AC Signal-Sensing 6 Orders of Magnitude above Cutoff Frequency in DRAMs with a Non-Equilibrium Nanoscale Dot

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Electric devices are systems operating out of equilibrium, and understanding such systems provides crucial insights into dynamic processes, where energy fluxes and transformations are fundamental, driving various phenomena. In this study, we focus on the high-frequency, non-equilibrium performance of a nanoscale dynamic random-access memory (DRAM) device, in which the DRAM reads out an AC signal over six orders of magnitude above its cutoff frequency Γ_0. Our investigation opens avenues for high-frequency energy storage and sensing applications using nanoscale devices.

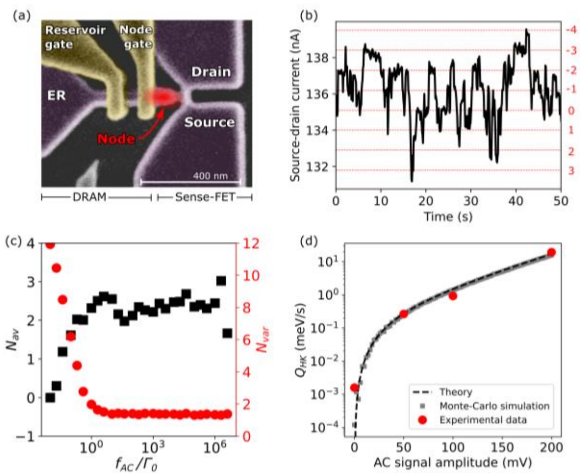

Fig.1. (a) False color scanning electron microscopy image of the DRAM. (b) Sense-FET's current over time. Discrete jumps are visible that correspond to the number $N - \langle N \rangle$ of electrons in the node. (c) Average N_{av} and variance N_{var} of $N - \langle N \rangle$ as a function of f_{AC}/Γ_0, frequency of the signal normalized by the DRAM's cutoff frequency. (d) Housekeeping heat as a function of the AC-signal amplitude.

In the DRAM shown in Fig. 1(a), single electrons shuttle between a nanometer-scale dot (the node) and an electron reservoir (ER). In Fig. 1(b), the current passing through the sense-FET capacitively coupled to the node is read out, the time evolution of the number of electrons *N* in the node can be determined with single-electron resolution at room temperature. Here *N* is defined so that its average value N_{av} is zero when only a DC signal is applied on the ER[1]. The addition of an AC modulation on the ER gives rise to a change in the probability distribution of *N*. The shuttling follows the modulation at frequencies lower than Γ_0, thus the system is nearly in equilibrium at every instant, as shown in Fig. 1(c): at low frequency, N_{av} remains zero, although the observed variance of *N*, N_{var}, is larger than its equilibrium value $N_{var}^{(\mathrm{eq})}$. On the other hand, the slow transitions die away at higher frequencies. As a result, N_{av} increases significantly while N_{var} approaches $N_{var}^{(\mathrm{eq})}$ [2]. This implies that the chemical potential in the node (the charging energy) is no longer aligned with the average potential in the ER. This state of non-equilibrium functionalizes the DRAM as an AC-signal sensor.

As the behavior of the system can be described in the context of thermodynamic equilibrium and non-equilibrium steady states, we present a mathematical model of the system based on Hatano-Sasa's framework[3], allowing for a description of the heat exchanges in and out of the node. Within this framework, it is possible to quantify the housekeeping heat, or the energy dissipated to maintain the system in the non-equilibrium steady state induced by the AC modulation on the ER. Fig. 1(d) plots this housekeeping heat as a function of the modulation signal amplitude, with the experimental data evaluated from transient characteristics of the chemical potentials of the ER and node showing a good agreement with our proposed model. This yields that the experimental data is exactly the housekeeping heat defined by the theory, and that the AC signal is converted to the charging energy in the node with theoretically minimum energy. In conclusion, our study highlights the potential of nanoscale DRAM devices as sensors for high-frequency AC signals, and mathematical model allows us to quantify its energy dissipation, opening the way for further works towards the efficiency optimization of such detectors.

REFERENCES:

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