

Thermodynamic Constraints in Dynamic Random-Access Memory Cells: Experimental Verification of Energy Efficiency Limits in Information Erasure

Takase Shimizu[✉], Kensaku Chida[✉], Gento Yamahata[✉], and Katsuhiko Nishiguchi
Basic Research Laboratories, NTT, Inc., 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan



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We measured the energy efficiency of information erasure using silicon DRAM cells capable of counting charges on capacitors at the single-electron level. Our measurements revealed that the efficiency decreased as the erasure error probability decreased, and notably, the Landauer limit was not achieved, even under effectively infinite-time bit erasure. By comparing the measured efficiency with the Landauer limit, we identified a thermodynamic constraint that prevents DRAM from reaching this limit: the inability to prepare the initial state in thermal equilibrium, which in turn, prohibits quasistatic operations. This finding has broad implications for DRAM cells and for many electronic circuits sharing similar structures. Furthermore, it validates our experimental approach to discovering thermodynamic constraints that impose tighter, practically relevant limits, opening a new direction in information thermodynamics research.

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Introduction—Information thermodynamics provides a framework for quantifying the energetic cost of information processing and clarifying its fundamental limits [1–6]. A cornerstone is the Landauer limit, which ties the minimum heat dissipated for erasure to the entropy change of a memory, achievable through quasistatic operations [1,2,7–10]. Recent research has moved beyond quasistatic operations to explore the efficiency limits of finite-time information processing [11–16].

While early studies focused on device-independent limits, there is growing interest in exploring tighter and practically relevant limits that incorporate specific constraints of concrete devices [17]. Thermodynamic descriptions applicable to electronic circuits have recently been developed [18–29], enabling discussions on the thermodynamic efficiency of practical devices such as SRAM and inverters. The resulting constraints are expected to guide the design of more efficient devices [30], yet many remain unexplored.

Experiments are essential for identifying unknown constraints, and the first step is to compare new experimental results with established limits, followed by considering the differences. Applying these methodologies to devices used in practical applications is crucial to finding the constraints relevant to real devices. However, previous experiments have mainly verified known theoretical limits, such as the

Landauer limit, using systems like colloidal particles, ion traps, and nanomagnetic bits [7–10], which are not representative of mainstream memory technologies. Consequently, the vast efficiency gap between practical devices and the Landauer limit [31] remains poorly understood.

Dynamic random access memory (DRAM) dominates modern memory systems [32], but its thermodynamic performance has not been quantified. A DRAM cell stores 1 bit in a transistor-capacitor pair [Fig. 1(a)]. Prior research has evaluated the power of an entire DRAM [33,34] or the

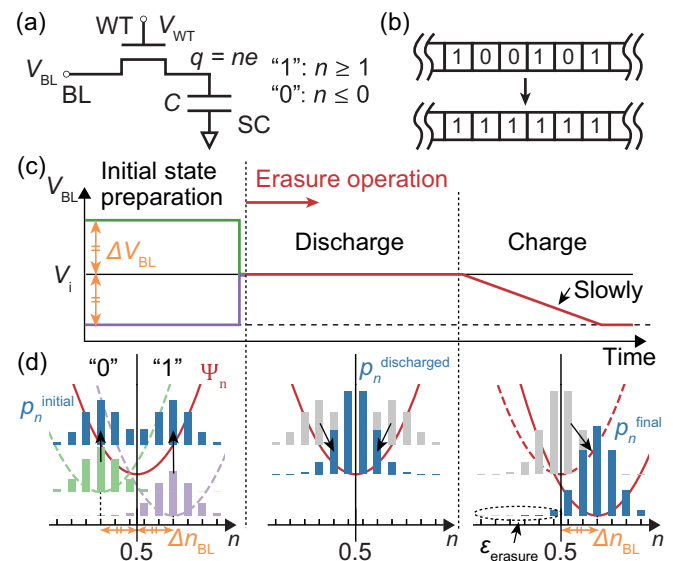


FIG. 1. Experimental scheme. (a) Circuit diagram of a DRAM cell. (b) Conceptual diagram for the erasure of a 1-bit memory. (c) Operational sequence of V_{BL} used in experiments. (d) Calculated p_n and Ψ_n during the erasure process, with parameters $E_c = 8.2$ meV, $T = 300$ K, and $\Delta n_{BL} = 2.5$.

*Contact author: takase.shimizu@ntt.com

heat dissipation of a DRAM cell during writing [35,36] or erasure [37,38] but has not measured the entropy change of the memory; therefore, the efficiency remains unexplored. The primary challenge lies in the technical difficulties of simultaneously measuring entropy change of the memory and heat dissipation.

