Remanent Moment and Interlayer Exchange Coupling Dependence of the Switching Behavior of AF Coupled Sense Layers

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January 8, 2004 (updated)

Introduction

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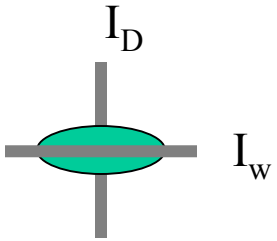
•Synthetic antiferromagnets (SAF) are of current interest for use as sense layers in MRAM bits.

- •Increased thermal stability
- •Decreased inter-bit interactions
- •And most recently for improved write margin

$FM_1(t_1)/Ru/FM_2(t_2)$

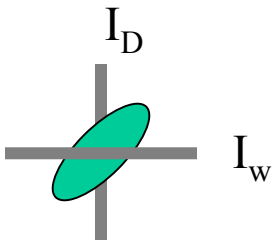
•Three modes stand out

- •Conventional Write



Mismatched layers – large M_{rem}

- •Direct Write
- •Toggle



Closely matched layers – small M_{rem}

Reference: US Patent 6,777,730

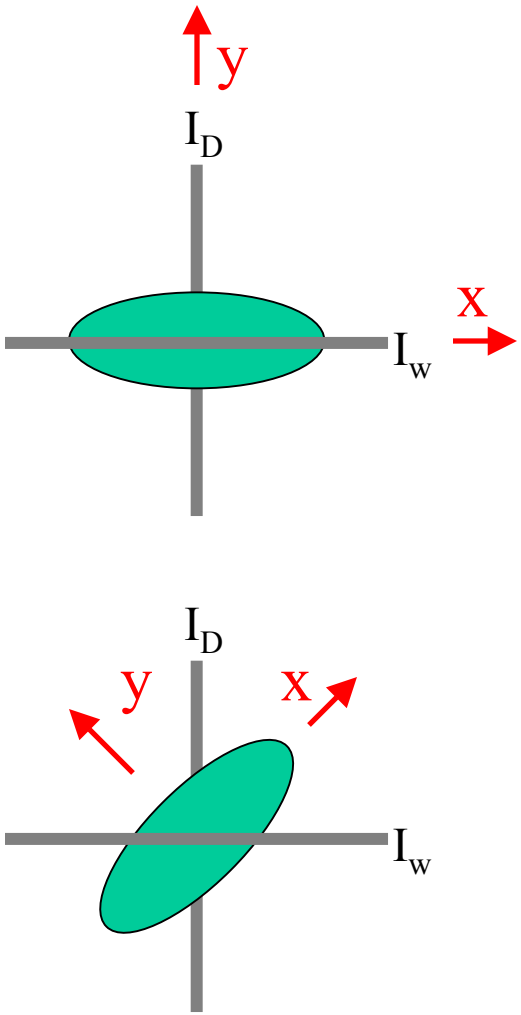
Outline

- **Micromagnetic Simulation of the Switching Modes**

- **Map out H_{sw} and Write Margin in terms of J-M_{rem} and K**
  - simplified coupled single-domain model
  - Describe fields sequences used to determine H_{sw} and write margin
  - Demonstrate
    - Toggle modes give best write margin
    - H_{sw} usually increases at small M_{rem}, large J
    - Margin usually decreases with increasing M_{rem}
    - Increasing K allows a larger M_{rem} bit to be written in toggle or direct modes

- **Generalized J-M_{rem} Switching Mode Diagram**
  - Toggle boundary related to J and uncompensated moment contributions to magnetic energy
  - Toggle and Direct modes best below the boundary
  - Conventional mode necessary above the boundary

Simulated Geometry



NiFe(4nm)/Ru/NiFe(t_2)

