Experimental test of Landauer’s principle in single-bit operations on nanomagnetic memory bits

Minimizing energy dissipation has emerged as the key challenge in continuing to scale the performance of digital computers. The question of whether there exists a fundamental lower limit to the energy required for digital operations is therefore of great interest. A well-known theoretical result put forward by Landauer states that any irreversible single-bit operation on a physical memory element in contact with a heat bath at a temperature $T$ requires at least $k_B T \ln(2)$ of heat be dissipated from the memory into the environment, where $k_B$ is the Boltzmann constant. We report an experimental investigation of the intrinsic energy loss of an adiabatic single-bit reset operation using nanoscale magnetic memory bits, by far the most ubiquitous digital storage technology in use today. Through sensitive, high-precision magnetometry measurements, we observed that the amount of dissipated energy in this process is consistent (within 2 SDs of experimental uncertainty) with the Landauer limit. This result reinforces the connection between “information thermodynamics” and physical systems and also provides a foundation for the development of practical information processing technologies that approach the fundamental limit of energy dissipation. The significance of the result includes insightful direction for future development of information technology.

INTRODUCTION

In 1961, Landauer (1) proposed the principle that logical irreversibility is associated with physical irreversibility and further theorized that the erasure of information is fundamentally a dissipative process. Among several seminal results, his theory states that for any irreversible single-bit operation on a physical memory element in contact with a heat bath at a given temperature, at least $k_B T \ln(2)$ of heat must be dissipated from the memory into the environment, where $k_B$ is the Boltzmann constant and $T$ is temperature (2). The single-bit reset operation process is schematically shown in Fig. 1A. As shown by Landauer (1, 2), the extracted work from the process, regardless of the initial state of the bit, is $W_{\text{operation}} \geq k_B T \ln(2)$. This energy, $k_B T \ln(2)$, corresponds to a value of $2.8 \times 10^{-21} \text{J}$ at 300 K. In the field of ultra-low-energy electronics, computations that approach this energy limit are of considerable practical interest (3).

The first direct experimental test of Landauer’s principle was reported in 2012 using a 2-μm glass bead in water manipulated in a double-well laser trap as a model system (4), and a higher precision measurement using 200-nm fluorescent particles in an electrokinetic feedback trap was recently reported (5). Although the topic is of great importance for information processing, the Landauer limit in single-bit operations has yet to be tested in any other physical system (5, 6), particularly one that is relevant in practical digital devices. Therefore, confirming the generality of Landauer’s principle in another, very different physical system is of great interest. Landauer and Bennett (1, 7) both used nanomagnets as prototypical bistable elements in which the energy efficiency near the fundamental limits was considered. Accordingly, we report here an experimental study of Landauer’s principle directly in nanomagnets.

RESULTS

In the micromagnetic simulations of Lambson and Madami (10, 11), and as shown in Fig. 1B, the reset sequence can be divided into four steps. Initially, the nanomagnet is in either 0 or 1 state, and afterward, it is reset to the 1 state. The internal energy dissipation in the nanomagnet is found by integrating the area of $m-H$ loops for magnetic fields applied along both the $x$ and $y$ axes (hard and easy axes, respectively) followed by their subtraction. To perform the hysteresis loop measurements of interest, the external magnetic fields are specified as 

