

Marquette University
e-Publications@Marquette

Physics Faculty Research and Publications

Physics, Department of

10-1-2006

Simulating the Maximum Domain Wall Speed in a Magnetic Nanowire

Andrew Kunz

Marquette University, andrew.kunz@marquette.edu

Accepted version. *IEEE Transactions on Magnetics*, Vol. 42, No. 10, (October 2006): 3219 - 3221.
DOI. © 2006 IEEE. Used with permission.

Marquette University

e-Publications@Marquette

Physics Faculty Research and Publications/College of Arts and Sciences

This paper is NOT THE PUBLISHED VERSION; but the author's final, peer-reviewed manuscript. The published version may be accessed by following the link in the citation below.

IEEE Transactions on Magnetics, Vol. 42, No. 10 (September 25, 2006): 3219-3221. [DOI](#). This article is © Institute of Electrical and Electronics Engineers (IEEE) and permission has been granted for this version to appear in [e-Publications@Marquette](#). IEEE does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from IEEE.

Simulating the Maximum Domain Wall Speed in a Magnetic Nanowire

[A. Kunz](#)

Physics Department, Marquette University, Milwaukee, WI

IEEE Keywords

Magnetic domain walls, Magnetic domains, Damping, Micromagnetics, Magnetization, Magnetic devices, Equations, Wire, Magnetic analysis, Magnetic anisotropy

Abstract:

The dynamics of domain wall motion in permalloy nanowires have been simulated utilizing the Landau-Lifshitz-Gilbert (LLG) equation of motion. The simulation results are presented in terms of the domain wall speed for ranges of the Gilbert damping parameter α and nanowire width. The maximum domain wall speed is independent of α . The speed of the domain wall can be increased by increasing the nanowire width, but this lowers the critical field. For applied fields below the critical field, the wall moves uniformly along the wire and the speed of

the wall increases with increases in the driving field. This behavior is consistent with current analytic models; however, the models overestimate both the value of the domain wall speed and the critical field

SECTION I.

Introduction

The ability to fabricate and observe magnetic devices with nanometer dimensions has created opportunities to investigate magnetization changes in systems that can be modeled as one-dimensional [1], [2]. Magnetization changes depend on the motion of domain walls, but even the most idealized cases can be complicated to understand due to the nonlinear behavior of the motion [3]. Magnetic devices have been proposed that would use domain wall motion to transmit information along a nanowire [4]. This motion can be driven both magnetically and electronically, but the speed at which the device operates depends only on the speed at which a domain wall can be moved [5]–[6][7]. Understanding the limitations on the speed a domain wall can move is critical to developing high-speed devices.

The Walker model is currently the best analytic theory available to describe the speed at which a one-dimensional domain wall will propagate [3], [8]. The Walker field is the critical field at which the domain wall moves with maximum speed. It is observed that driven domain walls obey the general behavior predicted by Walker, see Fig. 1, but it will be shown that the calculated values for the maximum wall speed and critical field overestimate what is observed [9].

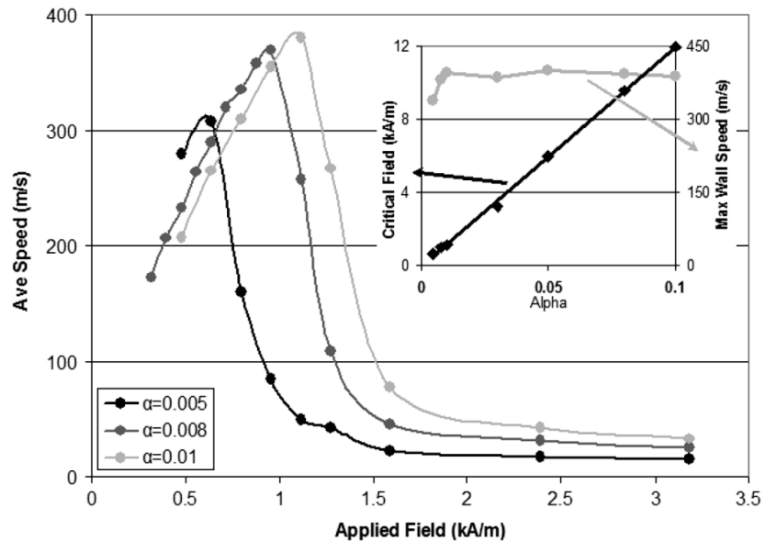


Fig. 1. Domain wall speed versus applied field for three values of the damping parameter in a 100 nm wide nanowire. Below the critical field, the field where the speed is greatest, the domain wall speed increases as the field strength increases. The inset shows the linear relationship between the critical field and the damping parameter over the full range of values simulated. The maximum domain wall speed is independent of the damping coefficient.