200 nm x 150 nm ellipse

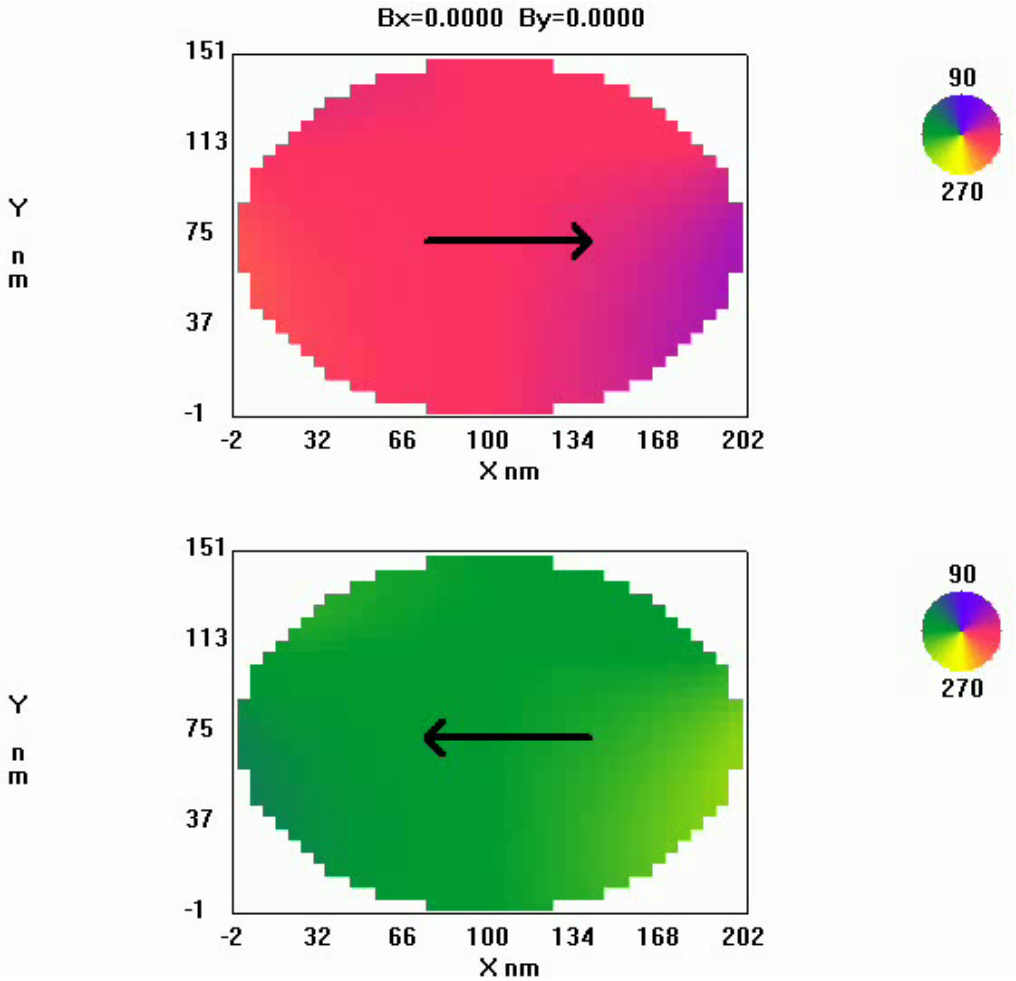
t_2 varied from 0 to 4 nm

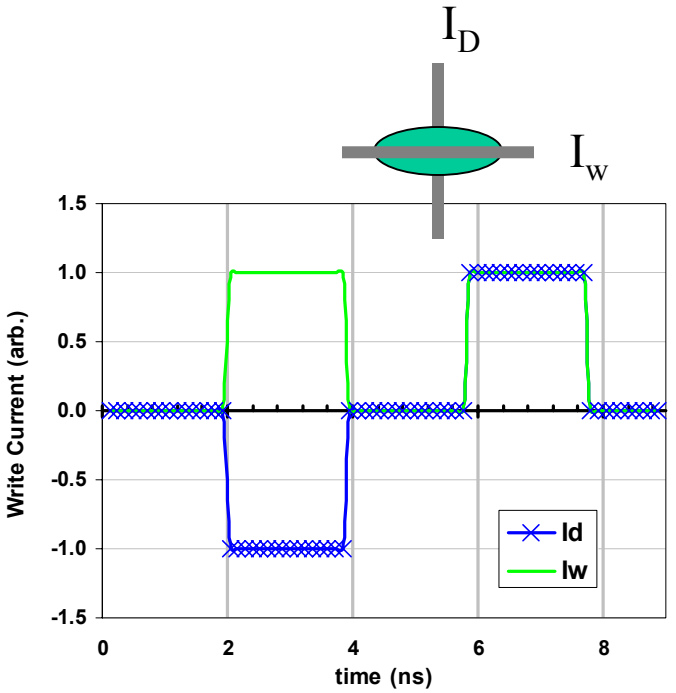
J varied from 0 to -0.5 mJ/m^2

Simulations performed using two techniques

1. Micromagnetics – LLG equation
2. Coupled single domains – Steepest descent solver

Conventional Write Mode

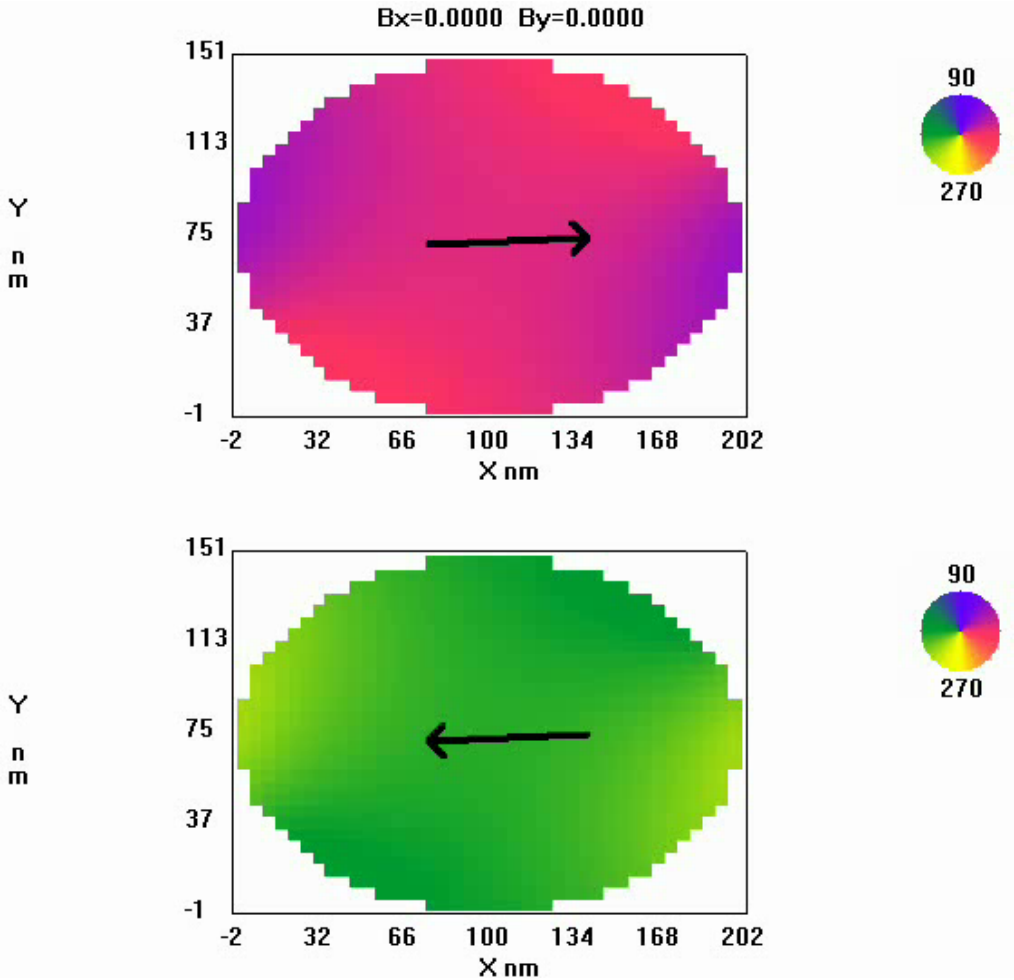


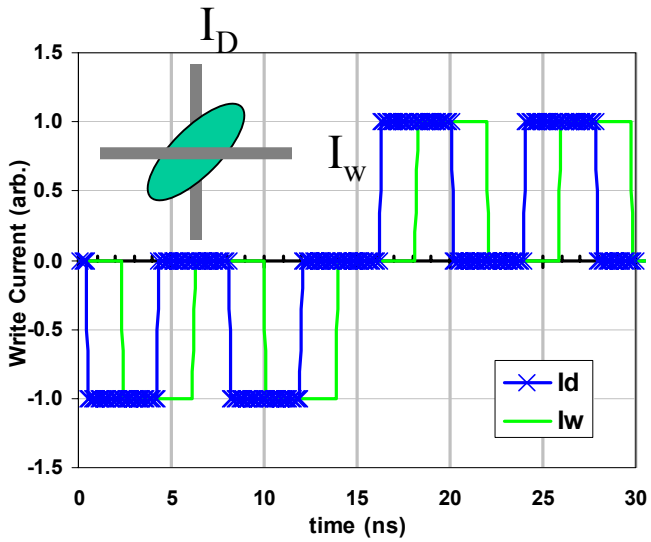


- Thick layer follows the total field
- $\phi_1+\phi_2 \approx \pi$

See file conventional_300%.avi

Direct Write Mode

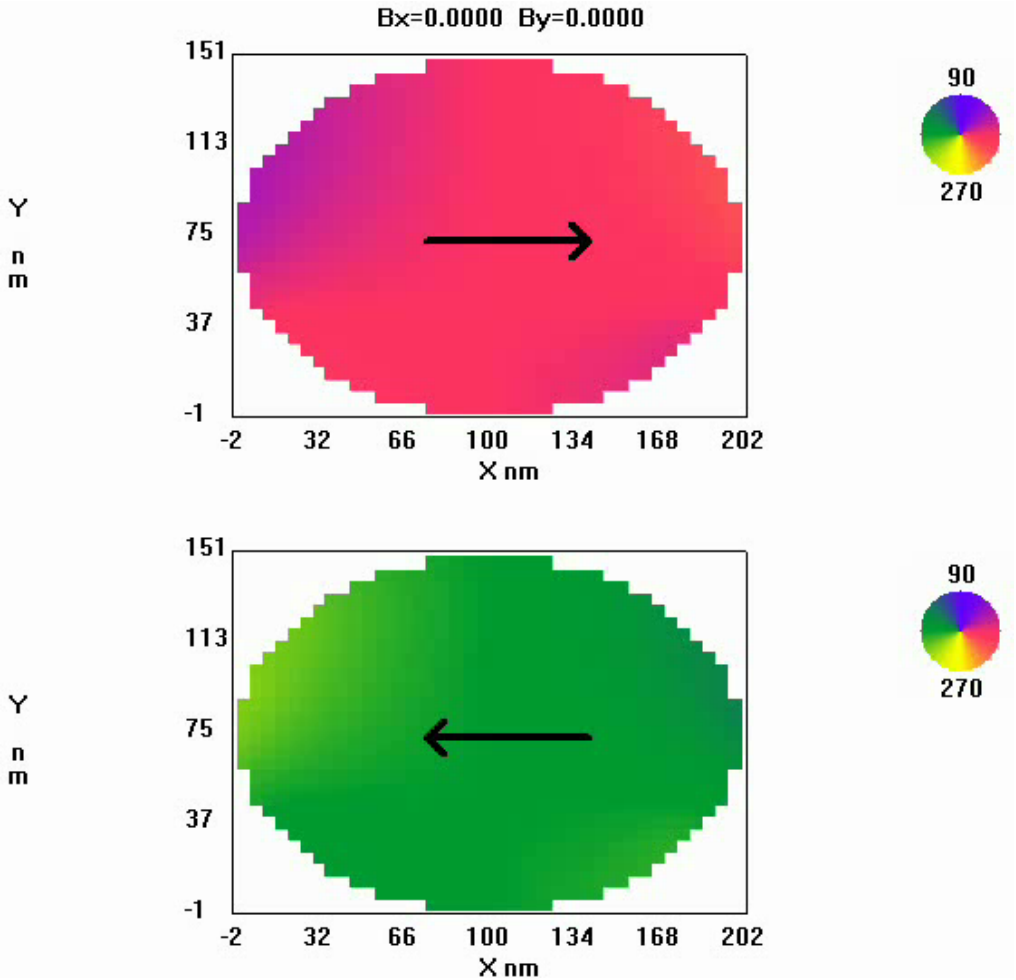


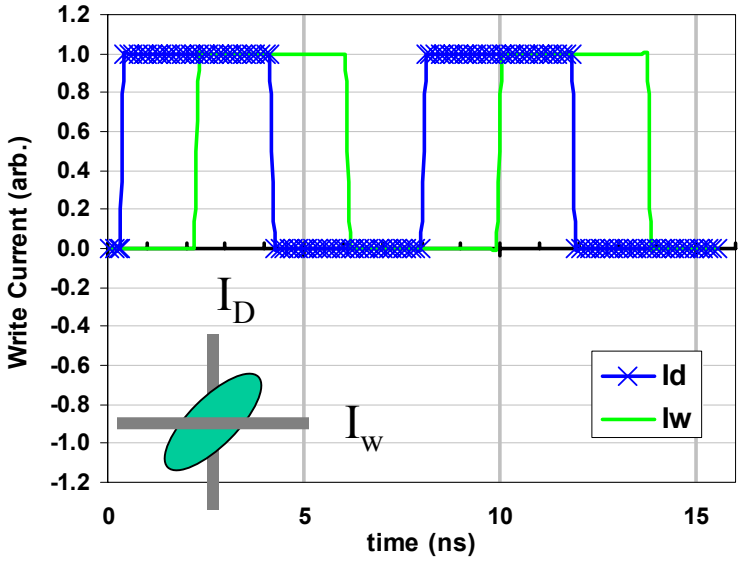


- Spin flop
- Bi-directional pulses required on at least 1 conductor

See file direct_example_300%.avi

Toggle Mode





- Spin flop
- unidirectional pulses

See file toggle_300%.avi

Single-Domain Simulation Method

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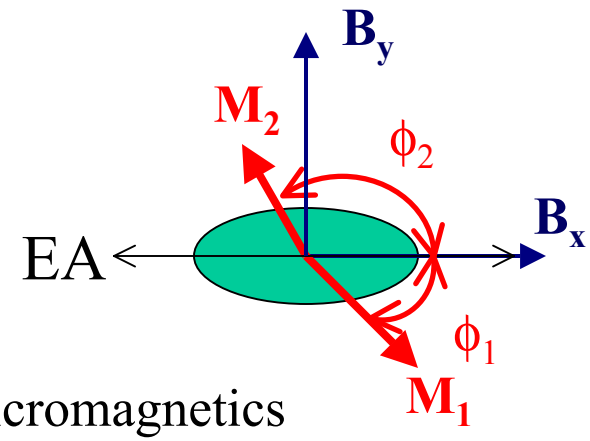
Synthetic AF stack

