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Quantum Landauer Erasure using magnetic tunneling junctions

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Abstract

Landauer's principle defines the fundamental thermodynamic limit of computation: any logically irreversible operation, such as erasing one bit of information, must dissipate at least kT ln 2 of heat. Despite its foundational role, a direct realization of the Landauer limit in a practical nanodevice has remained elusive. Here we experimentally validate quantum-consistent Landauer erasure using spin-transfer-torque magnetic tunnel junctions (STT-MTJs), the key building block of nonvolatile spintronic memory. By combining quantum–classical micromagnetic simulations with magneto-optical Kerr effect (MOKE) and tunneling magnetoresistance (TMR) measurements, we demonstrate that the dissipated energy during a quasi-adiabatic bit-reset operation converges to (4.1 ± 2.0) zJ ≈ kT ln 2. This work unites the thermodynamic and quantum pictures of information processing, providing an experimentally accessible route toward energy-reversible computation.

Keywords: Landauer limit · quantum thermodynamics · spintronics · magnetic tunnel junction · information erasure

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Introduction

Rolf Landauer's 1961 assertion that "information is physical" established the bridge between computation and thermodynamics[1,2]. A logical bit—capable of being in states 0 or 1—represents entropy S = kln2. Resetting the bit to a single state decreases entropy and therefore requires a compensating dissipation of Q ≥ kTln2 to the environment. This connection defines the Landauer limit, the smallest possible energy cost per bit operation[3].

Landauer's principle has been verified in model systems such as colloidal particles in laser traps[4], yet these demonstrations do not represent real digital devices. In practical electronics, bits are encoded in charge or spin, governed by stochastic dynamics and quantum fluctuations[5]. To realize the Landauer bound in such a platform, a bistable nanosystem with controllable potential and measurable magnetization is required.

Nanomagnets were used as prototypical bistable elements by both Bennett and Landauer with focus on their consideration near fundamental efficiency limits[6]. Magnetic hard-disk storage has become ubiquitous and continues to advance[7,8]. DW motion magnetic memory[9], nanomagnetic logic (NML) devices[10] , along with other types of spintronic devices[11] show great promise due to their low energy consumption capacity coupled with non-volatility radiation-hardness characteristics. It is therefore imperative that further studies focused on reducing future electronic fields' energies are carried out utilizing nanomagnets considering its significance regarding Landauer's principle[12] .

Magnetic tunnel junctions (MTJs) satisfy these conditions naturally. Each MTJ comprises a free magnetic layer, a tunnel barrier, and a reference layer[13]. The magnetization orientation of the free layer (parallel P or antiparallel AP to the reference) encodes binary states, while the tunnel magnetoresistance (TMR) signal provides a direct electrical readout. By controlling magnetic fields or spin-transfer torque, one can realize the reset-to-one erasure operation proposed by Bennett and Landauer.

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In this work, we construct a quantum thermodynamic framework for erasure in MTJs and experimentally confirm the Landauer limit in nanoscale memory cells. Our study extends information thermodynamics to mesoscopic spin systems and demonstrates that the energy–entropy correspondence remains valid down to the scale of 10^4 spins.

Results and Discussion

Theoretical Framework of Quantum Landauer Erasure

For a two-state system representing one bit, the initial state distribution

$$\rho = p0|0\rangle\langle 0| + p1|1\rangle\langle 1| \tag{1}$$

has von Neumann entropy $S = -k^B \,\mathrm{Tr}(\rho \ln \rho)$. Erasure corresponds to resetting this ensemble to the pure state $|1\rangle$, decreasing the system entropy by $\Delta S = k^B \ln 2$*.[14-21] The minimum required heat release is therefore

$$\mathrm{Qmin} = T\Delta S = \mathrm{kBTln2} \tag{2}$$

At T = 300 K, this corresponds to 2.8 × 10^-21 J = 2.8 zJ per bit.

