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Sub-Micron Vertical AlGaAs/GaAs Resonant Tunneling Single Electron Transistor

D G Austing, T Honda, and S Tarucha

NTT Basic Research Laboratories, 3-1 Wakamiya, Morinosato, Atsugi, Kanagawa 243-01, Japan, Tel: 0462 40 3479, FAX: 0462 40 4723.

Abstract: We explore vertical transport phenomena in sub-micron AlGaAs/GaAs double barrier structures (DBS's) by applying a bias to a special Schottky side gate which allows the effective area of the conducting channel to be adjusted or "tuned". The AlGaAs barriers are selectively doped to generate excess electrons in the GaAs well, and thus single electron transistor (SET) operation is possible because the number of electrons can be varied one by one with the side gate. Gate modulation of the drain current flowing through this channel is found to be strong, and this allows us to study Coulomb blockade, electron-electron interactions and lateral confinement effects. Observation of a broad (≈18mV) current plateau at zero bias when the quantum dot is occupied by a single electron, suggests that this technology is very promising for the realization of SET operation at temperatures well above 4.2K.

Experiments: Devices with a diameter, d, between 0.4 and 1.0μm are fabricated by a technique involving electron-beam lithography, etching of GaAs to a point just *above* the DBS, and the deposition of a Schottky gate parallel to the DBS, as shown schematically in figure 1. The depletion region associated with this gate defines a conducting channel through the DBS with a diameter which is less than d. By making the gate more positively or negatively biased the conducting channel can be increased, or decreased respectively. The starting material consists of an asymmetric $Al_{0.28}Ga_{0.72}As/GaAs$ DBS with barriers of thickness 92Å and 78Å (closest to the substrate). This asymmetry should promote the observation of single electron tunneling through the quantum dot in reverse bias ("thin" collector barrier), and of single electron charging in forward bias ("thick" collector barrier). Additionally, the barriers are modulation doped to ensure that electrons populate the quantum well at zero bias, i.e. the threshold bias of the lowest "normal" resonance is zero, and thus the electrochemical potential of the electrons in the well is nearly equal to that of the emitter and collector contacts close to zero bias. For SET operation, the number of electrons can then be varied by applying a gate bias. Lastly, the contacts are properly graded to maximize the "squeezing" effect in the vicinity of the DBS. The drain current- drain voltage (I_d-V_d), and the drain current- gate voltage (I_d-V_g) characteristics are measured respectively as a function of V_g, and V_d at 300mK and 1.6K.

Main results:

i. The peak and valley current of the main resonances seen in the I_d-V_d characteristics are strongly reduced as V_g is made negative, as shown in figure 2 for a 0.4μm device at 1.6K. This demonstrates very effective "squeezing" of the conducting channel. Concurrently, these resonances first shift towards zero bias, as the Fermi energy in the emitter is decreased, before moving to higher bias when "pinch-off" occurs.

ii. As illustrated in figure 3, additional features in the I_d-V_d characteristics, such as low bias resonances (indicated by arrows), and a broad (≈18mV) current plateau at the origin (V_g=-480mV), which can be effectively regulated by applying a gate voltage, are particularly interesting. The former may be related to lateral size quantisation, while the latter is associated with Coulomb blockade. The total dot capacitance is assessed to be 9aF (=e/18mV) when the current plateau is broadest. From this plateau, we also estimate that the largest energy required to add one electron to the dot is 9meV, which should allow SET operation up to 25K.

iii. Coulomb oscillations are clearly evident in the I_d-V_g characteristics when V_d is set to be 1mV or less as can be seen in figure 4. Starting from V_g=-1V, the quantum dot is empty until V_g has been increased to about -550mV. The two prominent peaks at a gate voltage close to -550mV and -400mV (N=1and N=2) correspond respectively to the addition of the first electron, followed by the second electron to the quantum dot. Figures 3 and 4 are closely related. In particular, the current plateau at the origin is widest when V_g is half way between the N=1 and N=2 peaks. This suggests a strong two-electron interaction in the "squeezed" dot, since the N=1 and N=2 quantised states are spin degenerate in the single particle excitation. The oscillatory behavior for V_g>-0.35V is less distinct because the well is "squeezed" less, i.e. the energy separation between the 0D states becomes very small, and as the number of electrons in the dot is greater than two, the electron-electron interaction energy tends towards an "average" value which is lower than the two-electron interaction energy.

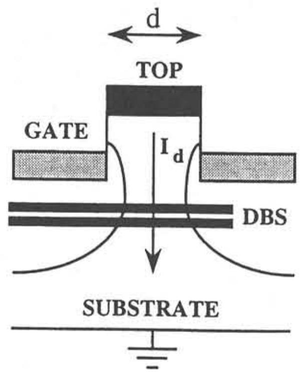

Fig. 1. Schematic diagram of the sub-micron vertical single electron transistor.