$FM_1(t_1,M_{s1},K_1)/Ru(J)/FM_2(t_2,M_{s2},K_2)$



Patterned into an elliptical plate

Demagnetization factors computed using micromagnetics

Steepest descent solver used to numerically minimize the energy

$$E_{tot}/A = E_z/A + E_{exc}/A + E_K/A + E_d/A + E_{di}/A$$

$$E_z/A = -B_x\left[M_{s1}t_1\cos(\varphi_1) + M_{s2}t_2\cos(\varphi_2)\right] - B_y\left[M_{s1}t_1\sin(\varphi_1) + M_{s2}t_2\sin(\varphi_2)\right]$$

$$E_{exc}/A = -J\cos(\varphi_1 - \varphi_2)$$

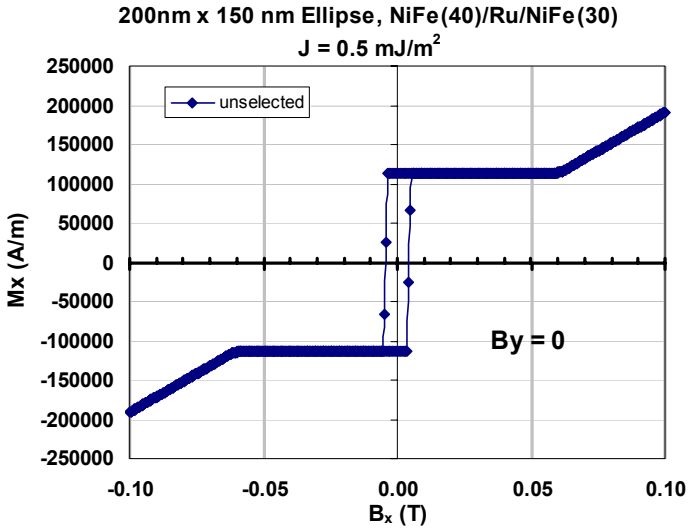
$$E_K/A = K_1t_1\sin^2(\varphi_1) + K_2t_2\sin^2(\varphi_2)$$

$$E_d/A = \frac{\mu_0 M_{s1}^2 t_1}{2}\left[N_{x1}\cos^2(\varphi_1) + N_{y1}\sin^2(\varphi_1)\right] + \frac{\mu_0 M_{s2}^2 t_2}{2}\left[N_{x2}\cos^2(\varphi_2) + N_{y2}\sin^2(\varphi_2)\right]$$

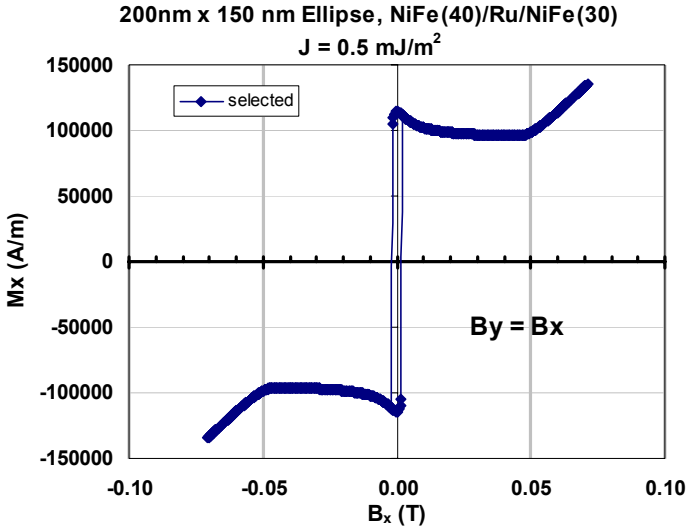
$$E_{di}/A = \frac{\mu_0 M_{s1} M_{s2}}{2}\left[(N_{x2}t_1 + N_{x1}t_2)\cos(\varphi_1)\cos(\varphi_2) + (N_{y2}t_1 + N_{y1}t_2)\sin(\varphi_1)\sin(\varphi_2)\right]$$

