Highlights from the University of Perugia, IT

According to the ITRS, the limits imposed by the physics of switch operation will be the roadblock for future scaling in the next 10-15 years. The ultimate limit on the minimum energy per irreversible switching is set at *kBT ln2*, identified with the so-called Landauer limit, that represents a fundamental lower bound imposed by thermodynamics.
Such a limit arises as a consequence of the so-called Landauer principle, which states that by erasing one bit of information, on average, at least kBT ln(2) of energy in dissipated into the environment, where *kB* is Boltzmann's constant and *T* is the temperature at which one erases. An erasing operation is an information decreasing transformation and thus it implies a decrease in the physical entropy of the system. As a consequence, according to the second principle of thermodynamics, an entropy change of $\Delta S < 0$ requires a minimum of energy to be dissipated during the transformation, and this is $Q=-kBT \Delta S$.
The Landauer principle has been experimentally demonstrated using a system of a single colloidal particle trapped in a modulated double-well potential in 2012, few months before the start of the project.

The scientific objective of the LANDAUER project is to test the fundamental limits in energy dissipation during the operation of physical switches representing the basic elements of logic gates. During the project we addressed the physical limits arising from a generic switch mechanism that is common to any digital device, with specific reference to the fundamental limit arising from the decrease of information in the computation procedure, also known as Landauer limit.

The main results obtained during the project can be summarized in four categories:

1. Understanding of the expected physical limits to the energy dissipation in basic switches in the classical [1,2,3] and quantum domain [4,5].
2. New physical switches aimed at overcoming the present technology-related limits and test the validity of the fundamental physics limits in nanomagnetic [6,7,8,9] and nanomechanical devices [10,11,12,13,14].
3. Novel computing devices based on Stochastic Resonance, which can be implemented by means of switches operating under uncertainty, randomness and unreliability as a result of lower energy consumption [15,16,17,18].
4. Test of computing models that can trade partially unreliable computation with lesser energy requirement [19,20,21].

Among the above mentioned results, strictly related to the objective of the project several other important results have been achieved in fields not directly related to the project.

To mention few of them:

1. Voltage fluctuations to current converter in a system consisting of two Coulomb-coupled quantum dots. The first quantum dot is connected to a reservoir where voltage fluctuations are supplied and the second one is attached to two separate leads via asymmetric and energy-dependent transport barriers. We observe a rectified output current through the second quantum dot depending quadratically on the noise amplitude supplied to the other Coulomb-coupled quantum dot. The rectification delivers output powers in the pW region. Future devices derived from our sample may be applied for energy harvesting on the nanoscale beneficial for autonomous and energy-efficient electronic applications. [22]

2. Developed a gas sensor with a standard functionalized cantilever driven strongly into the regime of nonlinear oscillations. In the nonlinearly driven cantilever, the adsorption and desorption-induced frequency shifts were enhanced by over a factor of three compared to resonant sensing with the same mode in the linear regime. This demonstrates a route towards gas detectors that exploit nonlinearity to enhance the responsivity, which can be implemented with standard cantilever devices. [23]
3. Observation of decoherence in a carbon nanotube mechanical resonator: in physical systems, decoherence can arise from both dissipative and dephasing processes. In mechanical resonators, the driven frequency response measures a combination of both, whereas time-domain techniques such as ringdown measurements can separate the two. In this work the first observation of the mechanical ringdown of a carbon nanotube mechanical resonator is presented. Comparing the mechanical quality factor obtained from frequency- and time-domain measurements, a spectral quality factor four times smaller than that measured in ringdown has been found, demonstrating dephasing-induced decoherence of the nanomechanical motion. This decoherence is seen to arise at high driving amplitudes, pointing to a nonlinear dephasing mechanism. Those results highlight the importance of time-domain techniques for understanding dissipation in nanomechanical resonators, and the relevance of decoherence mechanisms in nanotube mechanics. [24]

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