Energy Costs of Precise Erasure for Nanoscale Silicon Dot Memory with Non-equilibrium Initial State

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The Landauer's bound (LB), which elucidates the relation between the entropy change ΔS and the lower bound of heat Q dissipated during memory erasure, has been a central focus in applying stochastic thermodynamics to understand the energy costs of computation. For erasing a single-bit memory with logical states "0" and "1", the uniform probability distribution of initial state $P_\mathrm{i} = (p_{"0"}, p_{"1"}) = (1/2, 1/2)$ is transformed to final state $P_\mathrm{f} = (0, 1)$, leading to the LB $Q \geq -kT\Delta S = kT \ln 2$, where k is Boltzmann's constant and T is temperature. The memories used in previous demonstrations of the LB, such as quantum dots serving as two-level systems [1], can prepare the initial state P_i in equilibrium, thereby enabling the quasi-static operation necessary to reach the LB. In contrast, we focus on a nanoscale silicon dot memory with the initial state in non-equilibrium, inherently prohibiting quasi-static operation. We reveal that this memory does not reach the LB without compromising operation precision, by measuring the above quantities at the single-electron level.

The device consists of a detector, a nanoscale dot, a gate electrode forming a potential barrier, and a reservoir, fabricated on a silicon-on-insulator wafer [Fig. 1] [2]. We conducted the experiment at room temperature (300 K). The chemical potential of the dot is given by $\mu_n = 2E_\mathrm{C}n$, where E_C is the charging energy, and n is the excess number of electrons counted from the average at the equilibrium condition with the reference reservoir voltage $V_\mathrm{R} = V_\mathrm{i}$. We measured n from the detector current I_d [2]. Thermally excited electrons stochastically hop between the dot and the reservoir, and the heat accompanying an individual hopping equals the difference between μ_n and the reservoir energy eV_R [3].

We repeated the following experiment and obtained the probability distribution p_n and the total heat Q [Fig. 2]. We defined the logical states "0" and "1" as $n \leq -1$ and $n \geq 0$, respectively. (i) We prepared the initial state P_i by writing the same number of logical states "0" and "1" over the iterations. For the writing, we first lowered the barrier to allow hopping, and applied reservoir voltage $V_{0,1} = V_\mathrm{i} \pm \Delta\mathrm{V}$ and waited for equilibration, then increased the barrier to keep n unchanged. After that, we set V_R to V_i to simulate typical memory usage where the writing history is erased, pushing the system into non-equilibrium. Note that ΔV should be large enough to reduce initial error ε, which is defined as the overlap of p_n between the logical states. (ii) We started erasing by lowering the barrier and then wait for equilibration. (iii) We swept V_R to V_1 quasi-statically and then increased the barrier to finish erasing. Figure 3 shows the measured Q as a function of ε, demonstrating the trade-off relation between them. Notably, Q exceeds the LB by approaching the zero-error limit. We argue that the system does not reach the LB because the initial state is in non-equilibrium, inherently prohibiting quasi-static operation.

References: [1] M. Scandi, *et. al.*, Phys. Rev. Lett, **129**, 270601 (2022). [2] K. Nishiguchi, *et. al.*, Nanotechnol. **25**, 275201 (2014). [3] K. Chida, *et. al.*, Appl. Phys. Lett. **107**, 073110 (2015).

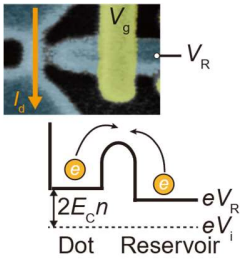

Fig.1. SEM image and energy diagram of the sample.

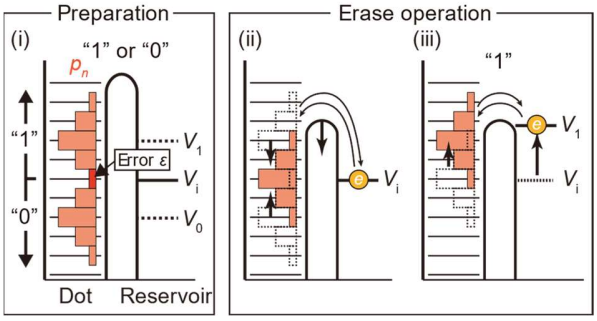

Fig.2. Procedure of the memory erasure experiment.

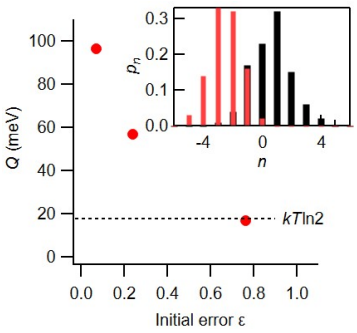

Fig.3. Total heat Q as a function of the initial error ε. Inset: typical p_n of initial state (Initial error $\varepsilon = 0.24$).