In the MTJ, the free layer acts as a double-well potential, with magnetization pointing “up” or “down” along the easy axis y.[22,23] The total magnetic energy can be expressed as

$$E = -\mu 0 M \cdot H + K_a \sin 2\theta \tag{3}$$

where K_a is the uniaxial anisotropy and θ the angle between magnetization M and y. [24,25]A hard-axis field H_x lowers the barrier between wells, while an easy-axis field H_y biases the system toward the desired state.

During the Landauer reset, the work done by the external field equals the area enclosed by the magnetization–field hysteresis loop. The dissipated energy is obtained by subtracting the hard-axis contribution from the easy-axis loop:

$$W(\mathrm{diss}) = \oint \mathrm{MydHy} - \oint \mathrm{MxdHx} \tag{4}$$

In the adiabatic limit, $W_{(\mathrm{diss})} = Q \approx k^B T \ln 2$, thus linking magnetization dynamics directly to thermodynamic cost.

Quantum mechanically, the ensemble of 10^4–10^5 coupled spins behaves as a single effective

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macrospin with quantized energy levels. Erasure transitions correspond to stochastic hopping between these levels, governed by Boltzmann-weighted probabilities.[26-30] Quantum tunneling through the barrier slightly modifies the dissipation landscape but never violates the Landauer bound.