Here, micromagnetic simulation is used as a tool to develop an understanding as to how a domain wall evolves when subject to an applied driving field for a range of values of the damping parameter alpha and nanowire widths. A physical interpretation of the micromagnetic simulations, and therefore of the domain wall dynamics, is necessarily dependent on the value of damping parameter used. The physical mechanisms behind alpha are not well-understood [10]; therefore, the results in this work are presented as a function of alpha.

SECTION II.

Simulation Details

Each simulated magnetic nanowire has a length of 3000 nm and a thickness of 10 nm. Unless otherwise noted each nanowire is 100 nm wide. Micromagnetic simulation follows the precessional motion of each magnetic moment, \vec{m} , in a magnetic field, \vec{H} , by integrating the three-dimensional Landau–Lifshitz–Gilbert (LLG) equation of motion

$$\frac{\partial \vec{m}}{\partial t} = -\gamma(\vec{m} \times \vec{H}) - \frac{\alpha\gamma}{M_s} \vec{m} \times (\vec{m} \times \vec{H}) \quad (1)$$

where $\gamma = 2.2 \times 10^5 \text{m/(As)}$ [11]. The field term, H , includes the applied field, the magnetostatic field, and the exchange field with the parameters $M_s = 8.0 \times 10^5 = 8.0 \times 10^5 \text{ A/m}$, $A = 1.3 \times 10^{-11} \text{ J/m}$, respectively, for permalloy. No crystalline anisotropy was used in this simulation. To assist in interpreting the magnetization dynamics, the damping parameter α has been varied from 0.005 to 0.1. In order to carry out the micromagnetic calculation, the nanowire was discretized into identical cubes of uniform magnetization, 5 nm on a side. The discretization has been checked with 2 nm cubes without any qualitative or quantitative difference in the results. The numerical integration is carried out using a fourth-order predictor-corrector method, with a subpicosecond time step. The wire is subject to free boundary conditions on all of its edges.

In order to determine the average speed of the domain wall, the speed was calculated over a 2 μm section in the central part of the wire where the wall speed was constant and not affected by the ends of the wire. Simulations were completed on wires up to 5 μm in length with no difference in the domain wall speed through the center of the wire.

The domain wall in the wire was generated by artificially placing a sharp head-to-head transition in the center of the wire. This abrupt transition was allowed to relax to its equilibrium state. A small field (to ensure no turbulent dynamics) was then placed on the wall to move it towards the left end of the wire. When the wall was about 400 nm from the left end, a steady (reversed) driving field was applied until the wall moved completely out of the right-hand side of the wire. The wire configuration with the wall 400 nm from the left-hand side was the initial state for every trial reported here.

SECTION III.

Results and Discussion

The average speed of a domain wall, as it moved along the nanowire, and the maximum speed of the wall were determined as a function of the applied driving field in 100 nm wide wires for damping parameters ranging from $\alpha=0.005$ to 0.1. The results are summarized in Fig. 1. The average speed as a function of the applied field is plotted for the three smallest values of alpha, the most likely physical values for permalloy, showing an increase in the critical field as alpha increases. The critical field is the field at which the domain wall moves with the greatest speed. The general shape of the speed curve is constant for all values of alpha, just shifted to higher critical fields as alpha increases. The inset in Fig. 1 shows the critical field, and the maximum (critical) domain wall speed for each value of alpha simulated. The critical field increases linearly for the full range of damping parameters simulated in this work, and the critical speed of the domain wall is independent of the value of the damping parameter.

Fig. 2 shows that for applied fields below the critical field, called the viscous regime, the domain wall moves uniformly down the wire. When the applied field is greater than the critical field there is a sharp drop in the average speed of the domain wall. As previously reported, the increased torque due to the large magnetic field induces precessional motion and vortex nucleation within the wall [8], [12]. Increasing the damping parameter suppresses the precessional motion, which leads to an increase in the critical field. It has been shown that adding edge roughness to the nanowire suppresses the precession as well [8]. The domain wall undergoes a ratcheting motion as it travels down the length of the wire. The ratcheting motion has periods when the wall moves with high speeds, and other periods when the wall is stationary, leading to the low values for the average speed [12]. It is noted that above the critical field when the domain wall is moving, the wall travels at speeds close to the critical speed.

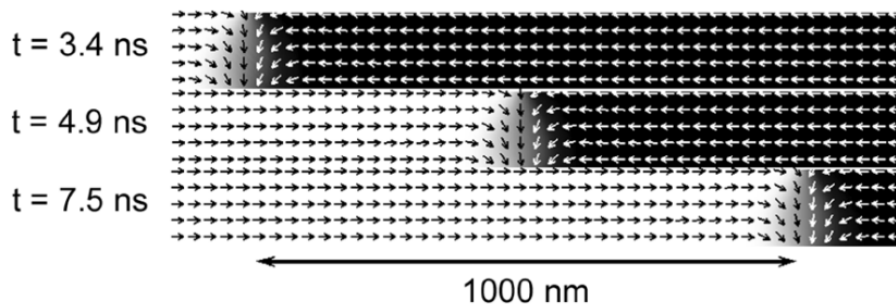


Fig. 2. Simulated time evolution of the domain wall propagation through the middle portion of a 100 nm wide nanowire driven by a 560 A/m applied field. The field strength is below the value of the critical field and therefore the domain wall moves uniformly along the wire in the direction of the applied field. Arrows are included to help visualize the direction of the magnetic moments in the nanowire.