Here, we measure the erasure efficiency of a silicon DRAM cell with single-electron charge sensitivity [39] under effectively infinite-time bit erasure. We find that efficiency degrades as the erasure error is reduced, and notably, the Landauer limit is not achieved. Our analysis shows that nonequilibrium initial states prevent quasistatic operation, imposing a device-specific constraint. Since the circuit structure of DRAM cells commonly appears in electronic circuits, such constraints provide general insight into the energy efficiency of electronic information-processing devices. In addition, our experimental methodology, which compares measured efficiencies with theoretical limits, provides a general approach to uncover practically relevant thermodynamic constraints and opens a new research direction in information thermodynamics.

Method—As in typical tests of Landauer’s principle [Fig. 1(b)], we assume a scenario where logical states “0” and “1” are written into a DRAM cell with equal probability (50% each), and we evaluate the energy efficiency

$$\eta = \frac{-k_B T \Delta S}{-Q} \quad (1)$$

by erasing the state to 1 and comparing the results with the Landauer limit of $\eta = 1$. Here, ΔS is the change in Shannon entropy of the logical states due to erasing, $-Q$ is the average total heat released from the system to the thermal bath for the erasure process, k_B is Boltzmann’s constant, and T is the temperature.

A DRAM cell consists of a bitline (BL), storage capacitor (SC), and wordline transistor (WT) [Fig. 1(a)]. A 1-bit logical state is determined by the charge $q = ne$ (e : electron charge) on the SC (capacitance: C), assigned as $[0:n \leq 0, 1:n \geq 1]$. Here, n represents the excess number of electrons on the capacitor and is an integer. The bitline voltage V_{BL} controls the charging and discharging of the SC, while the WT voltage V_{WT} regulates the electron hopping rate between the BL and SC.

We repeat the experimental cycle M times and obtain the probability distribution p_n of n at each time point. Specifically, the following steps constitute a single cycle: “initial state preparation $\rightarrow$ erasure operation.” Figure 1(c) shows the sequence of V_{BL} operations involved. For initial state preparation, half of the cycles follow the green trajectory and the other half the purple one. The erasure operation is shown in red. We measure ΔS and Q for the erasure operation and evaluate η .

Before detailing the experimental cycle, we define the “erasure-to-0” and “erasure-to-1” operations. Each consists

of three steps: “discharge $\rightarrow$ charge $\rightarrow$ quench.” During discharge, $V_{BL} = V_i$ is held until equilibrium. Here, $V_i = E_c/e$ denotes the BL voltage at which $\langle n \rangle$, the average value of n , takes the value 0.5 under equilibrium. $E_c = e^2/(2C)$ is the charging energy. For the erasure-to-1 operation, during the charge step, V_{BL} is swept slowly from V_i to $V_i - \Delta V_{BL}$ ($\Delta V_{BL} > 0$) and then held for equilibration. The quench step rapidly returns V_{BL} to V_i , so that the system is effectively erased [14]. The erasure-to-0 operation is defined similarly, except that V_{BL} is swept to $\Delta V_{BL} + V_i$ in the charge step.

First, we prepare the initial state in which 0 and 1 are equally occupied. Assuming repeated memory use, the initial ensemble is formed from the outcomes of both erasure-to-0 and erasure-to-1 operations (see also the Supplemental Material (SM) [40]). Practically, this is achieved by applying $V_{BL} = \pm \Delta V_{BL} + V_i$ and waiting for equilibration, which corresponds to preparing the postcharge condition, and then, quenching V_{BL} to V_i . The resulting V_{BL} trajectories are shown as the purple and green curves in Fig. 1(c). In each branch, we attempt to write 0 and 1 $M/2$ times each. Because of thermal fluctuations, some trials are miswritten, with error probability ϵ_{init} . If the error probabilities for the two operations are equal, the probabilities of obtaining 0 and 1 are $1 - \epsilon_{\text{init}}$ and ϵ_{init} for erasure-to-0 and the opposite for erasure-to-1. Averaging the two branches yields equal occupation of 0 and 1 regardless of ϵ_{init} .

Next, we perform the erasure-to-1 operation. In practice, only the discharge and charge steps are executed, as the quench step neither changes p_n nor generates heat. The corresponding V_{BL} evolution is shown as the red curve in Fig. 1(c). This protocol is state independent. We denote the erasure error probability by $\epsilon_{\text{erasure}}$, which is expected to satisfy $\epsilon_{\text{erasure}} = \epsilon_{\text{init}}$.