Conventional Mode Simulation

Compute unselected switching field, $H_{sw}(0)=H_c$



Compute selected switching field , $H_{sw}(H_y=H_x)$



Normalized margin defined as $[H_{sw}(0)-H_{sw}(H_y=H_x)]/ H_{sw}(0)$

Conventional J-M_{rem} Dependence

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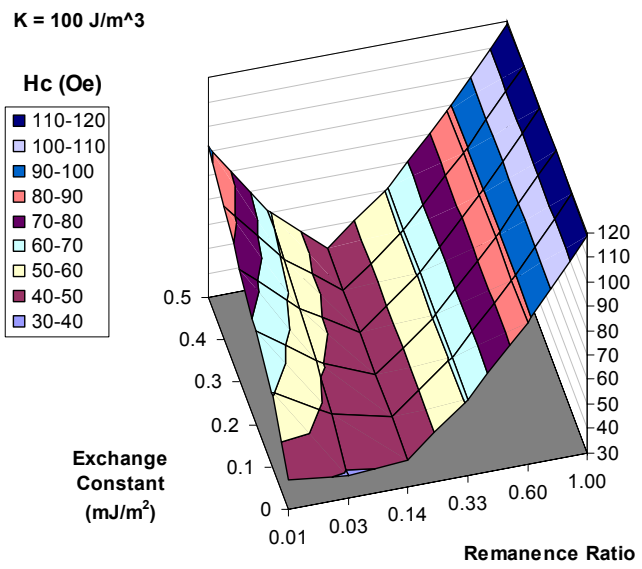
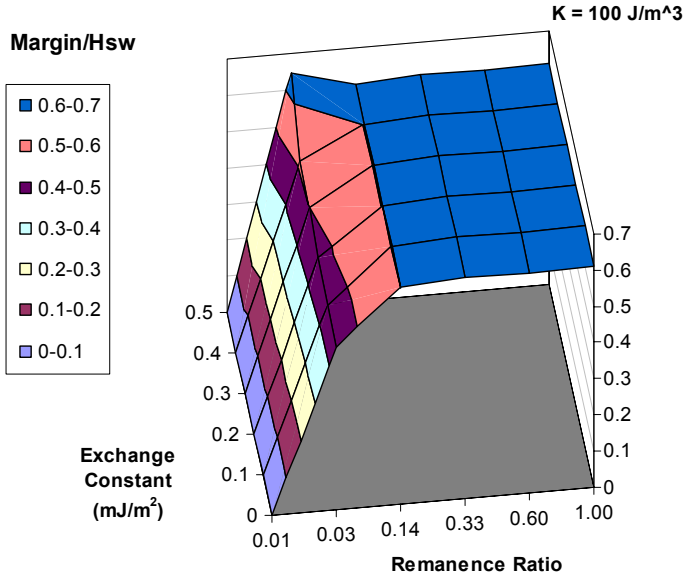
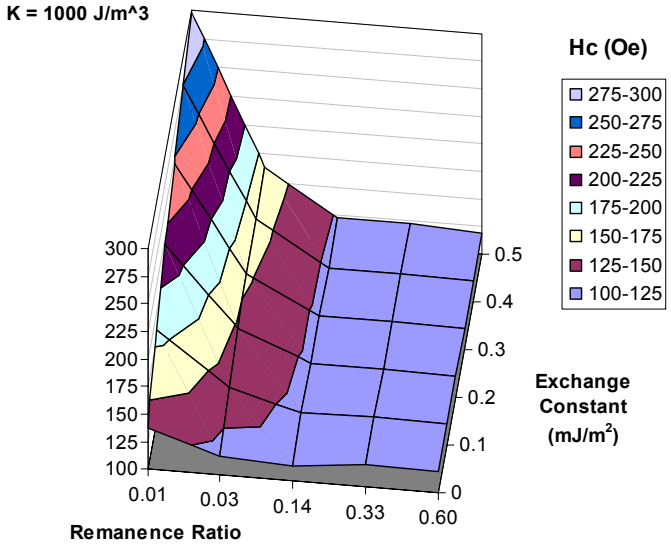
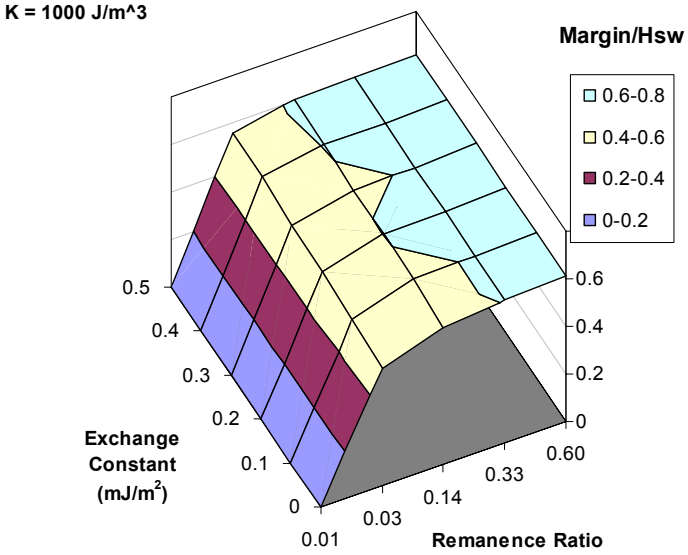
Low K





Higher K



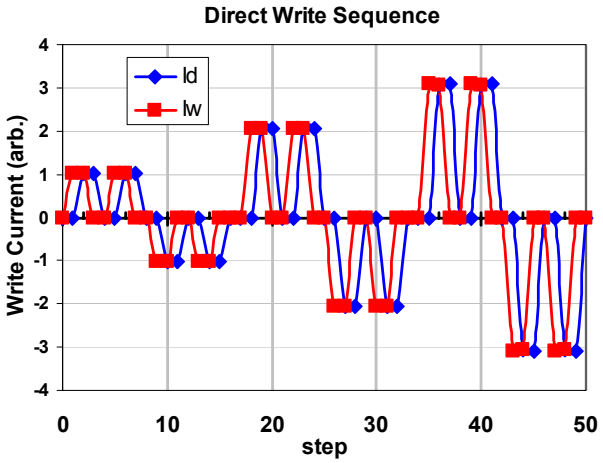


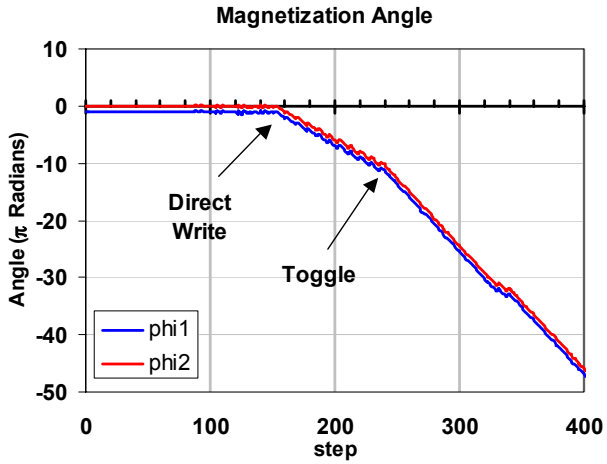
Switching Field

Write Margin

Direct Write Simulation

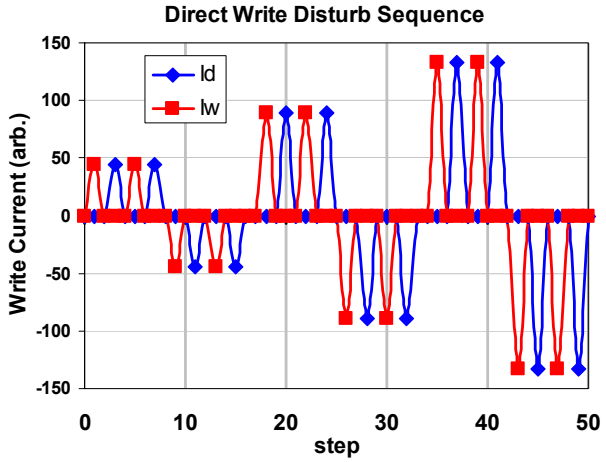
Write using ascending pulse sequence, monitor rotation angle

