Extended Abstracts of the 1998 International Conference on Solid State Devices and Materials, Hiroshima, 1998, pp. 184–185

Single Hole Tunnelling in Side-Gated SiGe Quantum Dots

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1. Introduction

Since the first demonstration of single electron effects in devices fabricated on SIMOX substrate [1], many variations of SIMOX-based structures have proved popular and rapid progress has resulted in SOI-based single electron transistors operating at room temperature [2-3] and single hole transistors operating at above 77 K [4]. In this paper we describe a novel side-gated SiGe quantum dot transistor on a SIMOX substrate. Our results show a Coulomb blockade and staircase at 4.2 K in the drain-source I-V characteristic. The drain current is controlled by a sidegate and is found to oscillate with a single frequency between gate voltages of ± 2 volts.

2. Material and Fabrication

The starting wafer is a SIMOX substrate with 50 nm undoped-Si on 400 nm SiO_2. A thin layer of undoped Si is grown by low-pressure CVD followed by 30 nm $Si_{0.9}Ge_{0.1}$ doped with Boron to $\sim 1\times10^{19}$ cm^{-3}. Finally a thin Si capping layer is grown to protect the underlying SiGe layer. (Figure 1)

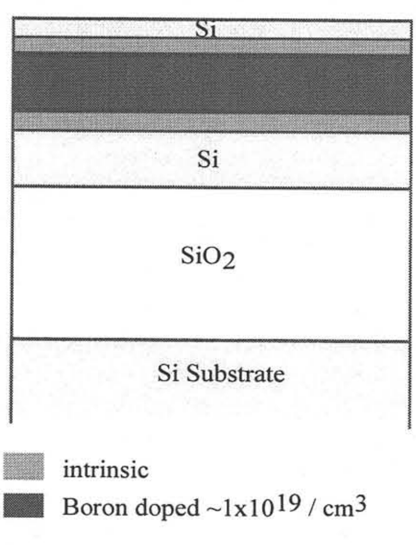

Fig.1 Material layer structure (not drawn to scale)

A 50 nm diameter dot was patterned into PMMA resist by electron beam lithography with a sidegate separated by 50 nm from the dot. The source and drain were connected via two notches to the dot as shown in Figure 2. After developing the resist a metal mask was deposited and lifted off. Reactive ion etching was carried out in $CF_4/SiCl_4$ gas mixture to transfer the pattern into the substrate. The etch depth was > 120 nm to ensure good electrical isolation of the device. The metal mask was then removed and a stage of optical lithography defined the Ohmic contacts to the source, drain and gate.

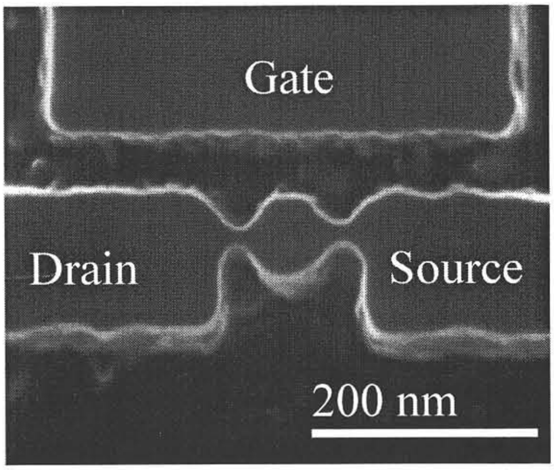

Fig.2 SEM of quantum dot structure with source, drain and sidegate

3. Results and Discussion

Measurements were carried out at 4.2 K using a HP4156A semiconductor parameter analyser. Figure 3 shows the current-voltage characteristics at $V_{gs} = 0$. A current blockade around zero V_{ds} and a staircase are evident. At this gate potential the Coulomb blockade region is 5 mV with the conductance peak spacing of ~20 mV. The total capacitance of the system, $C_\Sigma \sim 8$ aF which corresponds roughly to a SiGe island of radius

~ 20 nm which agrees to within 20 % with the geometrical dimensions of the dot. This supports the view that device characteristics arise from the Coulomb blockade effects in the dot.