We indirectly measure the heat associated with electron hoppings between the BL and SC based on the theory proposed by Freitas *et al.* [20]. In the equivalent circuit of a DRAM cell, the state function $\Psi_n(n_{BL})$ of the system is expressed as [40]

$$\Psi_n(n_{BL}) = \frac{q^2}{2C} - V_{BL}q = E_c(n - n_{BL})^2 - E_c n_{BL}^2, \quad (2)$$

assuming that the junction capacitance of WT is negligibly small compared to C . Here, $n_{BL} = eV_{BL}/(2E_c)$ is the normalized BL voltage. The stochastic heat associated with electron hoppings ($n = N \rightarrow N \pm 1$) is given by the change in the state function:

$$\delta Q_{N \rightarrow N \pm 1}(n_{BL}) = \Psi_N(n_{BL}) - \Psi_{N \pm 1}(n_{BL}). \quad (3)$$

By substituting Eq. (2) into Eq. (3), we obtain

$$\delta Q_{N \rightarrow N+1} = eV_{BL} - \mu_{N+1}, \delta Q_{N \rightarrow N-1} = \mu_N - eV_{BL}, \quad (4)$$

where $\mu_N = E_c N^2 - E_c(N-1)^2 = 2E_c(N-1/2)$ is the chemical potential of the capacitor, which corresponds to the energy change of the capacitor when n increases from $N-1$ to N . Therefore, Eq. (4) represents the difference between the BL potential and the chemical potential at the moment of electron hopping—namely, the heat absorbed (or dissipated) by the electron from the heat bath during the hopping process. Thus, by measuring n and E_c , the heat associated with electron hoppings can be indirectly measured.

Theory—We calculate ΔS and Q for the erasure process and later compare the calculation results with experimental results. Considering only thermal fluctuations, the probability distribution of n at equilibrium is given by

$$p_n^{\text{eq}}(n_{\text{BL}}) = \frac{\exp[-\Psi_n(n_{\text{BL}})/(k_B T)]}{\sum_n \exp[-\Psi_n(n_{\text{BL}})/(k_B T)]} \quad (5)$$

$$= \frac{\exp[-E_c(n - n_{\text{BL}})^2/(k_B T)]}{\sum_n \exp[-E_c(n - n_{\text{BL}})^2/(k_B T)]}. \quad (6)$$

This is a discrete distribution following the Gaussian shape centered around n_{BL} . Using $p_n^{\text{eq}}(n_{\text{BL}})$, the probability distributions immediately after quenching (initial state), after discharging, and after charging (final state) are, respectively,

$$p_n^{\text{initial}}(\Delta n_{\text{BL}}) = [p_n^{\text{eq}}(-\Delta n_{\text{BL}} + n_i) + p_n^{\text{eq}}(\Delta n_{\text{BL}} + n_i)]/2, \quad (7)$$

$$p_n^{\text{discharged}} = p_n^{\text{eq}}(n_i), \quad (8)$$

$$p_n^{\text{final}}(\Delta n_{\text{BL}}) = p_n^{\text{eq}}(\Delta n_{\text{BL}} + n_i), \quad (9)$$

as plotted in Fig. 1(d), where $\Delta n_{\text{BL}} = e\Delta V_{\text{BL}}/(2E_c)$. Thus, the initial distribution p_n^{initial} is a nonequilibrium state composed of two overlapping Gaussian shape distributions centered around $n = \pm\Delta n_{\text{BL}} + n_i$, with $n_i = eV_i/(2E_c) = 0.5$. As discussed later, this initial state precludes quasistatic operation in DRAM cells. Now, the entropy change is calculated as $\Delta S = S(p_n^{\text{final}}) - S(p_n^{\text{initial}})$, where S is the Shannon entropy of the logical states.

Let the average heat for the discharge and charge processes be $Q_{\text{discharge}}$ and Q_{charge} , respectively. The average total heat Q is given by $Q = Q_{\text{discharge}} + Q_{\text{charge}}$, with each component calculated as

$$Q_{\text{discharge}}(\Delta n_{\text{BL}}) = \sum_n [p_n^{\text{discharged}} - p_n^{\text{initial}}] \Psi_n(n_i), \quad (10)$$

$$Q_{\text{charge}}(\Delta n_{\text{BL}}) = k_B T [s(p^{\text{final}}) - s(p^{\text{discharged}})], \quad (11)$$

where $s(p) \equiv -\sum_n p_n \ln p_n$ is the Shannon entropy with respect to n . In Eq. (10), since the discharge process occurs

at fixed $n_{\text{BL}} = n_i$, the heat is calculated from the state function differences weighted by probability changes. As for Eq. (11), the charging process is assumed to be quasistatic, resulting in heat that equals the change in entropy.