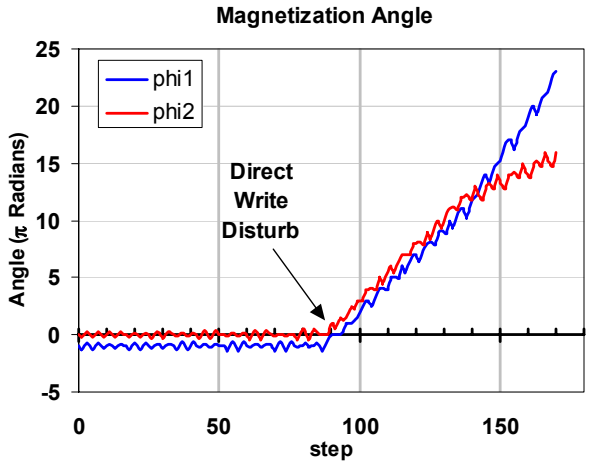




Test for disturb/error with ascending pulse sequence, monitor rotation angle

Normalized Margin = $\min\{(H_{toggle}-H_{dw})/H_{dw}\ ,\ (H_{disturb}-H_{dw})/H_{dw}\}$





Direct Write J-M_{rem} Dependence

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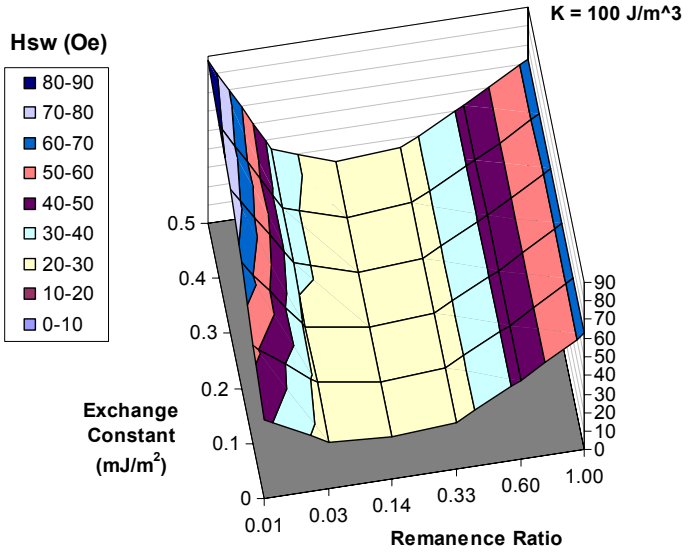
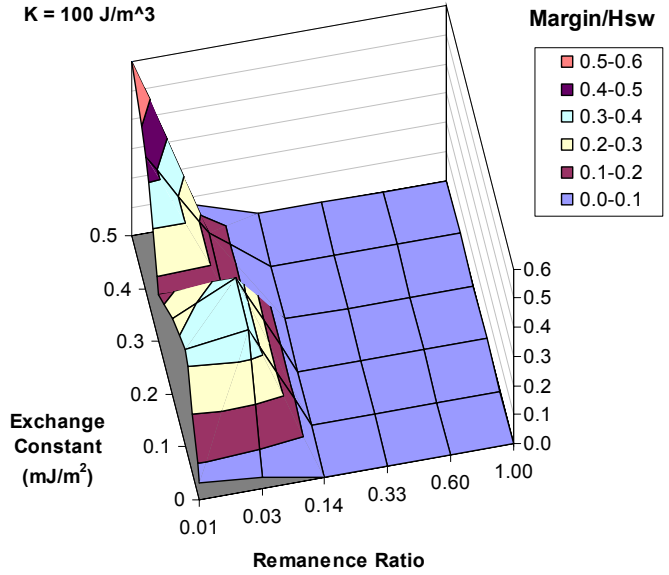
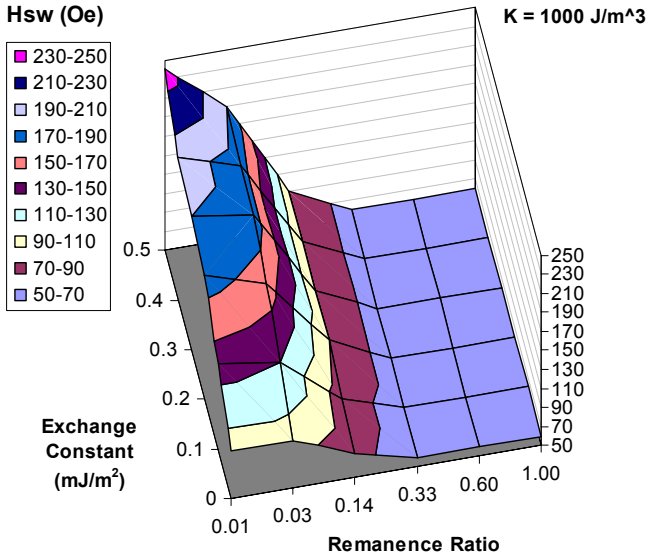
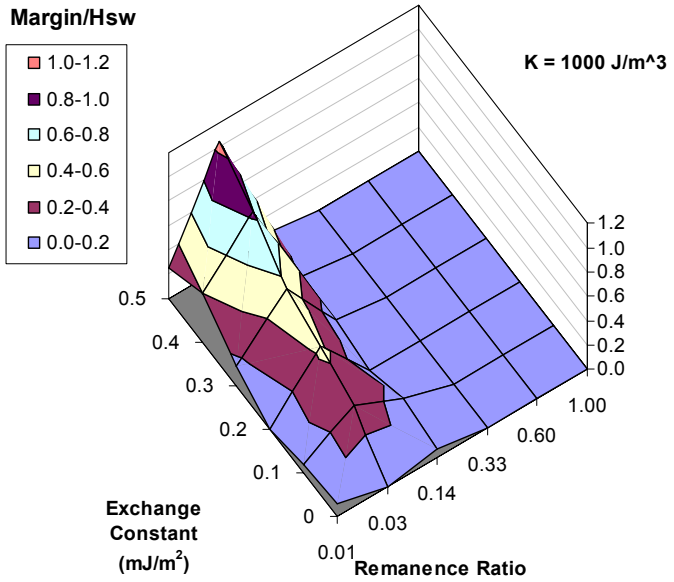
Low K





