Negative Differential Conductance and Threshold Voltage Distribution in Two-island Single-electron Tunnelling Structures

Gareth J. Evans[1] and Hiroshi Mizuta[2]
[1] *Microelectronics Research Centre, Cavendish Laboratory, Cambridge CB3 OHE, UK*
[2] *Hitachi Cambridge Laboratory, Cavendish Laboratory, Cambridge CB3 OHE, UK*

A huge variety of experimental devices have shown Coulomb Blockade (CB) effects in systems ranging from metal-insulator-metal systems to semiconductor dots produced by electrostatic, geometric or dopant fluctuation confinement. In principle, CB effects allow current flow to be manipulated on a *per electron basis* and has attracted attention as a possible future ULSI technology.

Single-island systems, which are called Single Electron Transistors (SETs), have well-understood simple characteristics. However, the next logical extension, a two-island system, exhibits a huge variety of complex characteristics (for example see [1]).

This paper describes the analysis of the two-island system in Figure 1 and relates its behaviour to the development of its two-dimensional phase space ($\tilde{\boldsymbol{q}}$) as the source-drain voltage $V_{\rm ds}$ changes. We propose a geometrical approximation called *the polytope approximation* to track the changes in phase space. (A *polytope* is a finite volume polyhedron and for the two-island case is a polygon.)

As an example of the variety of behaviour possible for two-island systems, we demonstrate a device that exhibits strong negative differential conductance (NDC) shown in Figures 2 and 3. Interestingly, this NDC is *not* connected to discrete quantum energy levels but due to the charging energy considerations. Previously, *Nakashima* et al. have shown NDC to exist in linear arrays of seven- and nine-island systems [2,3], while *Heij* et al. [4] demonstrated a two-island system that exhibited NDC. *Shin* et al. [5] have also shown that NDC can exists in ring-arrays of junctions. Our two-island system is most similar to *Nakashima* et al.'s device and the polytope approximation lets us derive the following necessary condition for NDC,

$$\frac{C_{1d}}{C_{s1}} > \frac{C_{2d}}{C_{s2}}$$

Figure 2 demonstrates that NDC exists only when the offset-charge or gate biases are tuned to the correct part of phase space. The offset-charge problem makes a system's characteristics very unpredictable. Assuming that the offset charge is uniformly distributed in the range $-0.5e$ to $+0.5e$ then the threshold voltage distribution for a structure can be calculated from the polytope approximation as shown in Figure 4 and the actual polytopes are shown in Figure 5, where regions less than 1 fA are black.[6,7]

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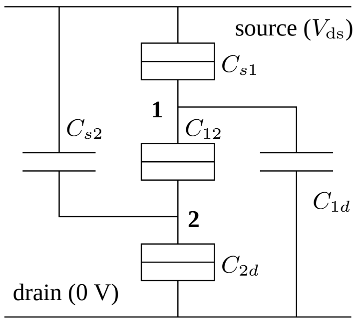

Figure 1: The two island circuit under analysis. This is the most general two-island *linear* array possible.

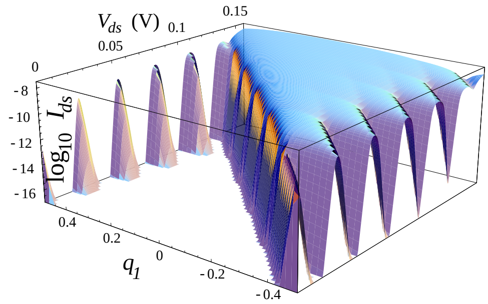

Figure 2: $\log_{10}[I_{\rm ds}]$ as a function of $V_{\rm ds}$ and the offset charge on island 1. Changing the offset charge on island 2 from -0.5 to 0 roughly changes the phase of the oscillations by π.