Setup and measurement of E_c and T —To accurately measure Q and ΔS , we used a silicon DRAM cell device capable of measuring the time evolution of n from the current I_d of a sensor transistor adjacent to the SC, as shown in Fig. 2(a) [39]. We focus on the DRAM cell in Fig. 1(a) and do not consider the readout cost of the sensor [40,41]. All measurements were conducted with the sample fixed on a stage thermally controlled at 300 K. Throughout the experiment, V_{WT} was kept constant at a value that ensured the hopping rate was sufficiently slow to allow individual electron hopping events to be measured. We modeled the system using the equivalent DRAM circuit in Fig. 1(a) and evaluated Q using Eq. (3). In practice, the SC is also capacitively coupled to the WT, upper gate, back gate, and sensor transistor, but these voltages were held constant and result in an offset in V_{BL} only, leaving our circuit assumption valid [40].

First, we conducted experiments to determine E_c and T . Figure 2(b) shows an example of the time evolution of I_d under equilibrium conditions. The discrete changes in I_d correspond to changes in n . Figure 2(c) presents p_n at $n_{\text{BL}} = 0$, which is well fitted by a Gaussian function. Figure 2(d) shows the mean value of n (n_{mean}) obtained

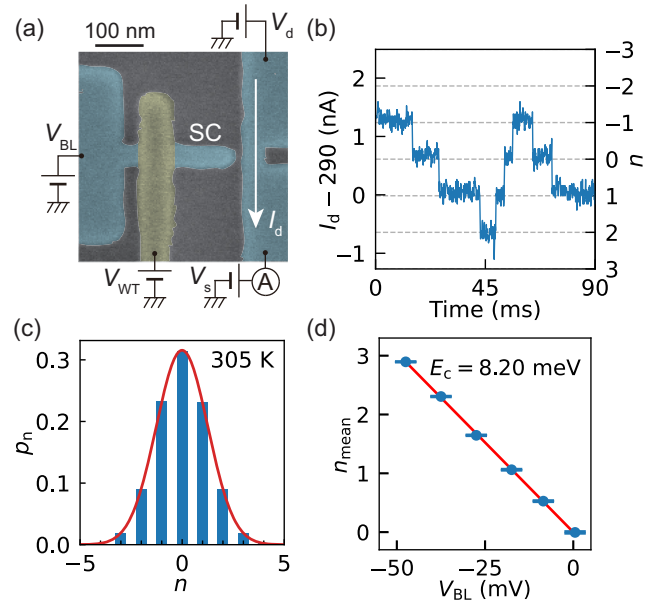


FIG. 2. Experimental setup and characterization. (a) Scanning electron micrograph of a device with measurement setup. (b) The sensor transistor current (I_d) under equilibrium conditions. (c) p_n at $n_{\text{BL}} = 0$, with a Gaussian fit (red line). (d) The mean value of n (n_{mean}) obtained from Gaussian fit of the distribution of n at various V_{BL} . The error bars for n_{mean} indicate the standard error of the mean.

from Gaussian fit of p_n at various V_{BL} . According to Eq. (6), n_{mean} equals n_{BL} at equilibrium. Thus, the E_c necessary to determine Ψ_n can be extracted from the slope dn_{mean}/dV_{BL} :

$$E_c = \frac{e}{2} \left(\frac{dn_{\text{mean}}}{dV_{BL}} \right)^{-1} = 8.20 \pm 0.08 \text{ meV}. \quad (12)$$

The reference point $V_{BL} = 0$ was chosen such that $n_{\text{mean}} = 0$. The temperature derived from the variance of the Gaussian fit in Fig. 2(c) was calculated to be $T = 305 \pm 5$ K, only 1.7% higher than the stage temperature of 300 K. This consistency confirms the assumed equilibrium state, indicates that external noise and sensor-current-induced Joule heating [42] are negligible, and supports the validity of the measurement. The assumption that the junction capacitance is negligible compared with C is also verified [40]. For subsequent analysis, we used $T = 305$ K.

Time evolution during erasure—We repeated the erasure cycle $M = 1998$ times, and here, we demonstrate the system behavior during the erasure process with $\Delta n_{BL} = 3.7$. Figure 3(a) shows p_n before erasure (dark blue), where 0 and 1 are nearly equally occupied, confirming the initial state preparation in Fig. 1(d). Figure 3(b) (top) presents the time evolution of p_n during discharge. The green dashed and purple solid lines represent $\langle n \rangle$ after quenches from $V_{BL} = V_i \pm \Delta V_{BL}$. n_{mean} is not shown here because the distribution is not necessarily a Gaussian shape. Both trajectories relax toward $\langle n \rangle = 0.5$, with the faster purple relaxation reflecting the asymmetry of the hopping rates with respect to n [43]. The bottom panel shows ensemble-averaged cumulative heat dissipation $-Q_{\text{cum}}$ during discharge, obtained from Eq. (4). Although the initial rise differs due to energy-dependent discharge speed, the final values converge, indicating that total heat generated during discharge is independent of discharge speed, consistent with Eq. (10). In Fig. 3(c) (top), the gray plot shows p_n during charging, with $\langle n \rangle$ (blue) closely following n_{BL} (red), indicating thermal equilibrium and a quasistatic process. The bottom panel shows that $-Q_{\text{cum}}$ during charging is minimal, owing to the small change in the distribution and, thus, in the entropy of the system. The final-state histogram in Fig. 3(a) (light blue) confirms that the erasure operation has been performed.

