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Room-temperature double quantum dot transistors for investigating Maxwell's Demon

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Introduction

Maxwell's Demon (Fig. 1), a thought experiment proposing that energy may be transferred without the expenditure of work at the microscopic scale, suggests limitations on the 2nd law of thermodynamics. These limitations were refuted by Szilard [1], who considered entropy changes in the demon's "memory" to restore the 2nd law. Furthermore, Szilard proposed a one-molecule gas engine which has been used to identify the link between information and entropy, and extended to a quantum mechanical version by Zurek [2]. Recent advances in nano-fabrication have made it possible to experimentally investigate Szilard's engine and analyse changes in energy, entropy, and information in nano scale systems [3].

This paper shows that a single dopant atom double quantum dot (DQD) transistor operating at room temperature (RT) can form a Szilard engine. Device fabrication methods are shown, and RT charge stability diagrams are measured. Simulation of these diagrams is then used to investigate Szilard engine operation at RT.

Fabrication and validation

- Silicon-on-insulator (SOI) wafer – ⟨100⟩ crystal orientation.
- Ultra-thin 12 ± 1 nm top Si layer.
- Heavily-doped *n*-type ~10^{20} cm^{-3} concentration of P.
- Point-contact region defined by electron beam lithography (EBL).
- Geometric oxidation of the point contact region produces a random array of dopant-atom (P) QDs.
- Gate voltages to tune array for DQD operation.

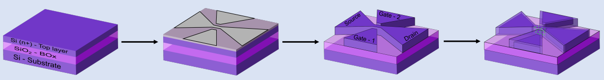

Figure 2. Fabrication sequence for a DQD system. From left to right: An SOI wafer with a bi-layer of PMMA is exposed by EBL, where device features are defined. Al evaporation is performed for reactive-ion-etching. Finally, geometric oxidation is performed to create tunnel barriers and isolate QDs.

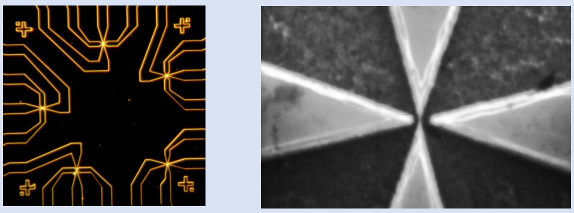

Figure 3 (Left) Dark field optical micrograph of the five DQD transistors with the nanostructure point-contact regions showing brightly. (Right) SEM image of a pre-oxidized single DQD transistor showing source-drain leads connected through a point-contact and two gates for electrostatic control.

Configuration and electrical measurements

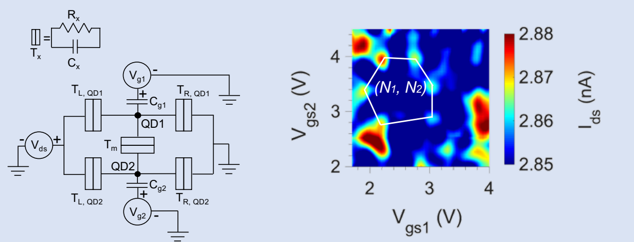

Figure 4. (Left) Circuit diagram for a parallel DQD. (Right) Experimental results of charge stability region showing signature DQD I-V characteristics. Current peaks form hexagonal patterns. Irregularities in shape correspond to DQD capacitance changes [4].

Maxwell's Demon and Szilard's Engine

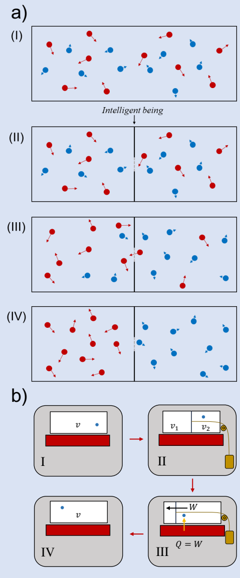

Figure 1. a) (I) Ideal gas consisting of fast (red) and slow (blue) moving particles in a container. (II) - (III) An intelligent being, the Maxwell Demon, inserts a partition and selectively allows fast moving particles to move to the left side, and slow moving particles to move to the right side. This builds a non-uniform energy distribution, where the left side is warmer than the right side, without expenditure of work, contradicting the 2nd law.

b) Szilard's engine (I) A particle occupies volume $\boldsymbol{v}$, coupled to a heat bath (red rectangle). (II) A partition is inserted, trapping the particle in $\boldsymbol{v}_2$ = $\boldsymbol{v}$/2. Demon "memory" records particle location. (III) Isothermal expansion of the reduced volume as the particle extracts *Q* amount of energy, performing work *W* = *Q*. (IV) System back to equilibrium, demon memory reset, and all entropy accounted for.

Monte Carlo simulation

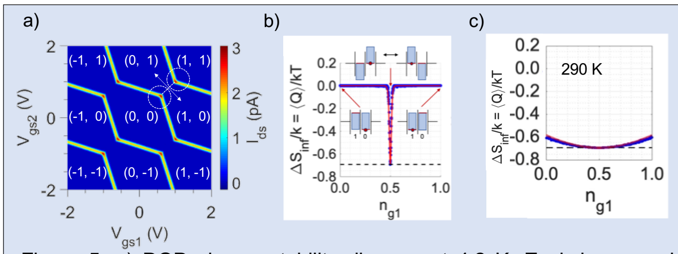

Figure 5. a) DQD charge stability diagram at 4.2 K. Each hexagonal region corresponds to the mean number of electrons on $QD_{1,2}$ (N_1, N_2). Triple points are circled, and the white arrow is the Szilard cycle trajectory for a (1, 0) to (0, 1) transition. b) Reduced entropy changes $\Delta S_{inf}/k=\langle Q\rangle/kT$ vs. gate-1 parameter n_{g1}; theoretical equation fit (red line). c) Reduced entropy changes for the same system at 290 K.

Conclusions

- RT operation of single dopant atom DQD transistors.
- Nano-fabrication of DQD transistors based on Si/SiO_2/Si point-contacts in SOI material.
- RT measurements of charge stability diagrams.
- Gate voltage trajectories for one-electron gas Szilard engine operation.
- Extraction of entropy changes in the engine at RT.

References

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Acknowledgements

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