Thermodynamic limits for approximate MEMS memory devices

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***Abstract*—In this paper we present the results obtained evaluating the energy cost of operating a micro elctro-mechanical system as a memory bit. The experiment has been conducted at an effective temperature above the room temperature in order to make the energy dissipated due to friction negligible respect to the energy required by the thermodynamics. Finally we have evaluated the impact of approximate memorization to the energy cost of the operation.**

I. Introduction

The minimum energy required to reset one bit of information represents one of the fundamental limits of computation arising when one bit of information is erased or destroyed. From thermodynamic principles it can be demostrated that the minimum energy required to reset on bit of information is $Q_{\mathrm{L}} = k_{\mathrm{B}}T \ln 2$. This takes the name of Landauer limit[1], and it is analogous to write one bit on a memory device regardless the previous state of the memory. If we consider the possibility to commit errors during the reset operation the heat produced becomes a function of the probability of success $Q(P_{\mathrm{s}}) \geq k_{\mathrm{B}}T \left[\ln(2) + P_{\mathrm{s}} \ln(P_{\mathrm{s}}) + (1 - P_{\mathrm{s}}) \ln(1 - P_{\mathrm{s}})\right]$ [2]. When P_{s} is 0.5 no reset operation is performed and thus there is no minimum heat to be produced during the operation [3], [4], [2]. We have recently shown that it is possible to use electro-mechanical devices to accomplish basic[5], [6] and complex logic operations[7], and thus the presented research is crucial to understand the fundamental limits in energy consumption considering approximate memorization.

II. Micro electro-mechanical memory bit

The mechanical system used to perform the experiment is depicted in Figure 1. A triangular micro-cantilever, 200 µm long, is used to encode one bit on information. In order to obtain two stable states two magnets with opposite magnetization are placed on the tip of the cantilever and on a movable stage facing the cantilever. In this way, depending on the distance between the magnets, d, and the relative vertical alignment, Δx, it is possible to induce bistability on the system. When the magnets are far away the effect of the repulsive force is negligible, the system is then monostable and can be approximated to a linear system. Decreasing the distance the repulsive force between magnets tends to soften the system up to the point where two stable positions appear. Logic states are encoded in the position of the cantilever tip in the bistable configuration: logic 0 for $x < 0$ and logic 1 for $x > 0$. The proposed system presents

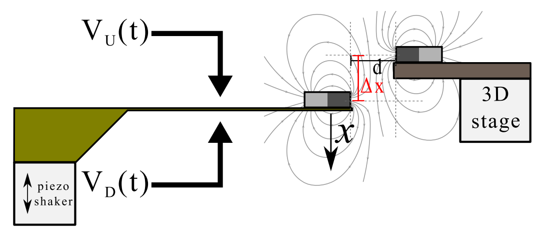

Figure 1. Schematic of the whole system and measurement setup. Lateral view of the whole system and measurement setup.

intrinsic dissipative processes that depend on the maximum displacement of the cantilever tip[7]. In order to make the energy dissipated due to friction negligible respect to the energy bounded by the thermodynamics we have considered to perform the experiment at an effective temperature above room temperature. A piezoelectric shaker is used to excite the structure with a band limited white Gaussian noise to mimic the effect of an arbitrary temperature of T_{eff} = 5×10^7 K. Two electrostatic probes, placed one on the top and the other on the bottom of the cantilever, are used to apply a negative and positive forces respectively. When a voltage different to zero is applied on one probe the cantilever feels an attractive electrostatic force toward the probe due to the polarization of the cantilever itself. The voltage on the probes, the distance between the magnets and their time evolution are used to specify the protocols used in order to change the bit stored in the system. The reset procedure applied is similar to the ones presented in Refs. [8] and [3]. Initially the barrier separating the two stable states is removed moving the counter magnet away making the system monostable. Once the barrier is removed a negative (positive) force is applyied to reset the bit status to 0 (1), applying a finite voltage V_{U} (V_{D}) on the top (bottom) probe. Once the force is set the barrier is restored to its original value. Finally, the electrostatic force is removed finishing the protocol in the original parameters configuration. At the end of the operation, if there are no errors, the cantilever position encodes the desired bit of information. In order to be sure to perform the operation starting from both initial states, we mimic a statistical ensemble where the initial probability is 50% to start in the left well and 50% in the right well. When the barrier is removed the system goes from the local prepared state to an undefined state with a free expansion, the entropy on the system thus increases in a irreversible manner[8], [9]. This increment is related to uncontrollable transitions from one well to the other once the barrier height is close to $k_{\mathrm{B}}T$. In the optimal case the initial configuration is a mixed logical 0 and 1 where both states have the same probability while the final configuration is the selected state with a 100% probability. This corresponds to an entropy variation of $\Delta S = -k_{\mathrm{B}} \ln(2)$ and a minimum heat produced of $Q_{\mathrm{L}} = -T\Delta S$. This limit applies only for symmetric potentials, considering asymmetries on the system the minimum produced heat can be lowered below Q_{L} [10]. In our setup the system is slightly asymmetric and we have evaluated the variation of entropy from the initial to the final state from the probability density function of the tip position being $\Delta S_{\mathrm{G}} = -0.61 k_{\mathrm{B}}$ and $\Delta S_{\mathrm{S}} = -0.68 k_{\mathrm{B}}$ for the Gibbs and Shannon entropy respectively, both close to $-k_{\mathrm{B}} \ln(2)$. In Figure 2 (a) we present the average heat

