ICT-ENERGY LETTERS

NEMS memory bit at Landauer limit

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***Abstract*——In this paper we present a study based on molecular dynamics simulations, where reset protocols are applied on a graphene buckled ribbon, employed here as a nano electromechanical memory bit working at the thermodynamic limit.**

I. INTRODUCTION

TODAY computing devices have a remarkable flaw: they produce heat. One of the main goals of the ICT community is than to develop a new generation of processors that produces significantly less heat than the current technologies. As a big contribution in transistors heating comes from internal currents (Joule heating), there is broad interest in devices where computations is not made by moving electrons but by moving mechanical parts: MEMS and NEMS are now widely investigated as the possible heirs of Transistors [1]. However changing processor technologies is not enough; physics imposes limits and boundaries to the heat that must be produced while a computation takes place. Among such limits (recently reviewed in [2]), the most famous one is Landauer limit, which sets to $k_B T ln2$ the heat produced while resetting one bit of information. As this value is non-zero, it becomes important to understand the conditions, if any, under which NEMS and MEMS devices reach that value. This task is the main topic of this work.

II. METHODS

To address the Landauer limit in NEMS, we use LAMMPS [3] to arrange 240 carbon atoms in a ribbon, clamped on both the short edges. A constant compression in applied to the clamping regions so that the ribbon buckles in the out-of-plane direction with two possible stable states. Those are used to encode information (Fig. 1): being (X,Y,Z) the coordinates of the central atom of the ribbon, we say that the ribbon represents a bit of information in the 0 (1) logic state if Z>0 (Z<0). Bit stability is ensured by taking the compression in such a way that the persistency time in each stable state is longer than the operation time of the device itself. To change the state of the bit, a set of four electrodes is arranged around the ribbon (see Fig. 1 for details) and driven according to a specified protocol.

To address the issue of the heat produced when protocols are applied on the ribbon, we take tools from stochastic energetics [4]. The total energy of the ribbon can be written as

$$H(\vec{P},\vec{R},t)=H_{kin}(\vec{P})+H_{REBO}(\vec{R})+H_{ext}(\vec{R},t)$$

where $\vec{P}=\{\vec{p}_i\}, \vec{R}=\{\vec{r}_i\}$ are the momenta and the positions of all carbon atoms, $H_{kin}(\vec{P})$ is the total kinetic energy of the ribbon, $H_{REBO}(\vec{R})$ is the interatomic interaction energy modelled through a REBO potential [5] and $H_{ext}(\vec{R},t)$ is the total atom-electrode interaction energy.

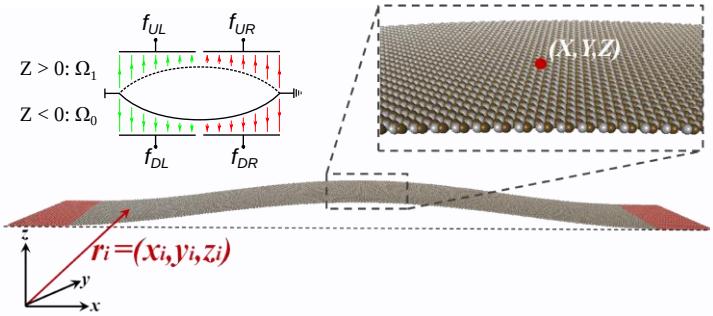

Fig. 1. Schematics of the 2D ribbon encoding one bit of information. The top left diagram shows the two stable configurations of the ribbon and the four electrodes used to actuate the ribbon as required by some protocol.

In this study we take

$$H_{ext}(\vec{R},t)=\sum_{i=1}^{n}\theta(l/2-x_i)\left(\frac{f_{UL}(t)}{g-z_i}-\frac{f_{DL}(t)}{g+z_i}\right)+\theta(x_i-l/2)\left(\frac{f_{UR}(t)}{g-z_i}-\frac{f_{DR}(t)}{g+z_i}\right)$$

where n is the number of atoms, l is the clamp-clamp distance, $ri=\{xi\ ,\ yi\ ,\ zi\}$, Θ is the Heaviside step function and g is the distance between the electrodes and the plane $z=0$. Parameters f_{UL}, f_{DL}, f_{UR} and f_{DR} are relative to the corresponding electrode and their time evolution depend on the protocol operated on the device. The work performed on the ribbon is, by definition

$$W=\left\langle \int_{t_0}^{t}\frac{\partial H_{ext}(R,t)}{\partial t}dt \right\rangle$$

where τ is protocol duration and $\langle . \rangle$ denotes averages over an ensemble of protocol realization.

III. RESET PROTOCOLS

By reset protocols we mean that we take a bit that is initially not defined and than we operate a procedure that brings it in a well defined logic state, e.g. 1. From the point of view of ribbons, this is equivalent to initially have the ribbon buckled either upward or downward and than actuate with a protocol such that when it ends:

1) the ribbon is always buckled upward
2) all the external fields are removed.

Thanks to system symmetry with respect to the plane $z=0$ and property 2), quasi-static protocol longer than the system relaxation times are characterized by a null variation in internal energy $\Delta H=0$. Consequently, the heat Q is given by the first principle of thermodynamics ($\Delta H=W-Q$) as

$$Q=W=\left\langle \int_{t_0}^{t}\frac{\partial H_{ext}(R,t)}{\partial t}dt \right\rangle$$

The simplest reset protocol we can realize is obtained by applying a constant electric field in the upper electrodes and than removing it.