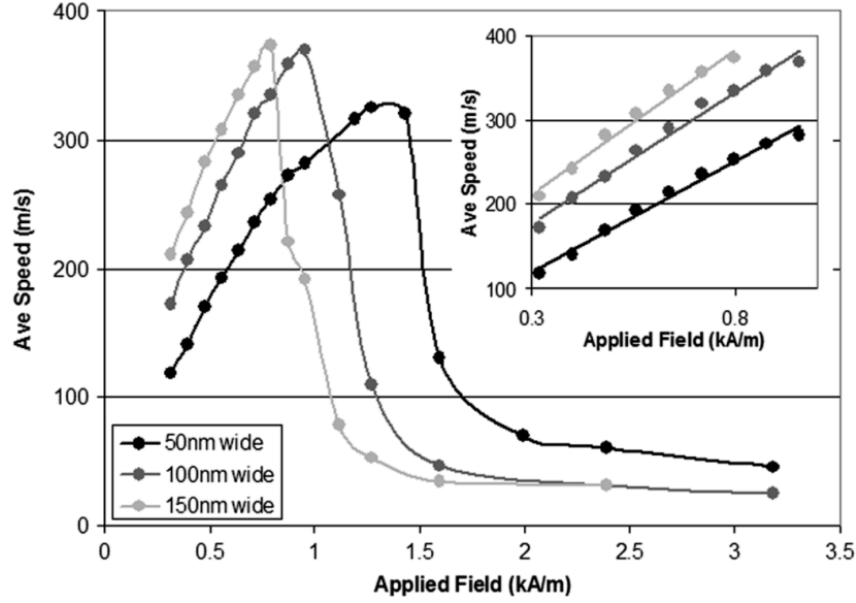


Fig. 3. Average domain wall speed versus applied field for three wire widths and $\alpha=0.008$. The critical field and the critical speed the of the domain wall depend on the width of the wire. The inset shows the linear relationship between the average speed and applied field in the viscous regime. This behavior is consistent with the Walker model.

Once it was determined that the maximum domain wall speed obtained in the wire was independent of the damping parameter the width of the nanowire was varied. For $\alpha=0.008$ the average domain wall speed is plotted as a function of applied field, Fig. 3, for wire widths of 50, 100, and 150 nm. The curves have the same shape as in Fig. 1, in that there is a viscous regime where the wall speed increases with applied field up to a critical speed at the critical field and a sharp decrease in speed above that field. It is shown that the value of the critical field decreases, and the critical speed increases as the width of the wire increases.

The inset of Fig. 3 shows that the domain wall velocity increases linearly up to the value of the critical field ($H_c = 796$ kA/m for the 150 nm wide wire), for each of the wire widths simulated, behavior that is consistent with the Walker model [3]. In the viscous regime the domain wall speed is predicted by

$$v = \left(\frac{\gamma\Delta}{\alpha}\right)H_a \quad (2)$$

where γ and α are the same as reported earlier, Δ is the domain wall width, and H_a is the driving field. In the viscous regime, see Fig. 2, the domain wall width is constant.