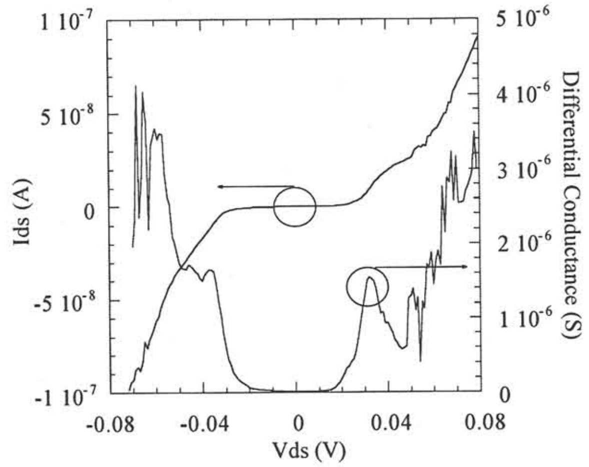

Fig.3 I-V characteristics and differential conductance of SiGe quantum dot at 4.2 K

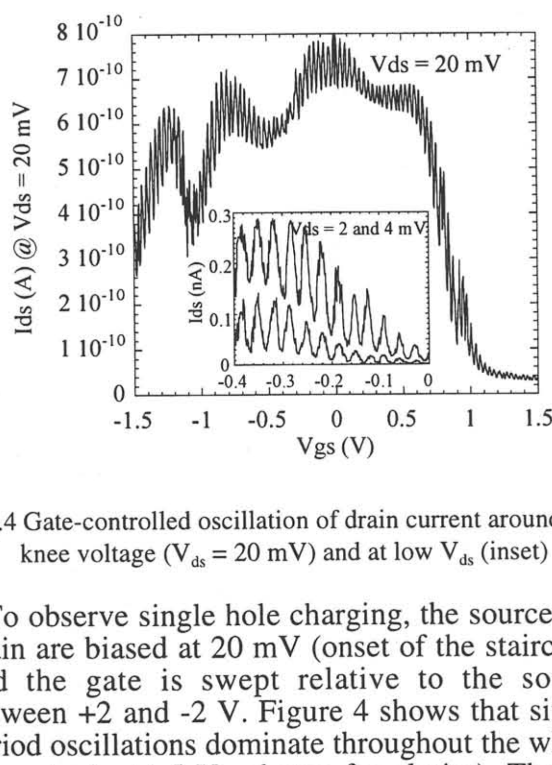

Fig.4 Gate-controlled oscillation of drain current around the knee voltage (V_{ds} = 20 mV) and at low V_{ds} (inset)

To observe single hole charging, the source and drain are biased at 20 mV (onset of the staircase) and the gate is swept relative to the source between +2 and -2 V. Figure 4 shows that single period oscillations dominate throughout the whole range (only ±1.5 V_{gs} shown for clarity). The dot remains transmissive over the range $-1.7 < V_{gs} < 0.7$ beyond which a significant drop in current occurs. The single period oscillation is attributed to the effects of the sidegate on the dot whereas the large current drops around -1.7/0.7 V_{gs} are probably due to changes in the characteristic of the tunnel junctions. The sidegate is in close proximity to the source/drain and the tunnel junctions, hole energy levels in the dot and the source/drain capacitances are therefore affected by the gate potential hence the complicated I_{ds} modulation.

The non-symmetrical I_{ds}-V_{gs} characteristic also suggests that the tunnel junctions are very different in nature, i.e. one being more transmissive than the other, this is manifested in the form of Coulomb staircase in Fig.3.

The gate-controlled oscillation as a function of small bias voltage is also shown in the inset. The period is determined to be 32±1 mV which corresponds to a gate capacitance of ~5 aF. Simple calculation using parallel plate capacitor model and the dimensions estimated from the SEM micrograph from Fig.2 yields a value of ~5.3 aF, in good agreement with the measured value.

4. Conclusions

SiGe quantum dots have been fabricated and characterised. Coulomb blockade and a staircase have been observed at 4.2 K. The Coulomb blockade voltage, the conductance peak spacing and the period of the drain current oscillation as a function of gate voltage agree well with the estimated values obtained from calculations using geometrical dimensions of the fabricated dot. Sidegating have been shown to be effective in controlling single charge transfer.

References

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