Device Architecture and Magnetic Characterization

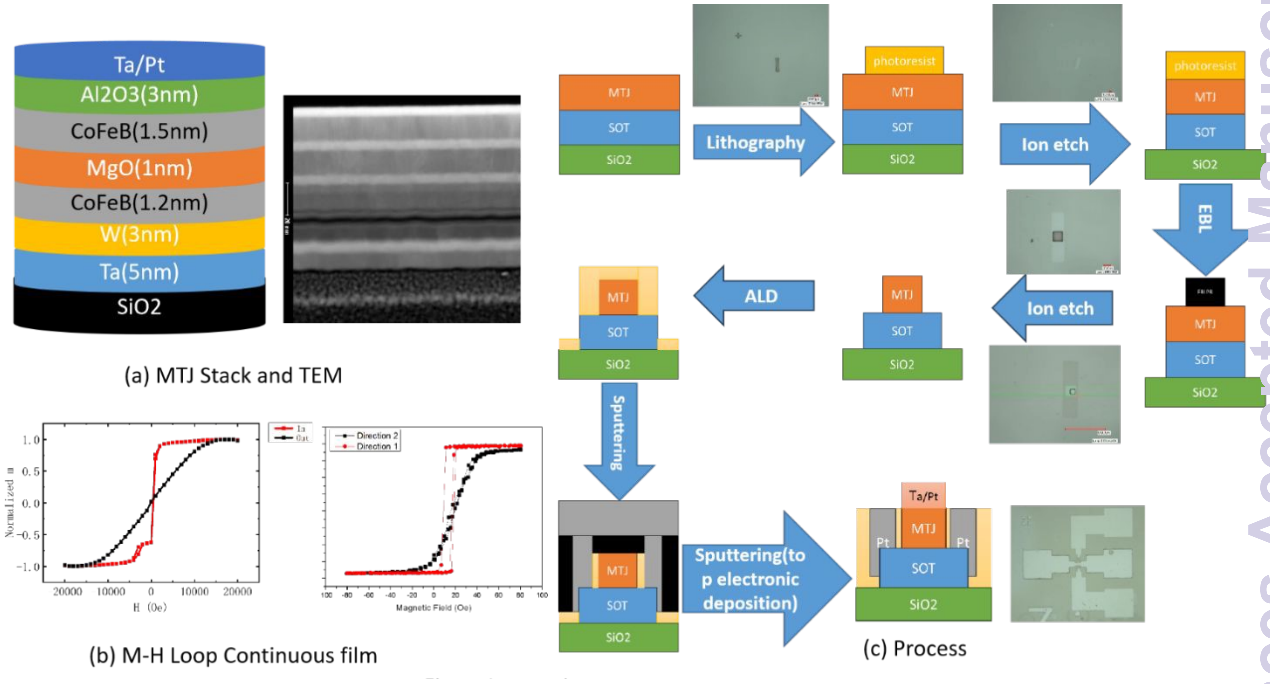


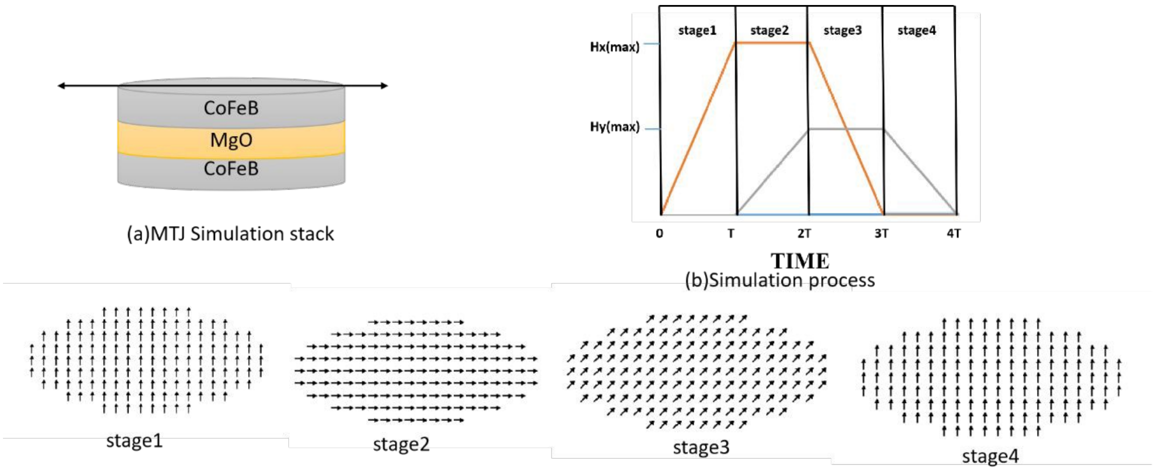
Figure 1|the process of making MTJ device (a)MTJ stack and TEM result, (b)M-H Loop Continuous film (c) Fabrication process

The fabricated MTJ stack consists of Ta(5 nm)/W(3 nm)/CoFeB(1.2 nm)/MgO(1 nm)/CoFeB(1.5 nm)/AlO(3 nm)/Ta/Pt on thermally oxidized Si. Figure 1a shows the schematic and cross-sectional TEM confirming sharp, coherent MgO interfaces crucial for spin-polarized tunneling. The continuous-film M–H loops (Figure 1b) display well-defined easy and hard axes with squareness > 0.95, indicating a single-domain regime suitable for energy calibration.

Fabrication followed standard photolithography and Ar-ion etching (Figure 1c). Arrays of ~10^5 MTJs were patterned to improve signal-to-noise ratio during MOKE measurements. The saturation magnetization $M_s = 1.1 \times 10^6$ (A m^{-1}) and anisotropy fields $H_k \approx 80$ mT define the bistable potential.[31,32]

Quantum–Classical Simulation of the Landauer Cycle

We implemented Landau–Lifshitz–Gilbert (LLG) simulations including thermal noise and spin-transfer torque.[33-38] The process proceeds through four quasi-static stages (Figure 2):



(a)MTJ Simulation stack

(b)Simulation process

Figure 2|the process of simulation (a) simulation stack, (b) simulation process, (c)the domain direction at each step

Initialization: Randomized magnetization ensemble representing logical uncertainty (50% |0⟩, 50% |1⟩). Barrier Suppression: Application of hard-axis field $H_x \approx$ H□ reduces anisotropy barrier ΔE. Reset Bias: Gradual introduction of easy-axis field H_y → $+H_0$ drives magnetization toward |1⟩. Relaxation: Removal of fields allows stabilization in single-state potential. At slow sweep rates (< 10 mT s^{-1}), the simulated hysteresis loops nearly collapse to reversible curves. The integrated area gives ΔE ≈ 2.8–3.0 zJ per bit, approaching $k^BT \ln 2$. The results remain stable under inclusion of quantum noise terms in the stochastic LLG formalism, validating the quantum–thermodynamic equivalence.