$$H_x = H_0 \cos(\omega t), \quad H_y = H_0 \sin(\omega t),$$

where $H_0 = 10 \text{mT}$ and $\omega = 5 \times 10^7 \text{rad/s}$. The anisotropy of the magnetic material is $K_u = 3 \times 10^6 \text{erg/cm}^3$, the saturation magnetization is $M_s = 1.8 \times 10^5 \text{emu/cm}^3$, and the gyromagnetic ratio is $\gamma = 2.8 \times 10^7 \text{rad/A/T}$. The effective field $H_e = H_x + \gamma M_s H_y$ is plotted in Fig. 1B. The fact that mesoscopic single-domain magnetic dots comprising more than $10^4$ individual spins can nevertheless behave as a simple system with a single informational degree of freedom has been explicitly analyzed and confirmed theoretically and experimentally (8, 9). Further theoretical studies (10, 11) in which the adiabatic “reset to one” sequence for a nanomagnet memory suggested by Bennett (7) was explicitly simulated using the stochastic Landau-Lifschitz-Gilbert formalism, confirmed Landauer’s limit of energy dissipation of $k_B T \ln(2)$ with high accuracy. For a nanomagnetic memory bit, magnetic anisotropy is used to create an “easy axis” along which the net magnetization aligns to minimize magnetostatic energy. As shown in Fig. 1A, the magnetization can align either “up” or “down” along the easy axis to represent binary “0” and “1.” We denote the easy axis as the $y$ axis. The orthogonal $x$ axis is referred to as the “hard axis.” The anisotropy of the magnet creates an energy barrier for the magnetization to align along the hard axis, allowing the nanomagnet to retain its state in the presence of thermal noise. To reset a bit stored in the nanomagnet, magnetic fields along both the $x$ and $y$ axes are used. The $x$ axis field is used to lower the energy barrier between the two states, and the $y$ axis field is then used to drive the nanomagnet into the 1 state.

1 Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, CA 94720, USA. 2 Haynes and Boone LLP, 525 University Avenue, Palo Alto, CA 94301, USA. 3 The Molecular Foundry, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA.

*Corresponding author. E-mail: jbobkoeecs.berkeley.edu
Applying the fields in this manner splits the operation into four stages, and during any given stage, one of the fields is held fixed while the other increased linearly from zero to its maximum value or vice versa, as shown in Fig. 1B. In stage 1, \( H_x \) is applied to saturate the hard axis, which removes the energy barrier and ensures that the energy dissipation is independent of the barrier height.

As explained by Bennett (7), whether the Landauer erasure operation is classified as reversible or irreversible depends on whether the initial state of the nanomagnet is truly unknown (that is, randomized) or known. However, in both the reversible and irreversible cases, the amount of energy transfer that occurs during the operation is \( k_B T \ln(2) \). The distinction between reversible and irreversible lies in whether or not the operation can be undone by applying the fields depicted in Fig. 1B in reverse. A more complete discussion is contained in Bennett’s work (7). Accordingly, for experimental purposes, there is no need to randomize or otherwise specially prepare the initial state of the nanomagnets to observe the \( k_B T \ln(2) \) limit. This can be further justified by observing that the first stage of the reset operation depicted in Fig. 1B (applying a field along the \( x \) axis) is symmetric with respect to the initial orientation of the nanomagnets along the \( y \) axis. After the first stage, there is no remaining \( y \) axis component of the magnetization of the nanomagnets, so subsequent stages of the operation are independent of the initial orientation of the nanomagnets along the \( y \) axis. As a result, the amount of energy dissipated during the Landauer erasure operation does not depend on the initial state of the nanomagnet.

Magneto-optic Kerr effect (MOKE) in the longitudinal geometry was used to measure the in-plane magnetic moment, \( m \), of a large array of identical Permalloy nanomagnets, whereas the magnetic field, \( H \), was applied using a two-axis vector electromagnet. The experimental setup is shown in Fig. 2A. The lateral dimensions of the nanomagnets were less than 100 nm to ensure they were of single domain, whereas the spacing between magnets was 400 nm to avoid dipolar interactions between magnets yet provide sufficient MOKE signal.

To quantitatively determine the net energy dissipation during the reset operation from the MOKE data, it is necessary to calibrate both the applied magnetic field and the absolute magnetization of the nanomagnets. The applied field was measured using a three-axis Hall probe sensor. To calibrate the MOKE signal, the total moment, \( M_s V_T \), for the full sample was measured using a vibrating sample magnetometer (VSM). \( M_s \) is the saturation magnetization for the full sample and \( V_T \) is the total volume of the magnetic layer on the sample. An example of experimental results from one run is shown in Fig. 3. The volume of each nanomagnet, \( V \), and the number of nanomagnets on the substrate were measured and calibrated using SEM for the lateral dimensions and count, and atomic force microscopy (AFM) was used to determine the thickness (see the Supplementary Materials for details). In this way, the \( M_s V \) value for an individual nanomagnet from the MOKE data could be absolutely determined.

