range of gate biases, and the single particle state separation energy ($\Delta E$) was consistently of the order of a few meV. The capacitance of the SET is deduced from its radius (given by the dashed contour in figure 4) as $C \propto \varepsilon r$ (where $\varepsilon$ is the permittivity of InSb), and from it the Coulomb blockade charging energy ($e^2/C$) is calculated. The capacitance of the ~100 nm radius dot shown in figure 4 is approximately 0.1 fF. The Coulomb blockade charging energy was seen to vary more strongly with gate voltage (as a result of the $1/r$ relationship) but remained slightly lower than $\Delta E$, i.e. around 1–2 meV, until the dot became extremely small, at which point no confined states remained. Figure 5 illustrates how the dimensions of the dot change with gate voltage. These parameters determine both the single particle and Coulomb blockade energy separations. The dot potential is defined as the ‘depth’ in potential at the centre of the dot (inset), which, combined with the average dot radius is used to calculate a parabolic fit to the
Figure 5. Average dot radius $\langle r \rangle$ (crosses) and dot potential $\phi$ (diamonds) as a function of gate voltage. As the negative bias is applied the radius of the dot diminishes until it is totally depleted. Inset shows cross-sectional profile of the central region of the device before pinch-off. The heavy dashed line shows the Fermi energy which defines the dot radius and potential and the light dashed line shows a typical harmonic oscillator (parabolic) potential approximation of the confinement potential.

potential (shown as a light dashed curve in the inset of figure 5), which gives the single particle states.

The feature separations in figure 3 are consistent with energy scales of the order of a few meV for both the Coulomb blockade and single particle states. The peak separation in figure 2 is suggestive of energy spacing smaller than $\sim 7$ meV, since it must be considered that the potential dropped in the 2DEG is smaller than that applied to the gates due to the distribution of space charge in the heterostructure. Although, the data does not preclude the possibility of impurity state resonance, rather than clean quantum dot formation, the observed energy spacings are consistent with values calculated using appropriate parameters.

We have demonstrated periodic conductance features in an electrostatically defined InSb SET, and estimated the quantisation energy to be of roughly the same magnitude as the Coulomb blockade energy gap, with the potential to become larger if deeper confinement can be achieved, for instance by controlling the dot potential with a plunger gate [20] and smaller lithographically defined gates. The sharpness of these peaks at temperatures as high as 4.5 K indicates that InSb may become an important material for quantum devices, where the low effective mass and high $g$-factor will provide significantly spaced energy levels for higher temperature operation and the potential for manipulation of electron spin.

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