Higher K



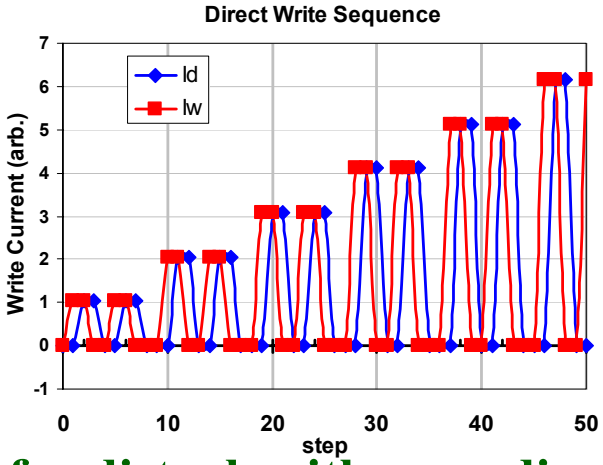


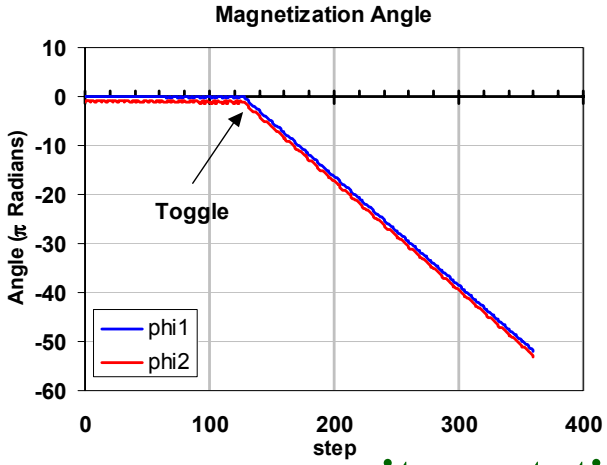
Switching Field

Write Margin

Toggle Write Mode Simulation

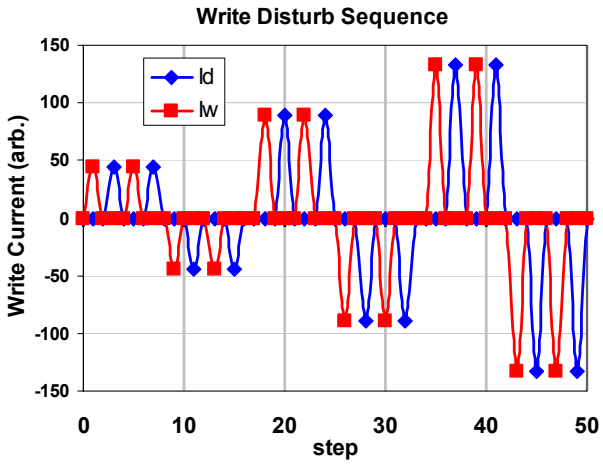
Write using ascending pulse sequence, monitor rotation angle