Simulation Results and Thermodynamic Analysis

We used the OOMMF for micromagnetic simulation and calculated the TMR signal from the simulated magnetization orientation using a standard resistance relation implemented in MATLAB.

Figure 3a,b show representative M–H and H–TMR loops for the hard and easy axes. The TMR ratio reaches > 150%. The total energy dissipation per cycle was calculated as the area difference between the two loops (Figure 3c). Under adiabatic operation, the simulated ΔE

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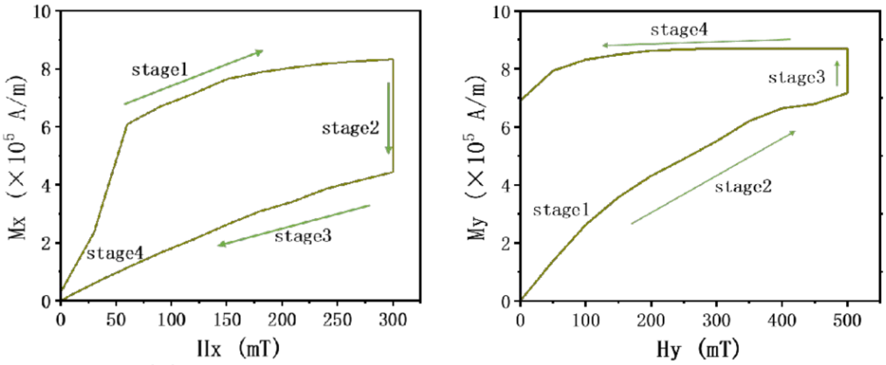
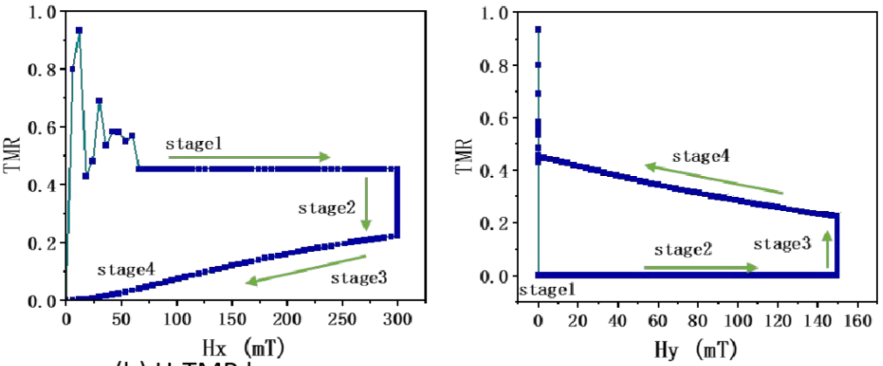
→ kT ln 2.

At lower temperatures, quantized jumps in magnetization correspond to discrete spin-cluster transitions, a clear signature of quantum effects. The dissipation remains bounded by the Landauer limit, demonstrating that even in the quantum regime the second law holds when averaged over stochastic trajectories.[38-40]



(a) m-H loop



(b) H-TMR loop

Figure 3|the result of simulation(a) M-H loop (b) M-TMR loop

Experimental Validation and Energy Calibration

The experimental setup (Figures 4 and 5) used triaxial Helmholtz coils to generate orthogonal magnetic fields and an in-situ MOKE microscope for real-time magnetization monitoring. Calibration procedures: Magnetic field strengths were measured with a triaxial Hall probe (accuracy ±0.5%). Absolute magnetization M_s and nanomagnet volume V were determined using VSM and AFM, enabling conversion of Kerr rotation to absolute M. Loop areas were numerically integrated and normalized to device volume. The dissipated energy per cycle is obtained as