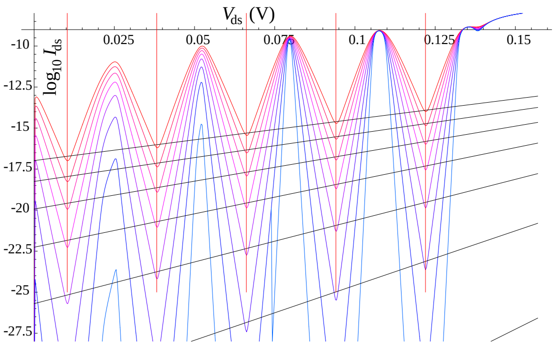

Figure 3: Part of Fig. 2 in the NDC region at temperatures from 8.2 K (top) to 1.2 K in 1 K steps. Vertical lines are predictions of the valley positions and the solid lines of valley currents.

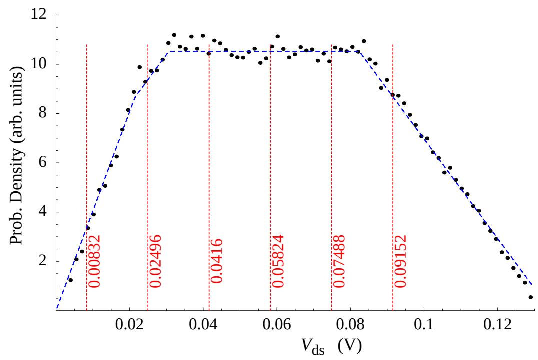

Figure 4: Threshold voltage distribution for a non-NDC circuit. The line is the polytope approximation's prediction and the dots are from a Monte Carlo simulation of the device.

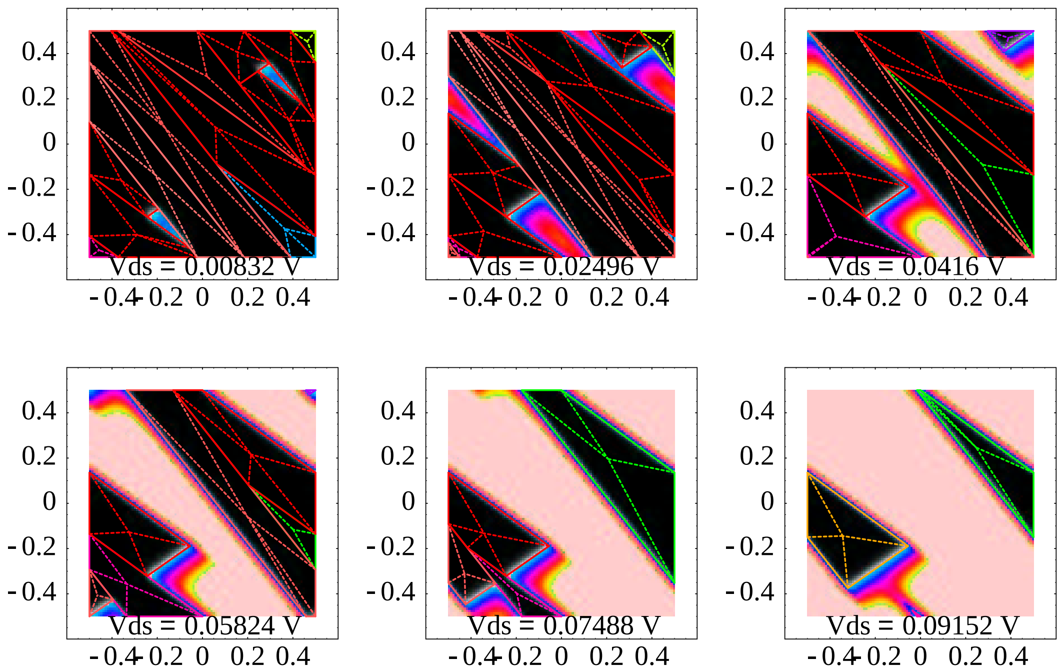

Figure 5: The current as a function of $\tilde{\boldsymbol{q}}$ at the $V_{\rm ds}$ corresponding to the vertical lines in Figure 4. The polytopes are marked with solid lines and their interiors indicated with dashed lines.