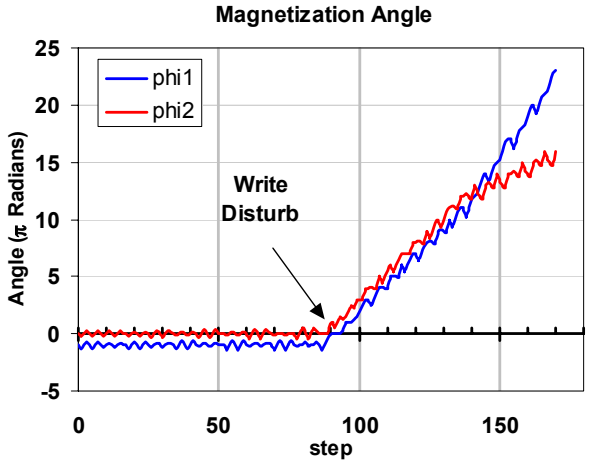




Test for disturb with ascending pulse sequence, monitor rotation angle

Normalized Margin = $(H_{disturb}-H_{toggle})/H_{toggle}$

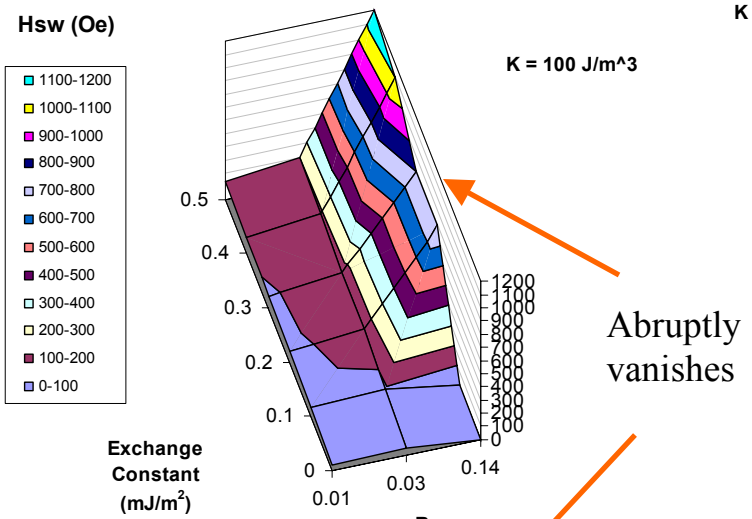




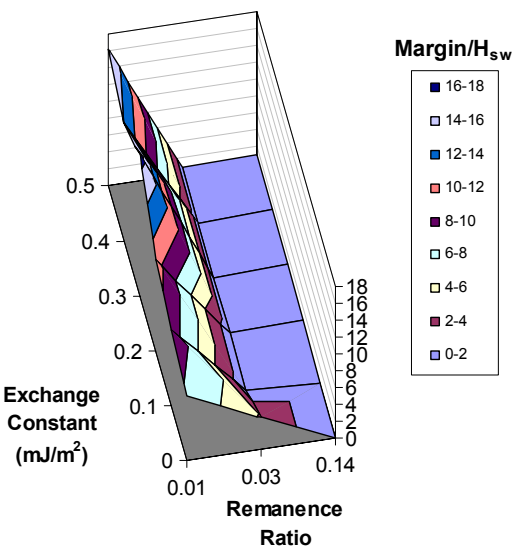
Toggle Write J-M_{rem} Dependence

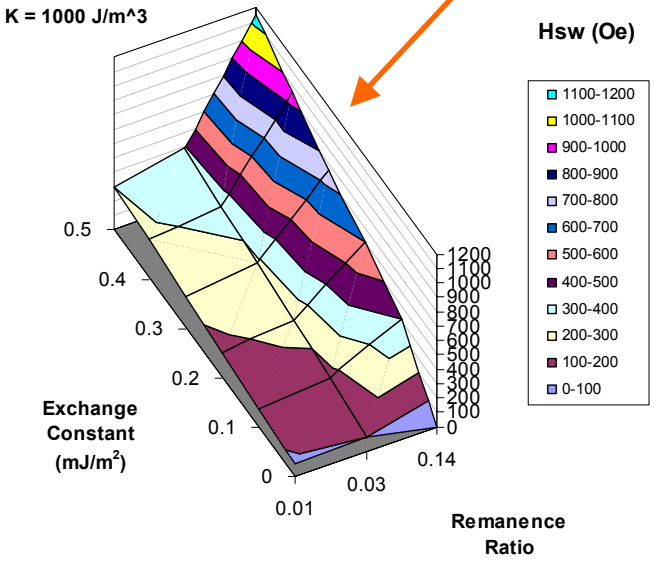
Low K

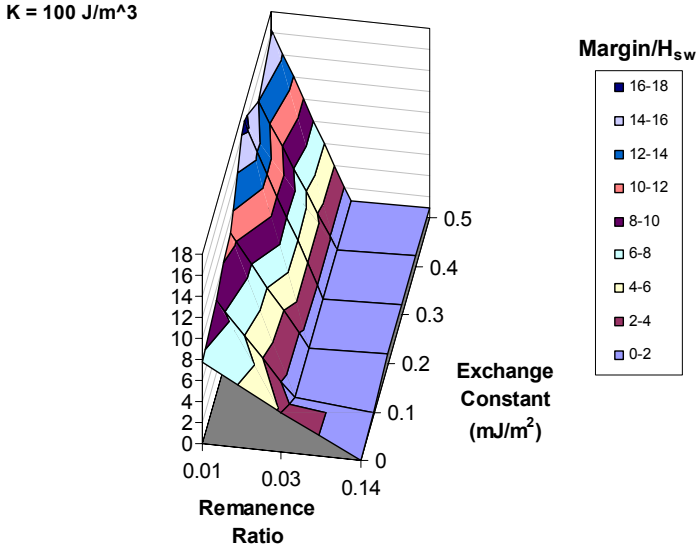
Higher K



Abruptly vanishes



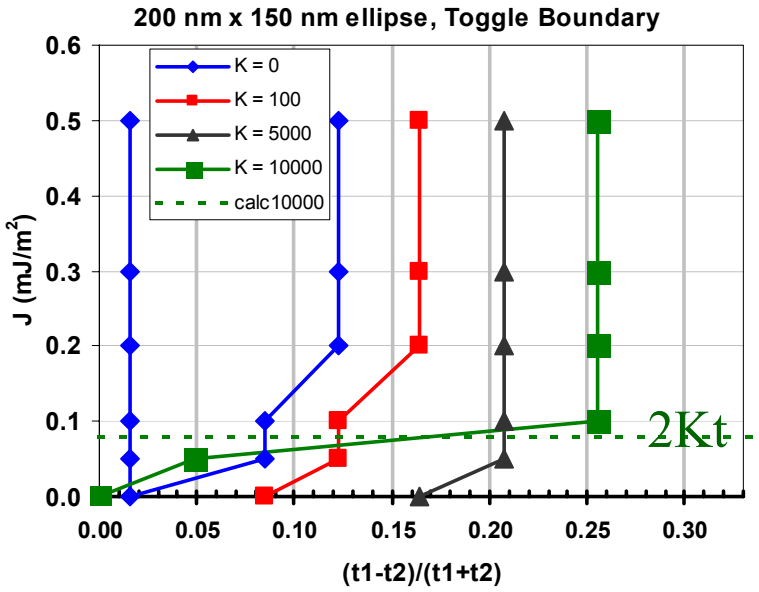


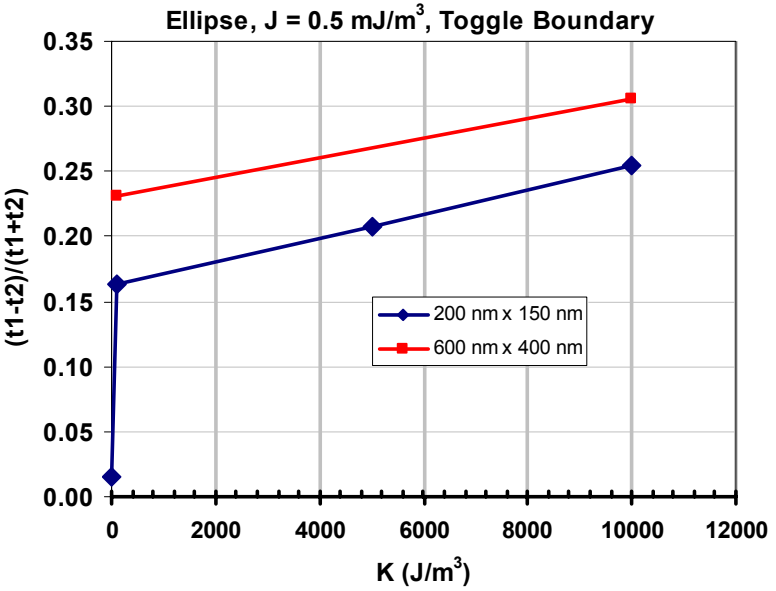


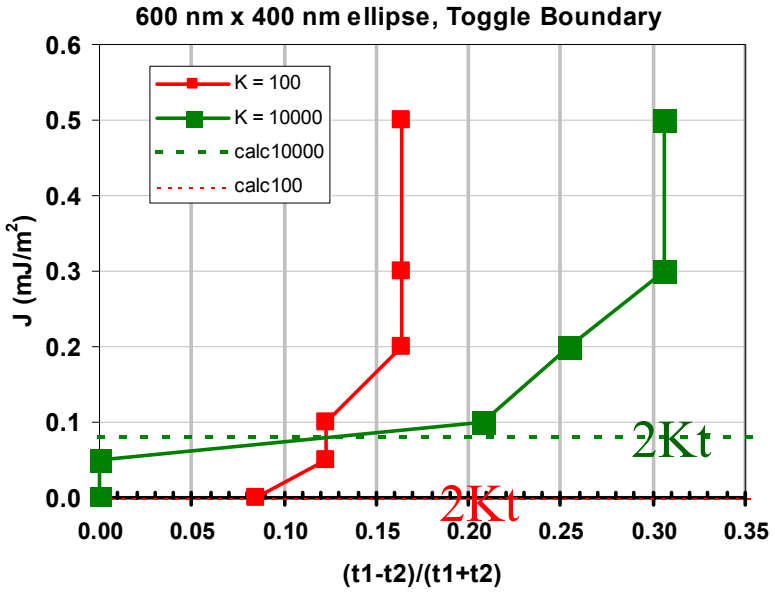
Switching Field

Write Margin

Toggle Boundary







- Maximum $(t_1-t_2)/(t_1+t_2)$ independent of J, increases with increasing K
- Minimum J increases with increasing K

Toggle Boundary Rough Analysis

- **Vertical Portion → $E_J = E_z$**

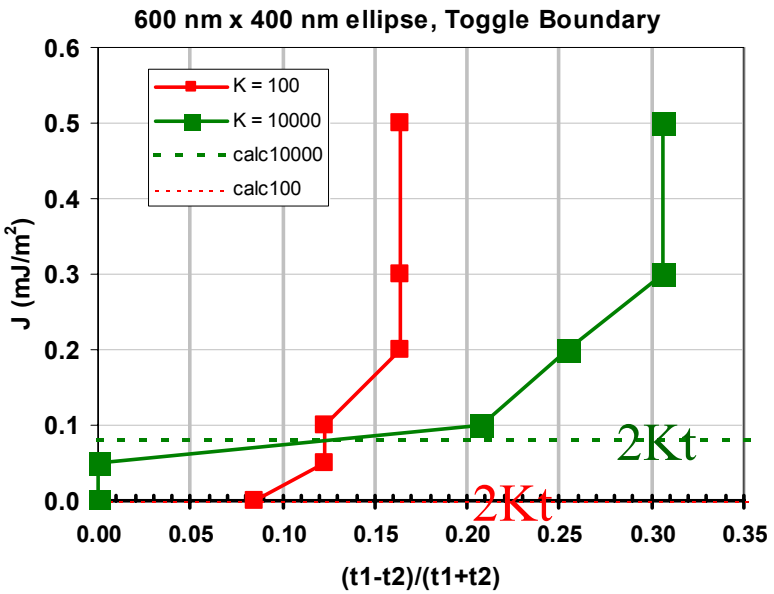
$J=\mu_0 H M_s (t_1-t_2)$ $\qquad H < H_{sat} = \dfrac{4J}{M_s(t_1+t_2)}$

$$J = \mu_0 \frac{4J}{M_s(t_1+t_2)} M_s |t_1 - t_2|$$

$$\rightarrow \quad \frac{|t_1 - t_2|}{(t_1+t_2)_{max}} \sim \frac{1}{4}$$

- **Horizontal Portion →$E_J=E_k$**

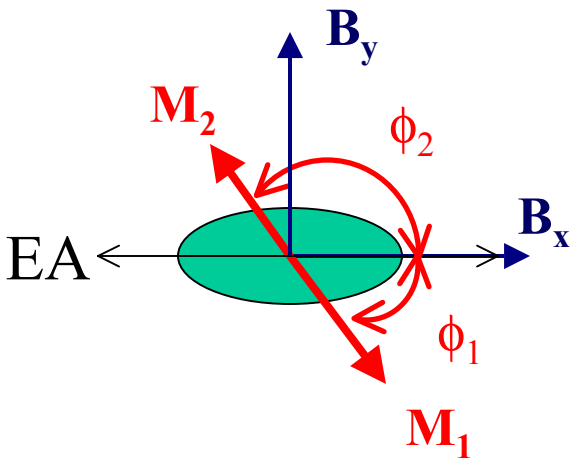
$J = K(t_1+t_2) \sim 2Kt$



Conventional Switching Field

Assume J large so that $\phi_1+\phi_2 \approx \pi$

$$E_{tot}/Area \approx B_y M_s (t_2 - t_1)\sin\varphi + B_x M_s (t_2 - t_1)\cos\varphi + K(t_1 + t_2)\sin^2\varphi + \frac{M_s^2}{2}\left[(n_{y1} - n_{x1})(t_1 - t_2) + (n_{y2} - n_{x2})(t_2 - t_1)\right]\sin^2\varphi$$