Erasure results—Figure 4(a) shows that $-\Delta S$ increases monotonically with Δn_{BL} and approaches $\ln 2$, reflecting that S of the initial state is always $\ln 2$, while S of the final state decreases and approaches zero once Δn_{BL} exceeds the thermal fluctuations of n . Figure 4(b) shows that $-Q$ also increases with Δn_{BL} , and Fig. 4(c) indicates that $-Q$ diverges as $-\Delta S \rightarrow \ln 2$. The Landauer limit $Q/k_B T = \Delta S$ (blue line) lies below all measured values, demonstrating that the heat dissipation always exceeds the Landauer limit. Figure 4(d) shows η , which remains below unity for all

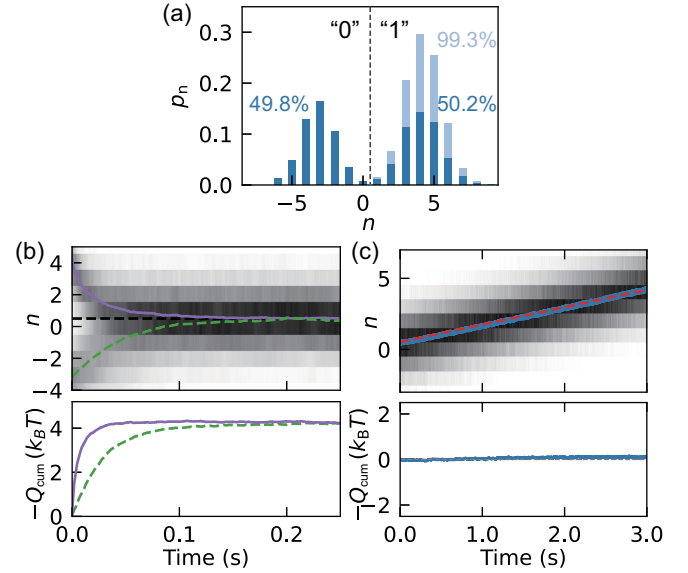


FIG. 3. Erasure process at $\Delta n_{BL} = 3.7$. (a) p_n before (dark blue) and after (light blue) erasure, with logical-state occupations. (b) Top: $\langle n \rangle$ during discharge. The green dashed and purple solid lines represent cases starting immediately after the initial state preparation with the quench from $V_{BL} = V_i \mp \Delta V_{BL}$, respectively. The grayscale background indicates p_n . Bottom: Ensemble-averaged cumulative heat dissipation $-Q_{\text{cum}}$ during discharge. (c) Top: p_n during charging, with $\langle n \rangle$ (blue) and n_{BL} (red). Bottom: $-Q_{\text{cum}}$ during charging.

$\epsilon_{\text{erasure}}$ and decreases as $\epsilon_{\text{erasure}}$ decreases. The solid curves in Figs. 4(a)–4(d) show theoretical predictions that agree well with the experiment, confirming the validity of the model in Fig. 1(d). Overall, the results show that this DRAM cell cannot reach the Landauer limit.

Discussion—The DRAM cell did not reach the Landauer limit because its initial state was nonequilibrium. Systems that can achieve the Landauer limit, like double-well potentials or two-level systems, start in equilibrium, and thus, allow quasistatic operation. In contrast, the DRAM's nonequilibrium initial state makes the discharge process nonquasistatic, leading to substantial heat dissipation [Fig. 3(b)].

Regardless of microscopic details, the DRAM circuit in Fig. 1(a) cannot perform quasistatic 1-bit erasure. No choice of the controllable parameters V_{BL} and V_{WT} yields a state function whose equilibrium distribution matches p_{init} . Such a distribution would require a double-well state function with minima at $0.5 \pm \Delta n_{BL}$. However, Eq. (2) shows that changing V_{BL} shifts only a single-well parabola, and V_{WT} affects only hopping rates, not the state function. Thus, DRAM cells cannot prepare their initial state in equilibrium, preventing the quasistatic operations required to reach the Landauer limit. This thermodynamic constraint highlights a fundamental difference from two-level or double-well potential systems [40], offering a thermodynamic interpretation of volatile memory.