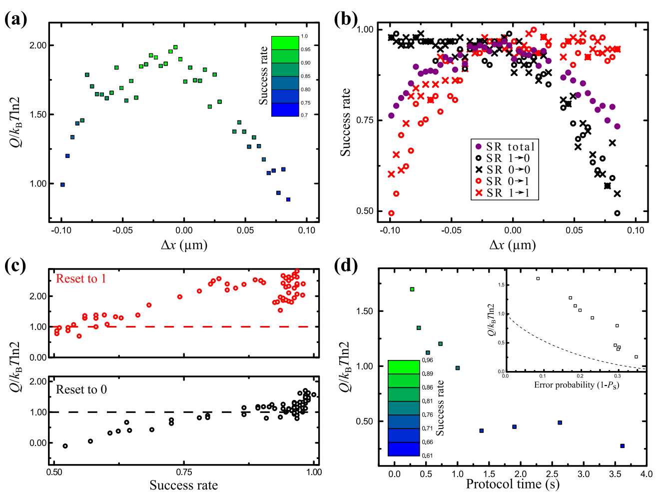

Figure 2. Produced heat and probability of success for the reset operation. (a) Average heat produced during the reset operation as function of the vertical alignment Δx. (b) Success rate of the reset operation as function of vertical alignment. (c) Relation between success rate and heat dissipated. (d) Dependence of Q with the protocol time duration, τ_{p}.[11]

produced for the reset operation as function of the vertical alignment of the counter magnet Δx. When the system is aligned closely to perfection (i.e. $\Delta x \approx 0$) we estimate a heat production slightly above $k_{\mathrm{B}}T$ and below two times Q_{L}. Asymmetrizing the potential, by means of setting $\Delta x \neq 0$, the heat produced tends to decrease reaching values below Q_{L}. However, in these conditions the error rate in performing the reset operation plays a major role, in fact in these configurations the probability of success, P_{s}, decreases rapidly. This is represented by the color map of dots in Figure 2 (a), where green represents higher success rate while blue represents a higher probability of error. In Figure 2 (b) the success rate of the reset operation is reported as function of the vertical alignment. Solid violet circles represent the overall success rate while red and black symbols represent the error rate for resetting to 1 or to 0 respectively. Circles are used to report the error probability for the same initial and final state while crosses are used for 0 to 1 and 1 to 0 transitions. We can now correlate the heat produced to the probability of success for resetting to 0 and 1 as presented in Figure 2 (c). Dashed lines represent the Landauer limit for a 100% of success rate ($\approx 0.7 k_{\mathrm{B}}T$). While in both cases the heat produced is above the Landauer limit, for $P_{\mathrm{s}} = 1$, in the reset to 0 case the obtained values are very close to Q_{L}. As expected, decreasing the success rate the obtained values goes below the Landauer limit for both case [11]. The adiabatic transformation in presence of dissipation mechanisms, like viscous damping, can be only reached if the operation is performed slowly enough, and thus when friction mechanisms are negligible. We have studied the heat produced increasing the protocol time for the reset operation from $0.25\,\mathrm{s}$ up to $3.5\,\mathrm{s}$, the results obtained are presented in Figure 2 (d). Increasing the protocol time the heat production decreases, reaching values well below the Landauer limit. However in these cases P_{s} is well below 1 since the system has more time to relax and therefore tends to thermalize before the reset operation is correctly performed. In fact for protocols lasting more than $1\,\mathrm{s}$ the success rate reaches values below 75%[11].

III. Conclusion

We have shown experimentally that it is possible to reach the thermodynamic limits of energy consumption operating a micro-mechanical device as memory bit. We have further shown that this limit can be lowered arbitrary decreasing the success rate of writing the bit of information on the device, showing that it is possible to save energy accepting approximation on memorization.

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