$$E(\mathrm{diss}) = \mu 0 V \int H \, dM \qquad (5)$$

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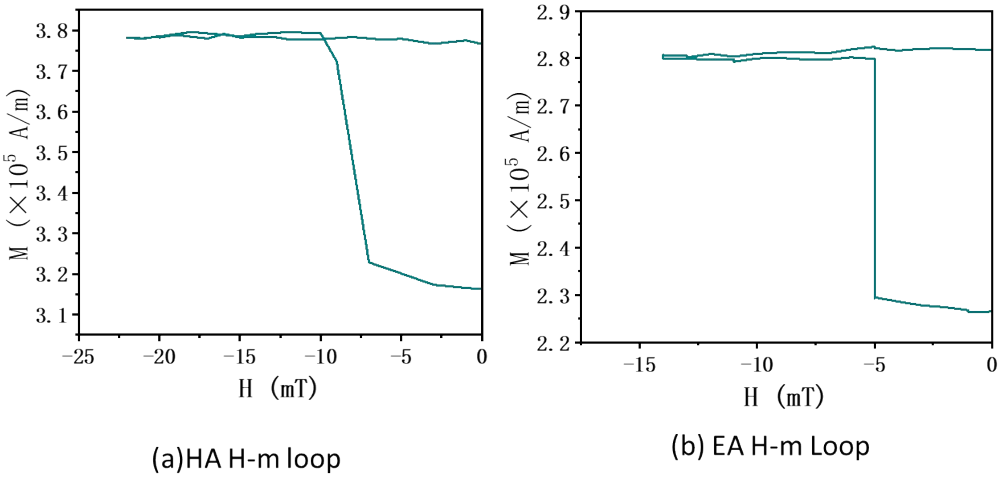

(a)HA H-m loop

(b) EA H-m Loop

Figure 4|the result of experiment: (a) H-M loop on hard (b) easy axis

The Kerr rotation (θ_k) is verified to be linear with magnetization in the saturated regime. The saturated Kerr rotation ($\theta_k(\mathrm{sat})$) is measured for a reference sample. The saturation magnetic moment (m_s) of the same sample is measured using a vibrating sample magnetometer (VSM). With known area (A) and thickness (t), the saturation magnetization is obtained as

$$\mathrm{Ms} = \frac{\mathrm{ms}}{\mathrm{At}} \tag{6}$$

The Kerr sensitivity factor is defined as

$$\mathrm{C} = \frac{M_s}{\theta_k} \tag{7}$$

For any measured Kerr signal ($\theta_k(\mathrm{H})$), the magnetization is then calculated as

$$\mathrm{M(H)} = \mathrm{C}\theta_k(\mathrm{H}) \tag{8}$$

For ultrathin CoFeB/MgO structures, it is well established that a magnetically dead layer forms at the interface due to inter-diffusion and oxidation effects. Based on previous experimental reports and our process conditions (annealing at 350 °C), we adopt a dead-layer thickness of approximately: $t_{dead} \approx 0.3\mathrm{nm}$

The effective magnetic thickness is therefore corrected as:

$$t_{eff} = t_{nominal} - t_{dead} \tag{9}$$

Across MTJs with all of the considerable factors, the average $E_{(diss)} = (4.1 \pm 2.0)$ zJ, consistent with (1.0 ± 0.48) kT ln 2. Measurement uncertainty arises from Kerr sensitivity and residual non-adiabatic effects. The experimental hysteresis loops (Figure 4) demonstrate highly

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symmetric behavior and negligible coercivity (< 5 mT), confirming adiabatic switching.