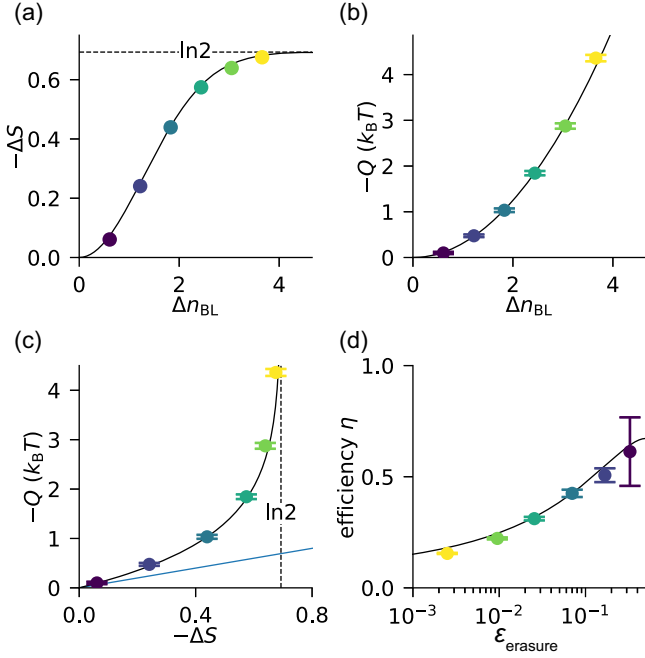


FIG. 4. Erasure experiment results. Time evolution data are in the SM [40]. (a) $-\Delta S$ versus Δn_{BL} . (b) $-Q$ versus Δn_{BL} . (c) $-Q$ versus $-\Delta S$. Blue line: the Landauer limit ($Q/k_B T = \Delta S$). (d) Efficiency η versus erasure error probability ϵ_{erase} . Black solid lines: theoretical calculations. Error bars: standard error of the mean for Q .

Finite-time operations during the evolution of the probability distribution are often regarded as a primary reason for failing to reach the Landauer limit. However, here we show that the Landauer limit is not reached even under effectively infinite-time operations of the discharge and charge processes governing this evolution. Note that the final quench erases only the writing history, marking the completion of the operation. Since the probability distribution is unchanged, it does not contribute to heat dissipation during the erasure itself.

However, the quench can cause heat dissipation in the subsequent erasure cycle. When restricted to the DRAM cell, attributing the extra heat above the Landauer limit to the initial nonequilibrium distribution is effectively equivalent to attributing it to the preceding quench, which generates that nonequilibrium state. Heat generation associated with such quenches has been qualitatively discussed in Refs. [35–38]. By contrast, in a two-level system, equilibrium can still be established after the quench [40]. Thus, from a thermodynamically universal perspective beyond the DRAM cell, the quench is only a possible contributing factor, whereas the initial nonequilibrium distribution is sufficient to prevent reaching the Landauer limit.

The initial nonequilibrium distribution arises not from a single operation but from the ensemble of outcomes of both “erase-to-0” and “erase-to-1” operations during information processing—a characteristic feature of information

thermodynamics. Its origin likely lies in the system being a multilevel system (three or more states) with a single potential well; however, a detailed investigation of this aspect is left for future studies.

Conclusion and outlook—We measured the energy efficiency of information erasure in DRAM cells and found that they do not reach the Landauer limit even under effectively infinite-time bit erasure. The key constraint is that the initial state cannot be prepared in thermal equilibrium, a distinctive property of DRAM cell. As most information-processing circuits are built from transistors and capacitors, and DRAM cell represents a minimal such unit, this constraint likely applies broadly across modern electronics.

This study suggests several directions for future research. First, exploring the dependence of erasure efficiency on E_c and $k_B T$ is intriguing, particularly in regimes $E_c/(k_B T) \gg 1$, where the system may approach two-level behavior. Second, the efficiency of finite-time operations [11–16] and multibit DRAM cell architectures [44] should be investigated. Third, studying the reliability of the read-out process, where sense amplifiers in actual DRAM extract free energy from nonequilibrium states to determine stored bits, is intriguing, especially for studying Maxwell’s demonlike, more efficient memory operation. Fourth, this methodology can be applied to other electronic circuits, such as SRAM cells [20], by integrating the sensor transistor adjacent to the free conductors. Finally, this work motivates a new classification framework for information-processing devices based on the thermodynamic constraints that determine their fundamental efficiency limits.

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Data availability—The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

- [1] R. Landauer, Irreversibility and heat generation in the computing process, *IBM J. Res. Dev.* **5**, 183 (1961).
- [2] C. H. Bennett, The thermodynamics of computation—a review, *Int. J. Theor. Phys.* **21**, 905 (1982).
- [3] U. Seifert, Stochastic thermodynamics, fluctuation theorems and molecular machines, *Rep. Prog. Phys.* **75**, 126001 (2012).
- [4] J. M. R. Parrondo, J. M. Horowitz, and T. Sagawa, Thermodynamics of information, *Nat. Phys.* **11**, 131 (2015).
- [5] T. Sagawa, Thermodynamics of information processing in small systems, *Prog. Theor. Phys.* **127**, 1 (2012).
- [6] D. H. Wolpert, The stochastic thermodynamics of computation, *J. Phys. A* **52**, 193001 (2019).