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**Fig. 1. Thermodynamics background.** (A) Description of single-bit reset by time sequence. Before the erasure, the memory stores information in state 0 or 1; after the reset, the memory stores information in state 0 in accordance with the unit probability. (B) Timing diagram for the external magnetic fields applied during the restore-to-one process. \( H_x \) is applied along the magnetic hard axis to remove the uniaxial anisotropy barrier, whereas \( H_y \) is applied along the easy axis to force the magnetization into the 1 state. Illustrations are provided of the magnetization of the nanomagnet at the beginning and end of each stage and of the direction of the applied field in the \( x-y \) plane.
The energy dissipation (the magnetization energy transferred by the applied magnetic field to a nanomagnet) is determined by the total area of the hysteresis curves. As seen in Fig. 3 and video S1, the \( x \) and \( y \) hysteresis curves are traversed in opposite directions during the course of the reset operation so that the total energy is found by subtracting the area of the \( y \) hysteresis (easy axis) loop from the area of the \( x \) hysteresis (hard axis) loop. Further details concerning the calculation of energy dissipation are given in the Supplementary Materials.

As expected, the temperature dependence between 300 and 400 K was very similar to the theoretical prediction based on the average of all 2000 simulations. The mean energy dissipation was found to be \( 0.6842 \, k_B T \), which corresponds to a 95% confidence interval of \( 0.6740 \) to \( 0.6943 \, k_B T \). These values are in very close agreement with the Landauer limit, \( k_B T \ln(2) \). The experimental energy dissipation was measured at temperatures varying from 300 to 400 K. As seen in Fig. S1, the hysteresis loops for both axes individually show a clear systematic temperature dependence that is consistent with micromagnetic simulations \((10, 11)\), but the temperature dependence of the measured net energy dissipation was smaller than the run-to-run variation, as seen in Fig. 4A. For the set of runs, the energy dissipation was measured to be \( (4.2 \pm 0.9) \, zJ \), which corresponds to a value of \((1.0 \pm 0.22)k_B T \) (for \( T = 300 \, K \)). Statistical experimental results for energy dissipation are shown in Fig. 4B. As explicitly demonstrated by Lambson and Madami \((10, 11)\), for “ideal” nanomagnets, the dissipation should average exactly to \( k_B T \ln(2) \) with a small run-to-run variation caused by thermal fluctuations. The average dissipation for five trials at room temperature was measured to be \( (6.09 \pm 1.43) \, zJ \) at \( T = 300 \, K \). This is consistent with a value of \((1.45 \pm 0.35)k_B T \), which is extremely close to the Landauer limit of \( k_B T \ln(2) \) or \( 0.69 \, k_B T \). The quoted error was determined by combining in quadrature the uncertainties in each of the measured variables: nanomagnet area and thickness, magnetic field calibration, magnetic moment, lithographic variation, and the statistical variation among the five trials.

A small remanent magnetization was typically observed in the hard axis (\( x \)) direction (curves in Fig. 3 do not pass through the origin). We attribute this to fabrication variations among the nanomagnets. When the symmetry axes of the individual nanomagnets are not perfectly aligned with the axes of the applied magnetic fields, each of their remanent easy axis magnetizations will have a small component along the hard axis direction. Because of fabrication variations, there will be a distribution of misalignments. Experiments involving small rotations of the sample to find the net symmetry axis and measure the effect of a net tilt of the array with respect to the magnetic field axes are described in the Supplementary Materials. On the basis of these
experiments, we estimate the magnitude of random variation of the symmetry axes of the nanomagnets across the array to be approximately ±1°, which is roughly consistent with the observed remanence (see also simulation in fig. S4C). We estimate that the small excess energy dissipation above the Landauer value that we observed in our experiment can be mainly attributed to this effect (see discussion in the Supplementary Materials). Other possible sources of excess dissipation include domain motion and pinning by defects and edge roughness (12, 13) and edge effects. The effects of dot shape and subdomain structure on energy dissipation are explicitly considered in the simulations reported by Madami et al. (11). At this time, it is not feasible to separately estimate the magnitude of these various contributions to the small excess energy dissipation observed in our experiments. However, the fact that our results depart by only 50 to 100% of the Landauer value strongly indicates that these Permalloy nanomagnets behave very closely to the ideal "single-spin" magnets and therefore provide a practical and viable system for further exploration of the ultimate energy dissipation in information processing. As an example, a nanomagnetic logic gate for demonstrating reversible logic operation with dissipation below the Landauer limit was analyzed theoretically by Lambson et al. (10). Our results suggest that such an experiment is indeed feasible.