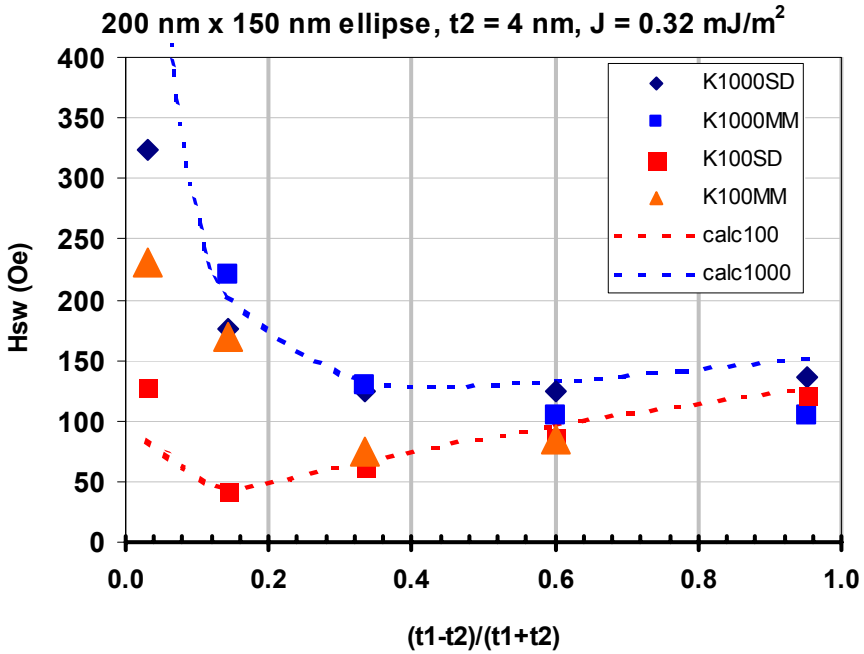
Solve $dE/d\phi = 0$

$d^2E/d\phi^2 = 0$

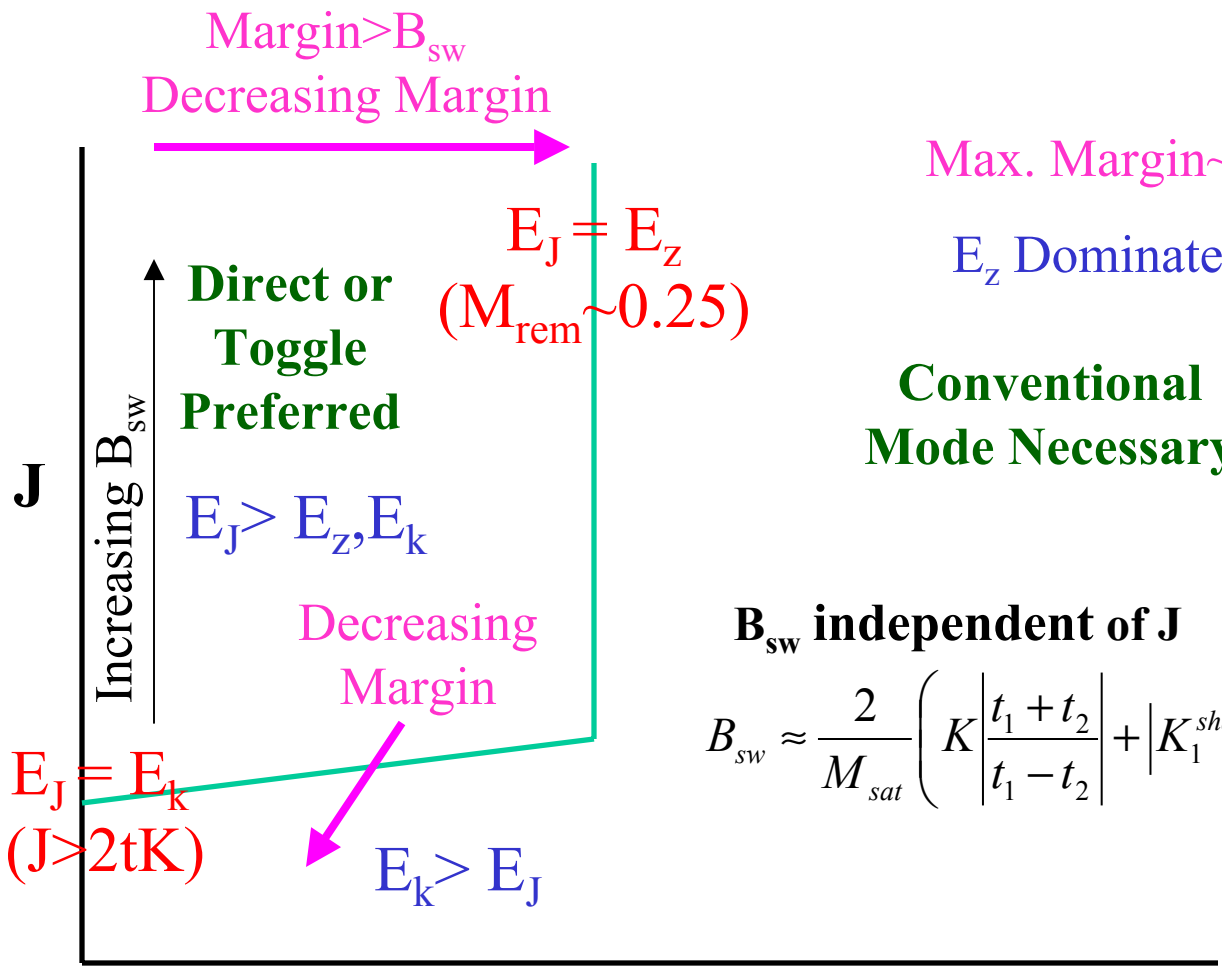
Yields ($B_y = 0$)

$$B_{sw} \approx \frac{2}{M_{sat}}\left(K\left|\frac{t_1 + t_2}{t_1 - t_2}\right| + \left|K_1^{shape} - K_2^{shape}\right|\right)$$

Consistent with numerical results



Generalized Switching Mode Diagram



Max. Margin~0.5B_{sw}

E_z Dominates

Conventional Mode Necessary

B_{sw} independent of J

$$B_{sw} \approx \frac{2}{M_{sat}}\left(K\left|\frac{t_1+t_2}{t_1-t_2}\right| + \left|K_1^{shape} - K_2^{shape}\right|\right)$$

$M_{rem} = |t_1-t_2|/(t_1-t_2)$

Direct Write Summary

- Due to overlap with toggle mode, margin not much better than the conventional write mode
- Increasing remanence ratio decreases margin
- Increasing J increases margin and write field

Toggle Mode Summary

- Switching field increases with increasing J, remanence ratio, and K
- Margin can be very high but falls to zero well below the maximum toggle field