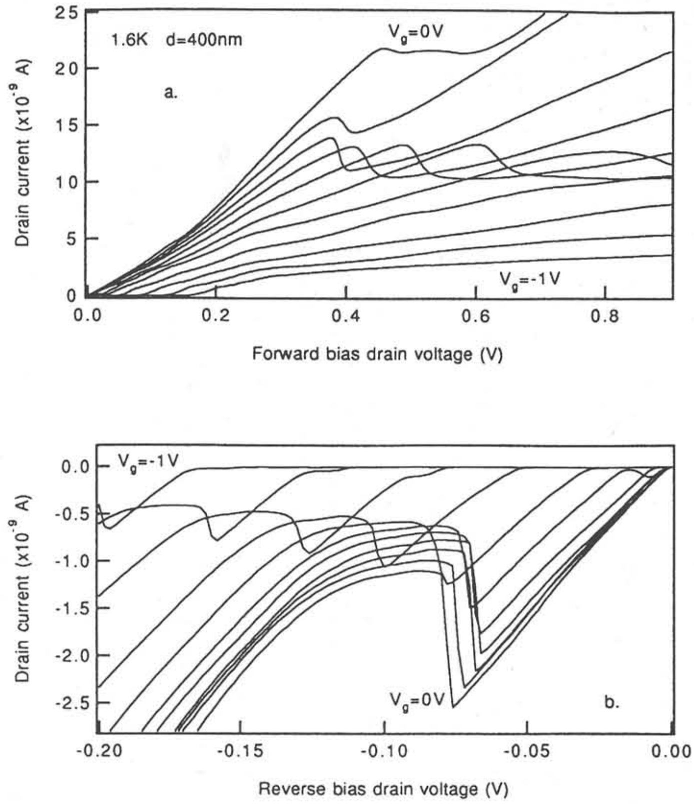

Fig. 2. a. Forward, and b. reverse bias I_d-V_d characteristic as a function of V_g (0V to -1V step -0.1V).

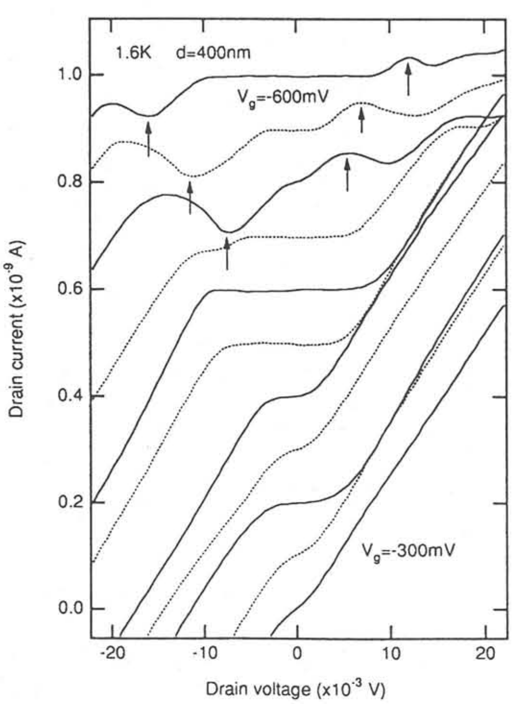

Fig. 3. Low bias I_d-V_d characteristic as a function of V_g (-300mV to -600mV step -30mV). The curves are offset vertically for clarity.

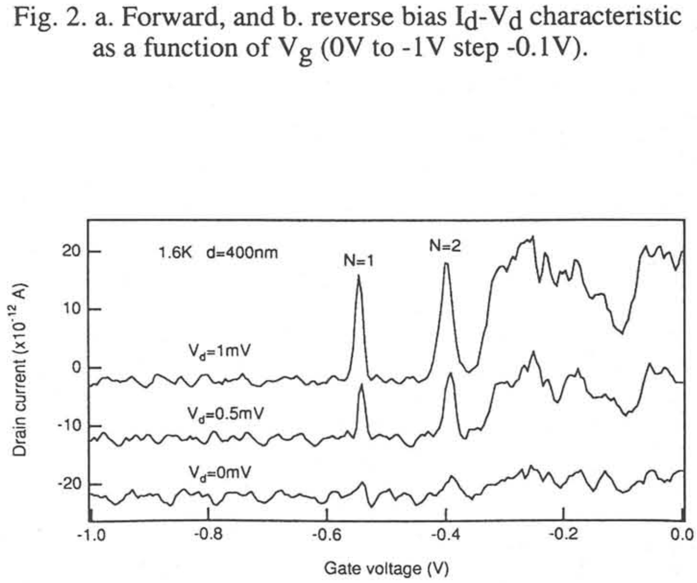

Fig. 4. I_d-V_g characteristic as a function of V_d (0, 0.5, and 1mV). The curves are offset vertically for clarity.