- [7] A. Bérut, A. Arakelyan, A. Petrosyan, S. Ciliberto, R. Dillenschneider, and E. Lutz, Experimental verification of Landauer's principle linking information and thermodynamics, *Nature (London)* **483**, 187 (2012).
- [8] Y. Jun, M. c. v. Gavrilo, and J. Bechhoefer, High-precision test of Landauer's principle in a feedback trap, *Phys. Rev. Lett.* **113**, 190601 (2014).
- [9] J. Hong, B. Lambson, S. Dhuey, and J. Bokor, Experimental test of Landauer's principle in single-bit operations on nanomagnetic memory bits, *Sci. Adv.* **2**, e1501492 (2016).
- [10] L. L. Yan, T. P. Xiong, K. Rehan, F. Zhou, D. F. Liang, L. Chen, J. Q. Zhang, W. L. Yang, Z. H. Ma, and M. Feng, Single-atom demonstration of the quantum Landauer principle, *Phys. Rev. Lett.* **120**, 210601 (2018).
- [11] K. Proesmans, J. Ehrich, and J. Bechhoefer, Finite-time Landauer principle, *Phys. Rev. Lett.* **125**, 100602 (2020).
- [12] J. S. Lee, S. Lee, H. Kwon, and H. Park, Speed limit for a highly irreversible process and tight finite-time Landauer's bound, *Phys. Rev. Lett.* **129**, 120603 (2022).
- [13] T. Van Vu and K. Saito, Thermodynamic unification of optimal transport: Thermodynamic uncertainty relation, minimum dissipation, and thermodynamic speed limits, *Phys. Rev. X* **13**, 011013 (2023).
- [14] M. Scandi, D. Barker, S. Lehmann, K. A. Dick, V. F. Maisi, and M. Perarnau-Llobet, Minimally dissipative information erasure in a quantum dot via thermodynamic length, *Phys. Rev. Lett.* **129**, 270601 (2022).
- [15] Y.-Z. Zhen, D. Egloff, K. Modi, and O. Dahlsten, Universal bound on energy cost of bit reset in finite time, *Phys. Rev. Lett.* **127**, 190602 (2021).
- [16] S. Oikawa, Y. Nakayama, S. Ito, T. Sagawa, and S. Toyabe, Experimentally achieving minimal dissipation via thermodynamically optimal transport, *Nat. Commun.* **16**, 10424 (2025).
- [17] A. Kolchinsky and D. H. Wolpert, Work, entropy production, and thermodynamics of information under protocol constraints, *Phys. Rev. X* **11**, 041024 (2021).
- [18] J. P. Pekola and O.-P. Saira, Work, free energy and dissipation in voltage driven single-electron transitions, *J. Low Temp. Phys.* **169**, 70 (2012).
- [19] N. Freitas, J.-C. Delvenne, and M. Esposito, Stochastic and quantum thermodynamics of driven RLC networks, *Phys. Rev. X* **10**, 031005 (2020).
- [20] N. Freitas, J.-C. Delvenne, and M. Esposito, Stochastic thermodynamics of nonlinear electronic circuits: A realistic framework for computing around kT , *Phys. Rev. X* **11**, 031064 (2021).
- [21] N. Freitas and M. Esposito, Information flows in macroscopic Maxwell's demons, *Phys. Rev. E* **107**, 014136 (2023).
- [22] N. Freitas, K. Proesmans, and M. Esposito, Reliability and entropy production in nonequilibrium electronic memories, *Phys. Rev. E* **105**, 034107 (2022).
- [23] N. Freitas and M. Esposito, Maxwell demon that can work at macroscopic scales, *Phys. Rev. Lett.* **129**, 120602 (2022).
- [24] A. Gopal, M. Esposito, and N. Freitas, Thermodynamic cost of precise timekeeping in an electronic underdamped clock, *Phys. Rev. B* **109**, 085421 (2024).
- [25] A. Gopal, M. Esposito, and N. Freitas, Large deviations theory for noisy nonlinear electronics: CMOS inverter as a case study, *Phys. Rev. B* **106**, 155303 (2022).
- [26] J. N. Freitas and M. Esposito, Emergent second law for non-equilibrium steady states, *Nat. Commun.* **13**, 5084 (2022).
- [27] A. Yadav, M. Yousef, and D. Wolpert, Minimal thermodynamic cost of computing with circuits, [arXiv:2504.04031](https://arxiv.org/abs/2504.04031).
- [28] D. H. Wolpert and A. Kolchinsky, Thermodynamics of computing with circuits, *New J. Phys.* **22**, 063047 (2020).
- [29] D. Yoshino and Y. Tokura, Thermodynamics of computation for CMOS NAND gate, *J. Phys. Soc. Jpn.* **92**, 124004 (2023).
