Thermodynamic Property of a CMOS Device beyond Landauer Limit

Daigo Yoshino and Yasuhiro Tokura

University of Tsukuba, 1-1-1 Tennodai, Tsukuba, 305-8571, Japan

Understanding the thermodynamic properties of computation is not only physically interesting but also holds significant practical implications. In 1961, Rolf Landauer from IBM introduced the Landauer principle, establishing a lower bound for the dissipation of energy required to reliably erasing one bit of information. The bound is expressed as $k_B T \ln 2$, where k_B is the Boltzmann constant, and T is the temperature of a thermal reservoir. This value is approximately 3.0×10^{-21} J at room temperature. Although extremely small, achieving this limit is feasible through the quasi-static erasure process of memory. However, practical implementation may result in increased energy dissipation. Beyond serving as mere memory systems, computers execute complex mathematical operations through logic circuits composed of numerous logic gates. Hence, discussing the thermodynamic properties of this system is interesting. Recent advancements in nonequilibrium statistical mechanics have unveiled instances of dissipation surpassing the Landauer bound in practical applications. In addition to memory systems, the thermodynamic analysis of more complex computers, such as logic circuits, Brownian computers, and models proposed in computer science, has become possible. However, existing studies are limited to ideal models and settings. For physically implemented computers, only a few studies have analyzed the relationship between computational processes and their thermodynamic properties. This study focuses on a specific logic gate and analyzes the thermodynamic properties in terms of the extended Landauer bound [1]. NAND gates, comprising CMOS transistors operating in sub-threshold regions, exhibit additional dissipation due to dynamic changes in the logical states encoded in the output voltage. These findings have been quantitatively revealed. The Landauer bound stems from logical irreversibility and the inability to accurately infer the input from the output state after computation. This reduces the number of logical states (M) to be realized before and after the computation, thus increasing the corresponding entropy (H), up to ln 2 in the case of a 1-bit complete information erasure. In this study, alongside the dissipation associated with this logical irreversibility, an additional dissipation, contingent on the initial system distribution, was identified through an investigation of the Kullback-Leibler divergence evaluated with Gillespie algorithm. While no difference was observed in the former dissipation under varying input voltage conditions, the latter exhibited greater dissipation under certain conditions. We interpret this factor as a consequence of logic state flipping.

This work was supported in part by a JSPS Grant-in-Aid for Scientific Research (B) (JP20H01827, JP24K00547).

[1] D. Yoshino and Y. Tokura, J. Phys. Soc. Jpn. 92, 124004 (2023), arXiv: 2308.15738.