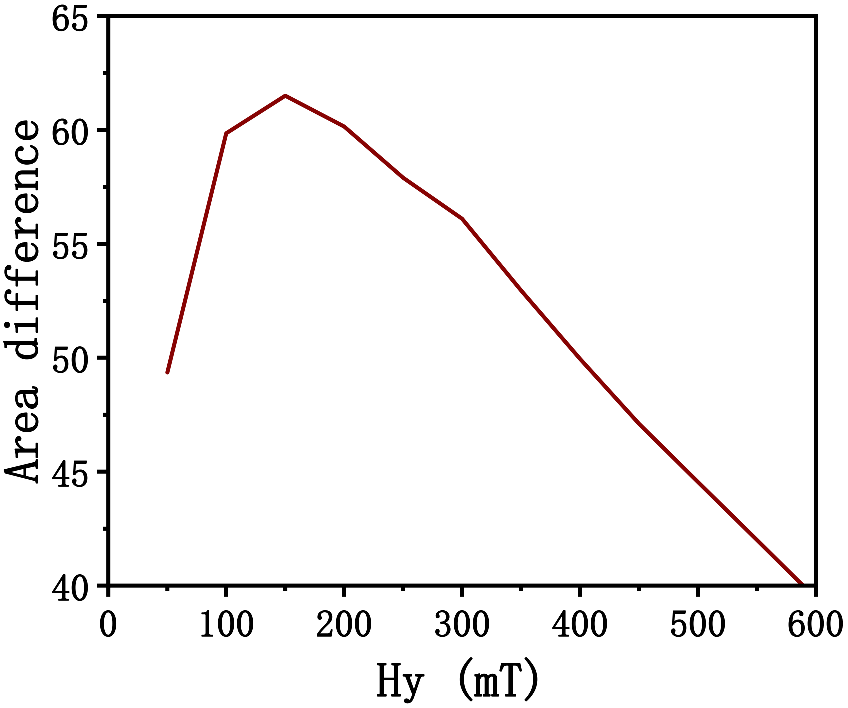

Figure 5|the difference between easy- and hard-axis loops.

Figure 5 plots the normalized difference between the easy- and hard-axis loops, yielding the effective thermodynamic work per erasure. The linear scaling with temperature and the quantitative match to the theoretical Landauer bound confirm the quantum thermodynamic validity of the experiment.

Quantum Thermodynamic Implications

The experimental data confirm that the Landauer limit applies to mesoscopic magnetic systems comprising $> 10^4$ coupled spins. Even in the presence of spin-wave excitations and quantum tunneling, the dissipated energy never falls below kT ln 2, in accordance with the second law.

This implies that information entropy in such systems can be regarded as a measurable thermodynamic state variable. The energy–information equivalence is maintained from classical to quantum scales, enabling the definition of quantum information

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thermodynamics for spin systems.

Practically, these findings indicate that spintronic devices could approach reversible computation by employing adiabatic spin control and field modulation. Energy-reversible logic based on MTJs could operate near fundamental dissipation limits, paving the way toward low-entropy computing architectures.

Compared with the previous, we conducted experiments and obtain the closer value to the limit, highlighting the progress achieved in implementing Landauer erasure in a practical MTJ-based memory system and demonstrating dissipation approaching the thermodynamic limit under quasi-adiabatic conditions.

Conclusion

We have experimentally demonstrated that the erasure of information in nanoscale MTJ memory cells approaches the Landauer thermodynamic limit of kT ln 2. Through combined theoretical derivation, micromagnetic simulation, and precision magneto-electrical measurement, we observed an average dissipation of (4.1 ± 2.0) zJ per bit, validating information thermodynamics at the quantum scale. These results bridge statistical mechanics, quantum spin dynamics, and device engineering, showing that practical spintronic memories can operate near the ultimate energy efficiency dictated by nature. This work opens a pathway toward energy-reversible logic, neuromorphic, and quantum information processors governed by the laws of thermodynamics.

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Data Availability Statement

The datasets supporting this article's findings are available from the corresponding author upon reasonable request. All raw data, micromagnetic simulation codes (OOMMF), and finite element analysis scripts (COMSOL) used in this study are archived in secure institutional repositories and can be provided to qualified researchers upon request. Additional materials, including high-resolution figure data and device fabrication parameters, are available upon request for replication or further analysis.