**DISCUSSION**

We have experimentally measured for the first time the intrinsic minimum energy dissipation during a single-bit operation using a nanoscale digital magnetic memory bit. Our result is within 2 SDs of the value of $k_B T \ln(2)$ predicted by Landauer. Although experimental tests of Landauer’s limit have previously been performed using trapped microbeads, our result using a completely different physical system confirms its generality and, in particular, its applicability to practical information processing systems. Any practical nanomagnetic memory or logic device will inevitably involve additional energy loss.
associated with the actuation mechanism (that is, the external applied magnetic fields in this experiment); however, our results demonstrate the potential to approach Landauer’s limit in future information processing systems. Therefore, the significance of this result is that today’s computers are far from the fundamental limit and that future marked reductions in power consumption are possible with further development of nanomagnetic memory and logic devices. Given that power consumption is the key issue that limits the continued improvement in digital computers, the result has profound suggestions for the future development of information technology.

**MATERIALS AND METHODS**

**Fabrication of nanomagnetic memory bits**

We fabricated an array of identical, single-domain, noninteracting, elliptically shaped nanomagnets by lift-off patterning of an electron beam (e-beam) evaporated amorphous Permalloy (NiFe) film on a silicon substrate using e-beam lithography. The base pressure of the e-beam evaporator was $2 \times 10^{-7}$ torr, and the film thickness was 10 nm. The sample was fabricated at The Molecular Foundry at Lawrence Berkeley National Laboratory.

**Dimensional metrology of nanomagnet islands using SEM and scanning probe microscopy**

SEM images were collected with a Carl Zeiss LEO 1550. The statistical accuracy of area of the magnet and thickness measurements were 1.2 and 7.9%, respectively. The image analysis was performed using ImageJ software from the National Institutes of Health. The average size of magnets was calculated with the software and calibrated to the highly accurate average pitch of the nanomagnet array produced by the e-beam lithography tool (Vistec VB300). The thickness of the nanomagnets was determined with AFM performed in noncontact mode using the Veeco Dimension 3100 system. MFM measurements using the same instrument were conducted in a dynamic-lift mode with a lift-off distance of 30 nm.

**Magneto-optic Kerr spectroscopy**

To perform high-resolution magneto-optic Kerr spectroscopy, we used a focused MOKE system in lateral mode. A 635-nm diode laser was directed toward the sample, which was located between the poles of a vector magnet. The laser spot size on the sample was approximately 50 μm, covering approximately $10^6$ nanomagnets. However, the magnetic field at the probe spot was calibrated by a three-axis Hall probe sensor (C-H3A-2m Three Axis Magnetic Field Transducer, SENIS GmbH). The accuracy of the magnetic field measurement is estimated at ~1%. The time to sweep full hysteresis loops was 20 min (1 Oe/s).

**Energy dissipation calculation**

The energy dissipation was calculated by the following equation

$$M \cdot dH = \int \left\{ (M_x \times dH_x) + (M_y \times dH_y) \right\}$$

$$= \int (M_x \times dH_x) + \int (M_y \times dH_y)$$

$$= \text{Area}_{M_x-H_loops} + \text{Area}_{M_y-H_loops}$$

The measured value of the energy dissipation is not dependent on the laser spot size/shape or the number of nanomagnets illuminated by the spot. This is because the saturation magnetization $M_s$ and the average spin moment for the nanomagnets $\mu$ ($=M_sV$) of each individual magnet were separately measured as described below. The magnetization as measured by MOKE was calibrated by setting the saturated value of the MOKE signal to this average saturated spin moment, $\mu$. 

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/3/e1501492/DC1

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the project. J.H. and B.L. established and performed MOKE experiments and simulation. J.H. performed AFM/MFM and SEM measurements and error analyses. S.D. fabricated nanomagnets using e-beam lithography. J.H., B.L., and J.B. wrote the manuscript with input from all authors.

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