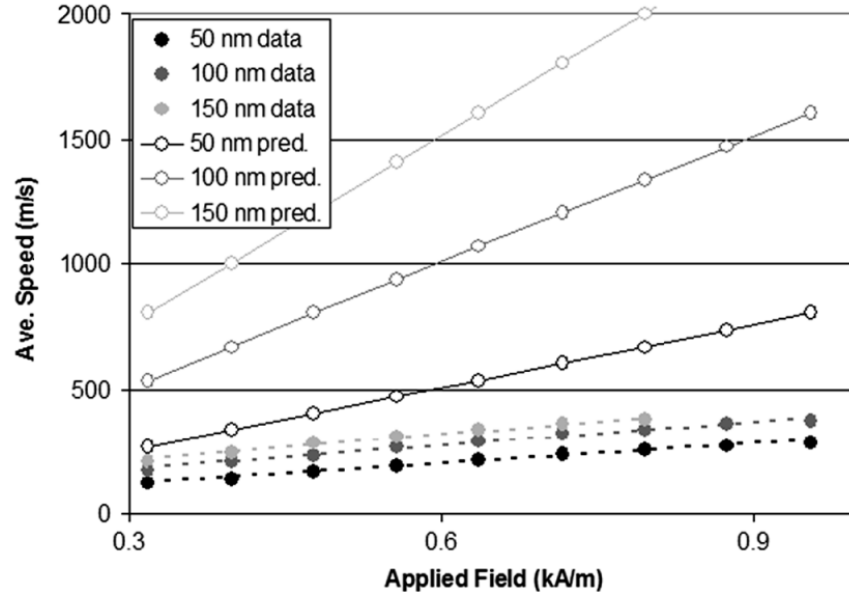


Fig. 4. Simulated domain wall speed versus applied field (below the critical field) for three wire widths and $\alpha=0.008$ and predicted wall speeds calculated from the Walker model. While the general behavior is similar, the predicted speeds are greater than what is observed.

The domain wall width is measured from simulation, and the calculated domain wall speed, using the Walker model, is plotted in Fig. 4 as a function of the driving field. The domain wall speed obtained from the simulations is plotted on the same axes, showing that the Walker model overestimates the wall speed. It is found that the difference is around a factor of three. This discrepancy is in agreement with previously published results where unphysical domain wall widths or unphysical values of the damping parameter must be used to force agreement with theory [2], [8]. The Walker model also overestimates the value of the critical field for which the maximum wall speed can be reached. The expression for the Walker field is

$$H_c = \frac{M_s \alpha}{2} \quad (3)$$

where M_s is the saturation magnetization, and α is again the damping parameter. In a 100 nm wide permalloy nanowire with $\alpha=0.008$, the critical field is found to be 3.2 kA/m. When compared to the critical field in Fig. 1 the difference is found to be about a factor of three, although this factor changes with wire width. The expression for the Walker field (3) does not account for differences in material shapes or sizes. The discrepancy between the model and the observation is most likely due to the reduced dimensionality of the nanowire. The Walker model was derived for one-dimensional domain walls in a thin film, therefore, the further reduction in dimensionality for nanowires needs to be accounted for.

SECTION IV.

Conclusion

Domain wall speeds in permalloy nanowires have been calculated using micromagnetic simulation. The maximum value of the domain wall speed is found to be independent of the damping parameter (giving rise to another potential method of measuring α), but dependent on the width of the wire. Improved models are necessary in order to predict analytically the wall speed and critical field for the reduced nanowire geometry.

ACKNOWLEDGMENT

The author would like to thank D. Dahlberg for useful contributions to this work. This work was supported by Marquette University and the Helen Way Klingler College of Arts and Sciences SFF.

References

- ¹ E. Y. Vedmedenko, "Domain wall orientation in magnetic nanowires", *Phys. Rev. Lett.*, vol. 92, pp. 077207, Feb. 2004.
- ² D. Atkinson, "Magnetic domain wall dynamics in a permalloy nanowire", *IEEE Trans. Magn.*, vol. 39, no. 5, pp. 2663-2665, Sep. 2003.
- ³ N. L. Schryer, L. R. Walker, "The motion of 180° domain walls in uniform dc magnetic fields", *J. Appl. Phys.*, vol. 45, pp. 5406-5421, Dec. 1974.
- ⁴ X. Zhu, "Spatially resolved observation of domain wall propagation in a submicron ferromagnetic NOT-gate", *Appl. Phys. Lett.*, vol. 87, pp. 062503, 2005.
- ⁵ J. C. Slonczewski, "Current-driven excitation of magnetic multilayers", *J. Magn. Magn. Mater.*, vol. 159, pp. L1-L7, Jun. 1996.
- ⁶ A. Thiaville, Y. Nakatani, J. Miltat, N. Vernier, "Domain wall motion by spin-polarized current: A micromagnetic study", *J. Appl. Phys.*, vol. 95, pp. 7049-7051, Jun. 2004.
- ⁷ T. G. Sorop, "Magnetization reversal of ferromagnetic nanowires studied by magnetic force microscopy", *Phys. Rev. B.*, vol. 67, pp. 014402, 2003.
- ⁸ Y. Nakatani, A. Thiaville, J. Miltat, "Faster magnetic walls in rough wires", *Nat. Matr.*, vol. 2, pp. 521-523, Aug. 2003.
- ⁹ A. Yamaguchi, "Real-space observation of current-driven domain wall motion in submicron magnetic wires", *Phys. Rev. Lett.*, vol. 92, pp. 077205, Feb. 2004.
- ¹⁰ R. D. McMichael, D. J. Twisselmann, A. Kunz, "Localized ferromagnetic resonance in inhomogeneous thin films", *Phys. Rev. Lett.*, vol. 90, pp. 227601, Jun. 2006.
- ¹¹ *Micromagnetic Simulator*.
- ¹² A. Kunz, "Simulated domain wall dynamics in magnetic nanowires", *J. Appl. Phys.*, vol. 99, no. 08G107, Jun. 2006.