- [30] D. H. Wolpert, J. Korbel, C. W. Lynn, F. Tasnim, J. A. Grochow, G. Kardeş, J. B. Aimone, V. Balasubramanian, E. D. Giuli, D. Doty, N. Freitas, M. Marsili, T. E. Ouldrige, A. W. Richa, P. Riechers, Édgar Roldán, B. Rubenstein, Z. Toroczkai, and J. Paradiso, Is stochastic thermodynamics the key to understanding the energy costs of computation?, *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2321112121 (2024).
- [31] V. Zhirmov, R. Cavin, and L. Gammaitoni, Minimum energy of computing, fundamental considerations, in *ICT—Energy—Concepts Towards Zero*, edited by G. Fagas, L. Gammaitoni, D. Paul, and G. A. Berini (IntechOpen, Rijeka, 2014), Chap. 7, [10.5772/57346](https://doi.org/10.5772/57346).
- [32] A. Spessot and H. Oh, 1T-1C dynamic random access memory status, challenges, and prospects, *IEEE Trans. Electron Devices* **67**, 1382 (2020).
- [33] T. Vogelsang, Understanding the energy consumption of dynamic random access memories, in *Proceedings of the 2010 43rd Annual IEEE/ACM International Symposium on Microarchitecture* (2010), pp. 363–374, [10.1109/MICRO.2010.42](https://doi.org/10.1109/MICRO.2010.42).
- [34] S. Ghose, A. G. Yaglikçi, R. Gupta, D. Lee, K. Kudrolli, W. X. Liu, H. Hassan, K. K. Chang, N. Chatterjee, A. Agrawal, M. O'Connor, and O. Mutlu, What your DRAM power models are not telling you: Lessons from a detailed experimental study, *Proc. ACM Meas. Anal. Comput. Syst.* **2**, 1 (2018).
- [35] L. Van Brandt and J.-C. Delvenne, The non-Landauer bound for the dissipation of bit writing operation, in *Proceedings of the 2023 IEEE 23rd International Conference on Nanotechnology (NANO)* (2023), pp. 726–731.
- [36] L. Van Brandt and J.-C. Delvenne, Noise–dissipation relation for nonlinear electronic circuits, *Appl. Phys. Lett.* **122**, 263507 (2023).
- [37] A. O. Orlov, C. S. Lent, C. C. Thorpe, G. P. Boechler, and G. L. Snider, Experimental test of Landauer's principle at the sub-kBT level, *Jpn. J. Appl. Phys.* **51**, 06FE10 (2012).
- [38] C. Lent, A. Orlov, W. Porod, and G. Snider, *Energy Limits in Computation: A Review of Landauer's Principle, Theory and Experiments* (Springer International Publishing, Cham, 2018), [10.1007/978-3-319-93458-7](https://doi.org/10.1007/978-3-319-93458-7).
- [39] K. Nishiguchi, C. Koechlin, Y. Ono, A. Fujiwara, H. Inokawa, and H. Yamaguchi, Single-electron-resolution electrometer based on field-effect transistor, *Jpn. J. Appl. Phys.* **47**, 8305 (2008).
- [40] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/1sgm-dhys> for details on the device structure and fabrication process; details of the measurement method; the derivation of the state function $\Psi(q)$; time evolution of S , ΔS , and Q_{cum} during the erasure process;

- comparison between the DRAM cells and two-level systems; and a discussion on the readout cost of the charge sensor.
- [41] V. Wadhia, F. Meier, F. Fedele, R. Silva, N. Nurgalieva, D. L. Craig, D. Jirovec, J. Saez-Mollejo, A. Ballabio, D. Chrastina, G. Isella, M. Huber, M. T. Mitchison, P. Erker, and N. Ares, Entropic costs of extracting classical ticks from a quantum clock, *Phys. Rev. Lett.* **135**, 200407 (2025).
- [42] K. Chida, A. Fujiwara, and K. Nishiguchi, Seebeck effect in a nanometer-scale dot in a Si nanowire observed with electron counting statistics, *Appl. Phys. Lett.* **121**, 183501 (2022).
- [43] K. Nishiguchi, Y. Ono, and A. Fujiwara, Single-electron thermal noise, *Nanotechnology* **25**, 275201 (2014).
- [44] K. Nishiguchi, A. Fujiwara, Y. Ono, H. Inokawa, and Y. Takahashi, Room-temperature-operating data processing circuit based on single-electron transfer and detection with metal-oxide-semiconductor field-effect transistor technology, *Appl. Phys. Lett.* **88**, 183101 (2006).