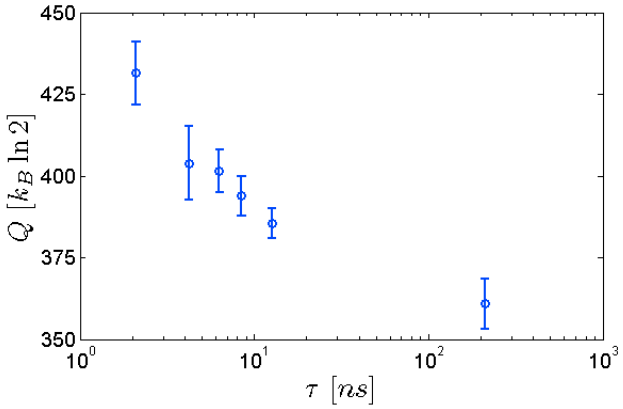

Fig. 2. Heat produced by the naive reset protocol realized by applying a constant force with the upper electrodes. Even increasing the protocol duration, heat is still orders of magnitude higher than Landauer limit.

The results obtained in this way are illustrated in Fig. 2 and clearly shows that this reset protocol produces heat that is orders of magnitude larger than k_BTln2, even if protocol duration is increased. This can be explained as follow: when a constant force is applied, the ribbon is forced to assume a shape that is close to the flat one. As this is unstable, the ribbon spontaneously buckles to a more stable configuration with a high velocity. As a consequence a great amount of heat is produced by friction. As proposed in [6] the only way to avoid this kind of excess heat production is to use protocols where the system is always close to a stable configuration.

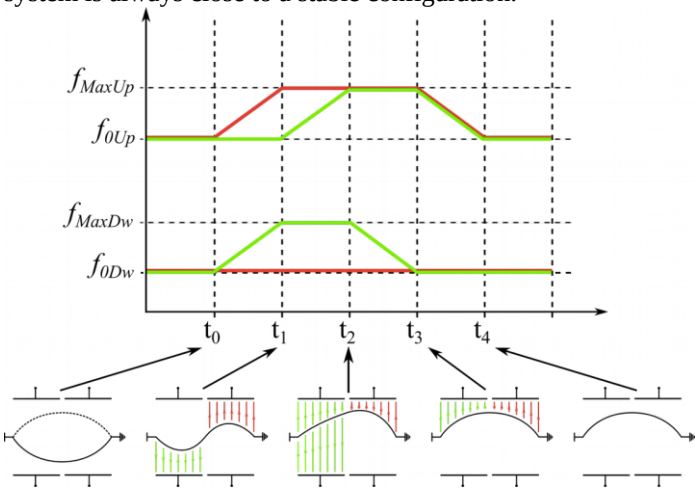

Fig. 3. Time diagram of the electrostatic forces acting on the ribbon for an alternative reset protocol. Top curves are relative to the top electrodes, while the bottom ones are relative to the bottom electrodes; green and red colours represent left and right electrodes, respectively. The lower panel represents the ribbon profile at different times.

One realization of such protocols is shown in Fig. 3, where the *S*-shape in which the ribbon is put at the beginning ensures that the velocity of each atom is carefully controlled. By increasing protocol duration is than possible to reach the thermodynamic limit k_BTln2 (Fig. 4).

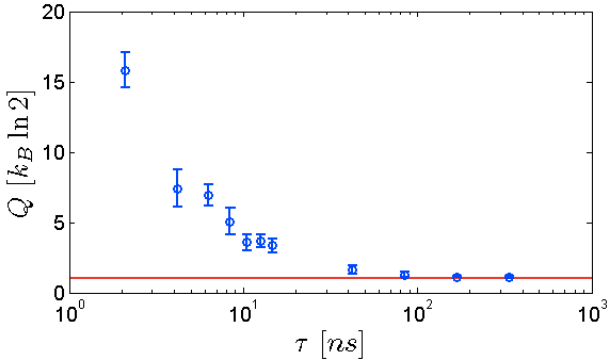

Fig. 4. Heat produced by the reset protocol presented in Fig. 3. The red line is Landauer limit, k_Bln2. We clearly see that this value is approached if protocol duration is sufficiently long.

IV. CONCLUSIONS

This work shows that NEMS systems can in principle be used to realize computing devices that produce the minimum heat required by the thermodynamic. However, this requires that the protocol used do not involve events where the velocity of the device itself can't be controlled externally. As shown here, these are the main mechanism that generates undesired high heat productions.

V. ACKNOWLEDGMENTS

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REFERENCES

[1] M. L. Roukes, “Mechanical computation, redux?”, Proceedings of the IEEE, vol. 98. issue. 12, pp. 539-542, Dec 2004

[2] T. Sagawa, “Thermodynamic and logical reversibilities revisited,” J. Stat. Mech. vol. 2014, , pp. P03025, Mar 2014.

[3] http://lammps.sandia.gov/

[4] K. Sekimoto, Stochastic energetics , 1st ed., Springer-Verlag Berlin Heidelberg, 2010

[5] D. W. Brenner et al., “A second-generation reactive empirical bond order (REBO) potential energy expression for hydrocarbons”, J. Phys.: Condens. Matter, vol. 14, pp. 783, 2002

[6] M. Madami et al., “Fundamental energy limits in the physics of nanomagnetic binary switches”, Nano Energy, vol. 15, pp. 313-320, Jul 2015