Dynamic Verilog-A Model of a Magnetoresistive Spin Valve

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Outline

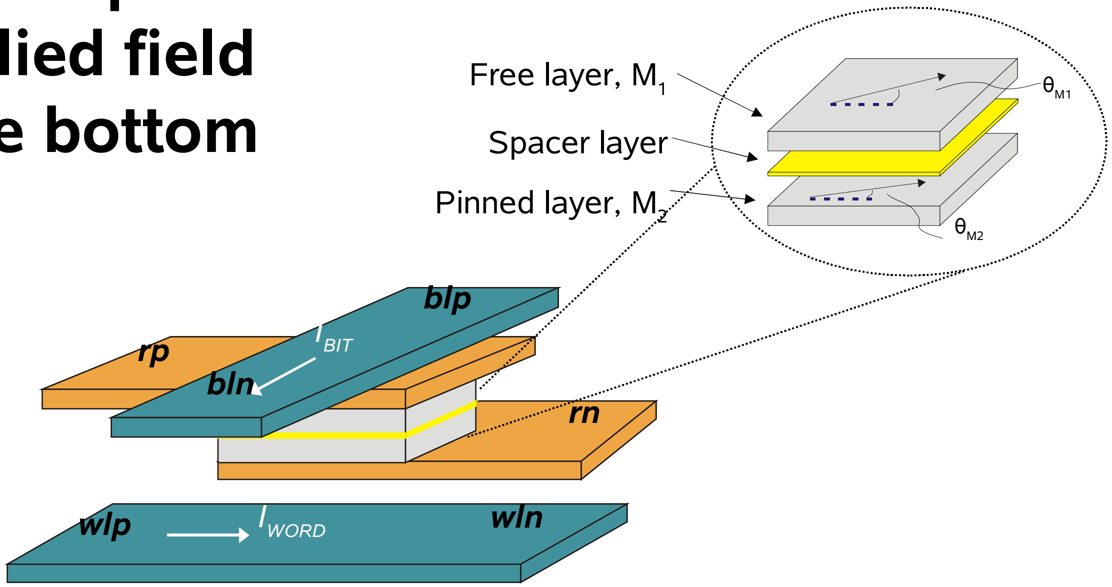
1. **Motivation**
2. **Spin Valve description**
3. **Magnetostatics and dynamics**
4. **Verilog-A**
5. **Results**
6. **Conclusion and Future Work**

Why Model Spintronic Devices?

- **Spintronic devices (GMR spin valves) are currently used in many different kinds of sensors**
  - •Magnetic RAM
  - •Pacemakers and hearing aids
  - •Missile guidance
  - •Read sensors in hard disk drives
  - •Fuel, antiskid, and engine control
  - •Position and motion sensing
- **Need for Interfacing magnetic devices with their control logic in system-level circuit simulations.**
- **Spintronic devices work better as they get smaller – promising future….**

Spin Valve description

- Inner M/NM/M sandwich, with a "pinned" or fixed magnetization on bottom M layer.
- Magnetization angle of top layer rotates with applied field from conductors while bottom layer is fixed.
- Output resistance depends on the relative orientation of the magnetic layers.



Magnetoresistance

Magnetoresistance is lowest when the layers are magnetized in the same direction and highest when magnetized oppositely.

Resistance is described by the function:

$$R = R_{MIN} + \frac{1}{2}\left(R_{MAX} - R_{MIN}\right) \cdot \underline{\left(1 - \cos\left(\theta_{M1} - \theta_{M2}\right)\right)}$$

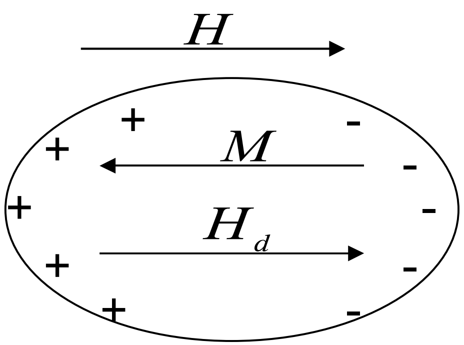
The magnetoresistance is sensed by applying a voltage across rp and rn and measuring the current through the layers.

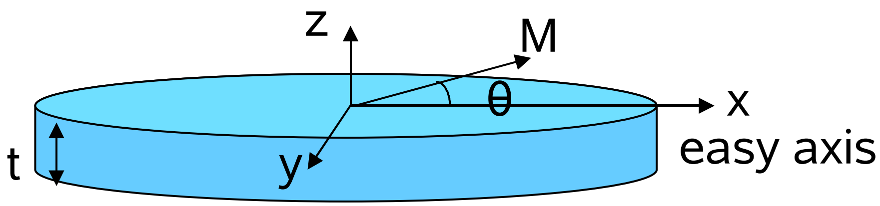
Magnetic Anisotropy (shape)

$$H_{\text{int}} = H + H_d = H - NM$$

$$H_d = -N_X M_X \hat{i} - N_Y M_Y \hat{j} - N_Z M_Z \hat{k}$$

$$M_X = M_S \cos\theta \qquad M_Y = M_S \sin\theta$$



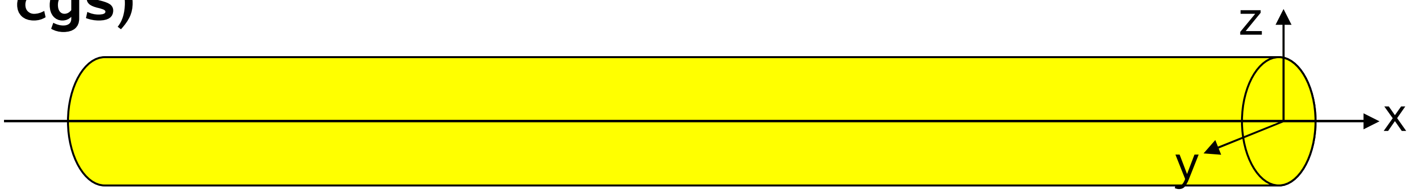


$$E = -MV \cdot B$$

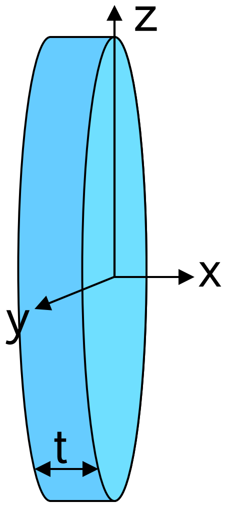
Anisotropy indicates that certain directions of magnetization are energetically more favorable than others. These are called "Easy axes".

Examples of Demagnetization Factors

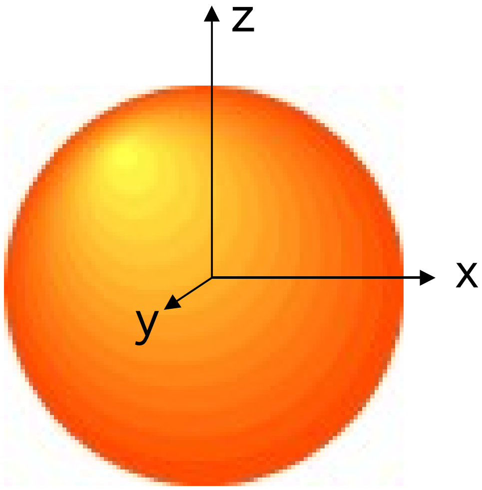
- **Demagnetization factors in x,y, and z must sum to 1 (4π in cgs)**



Long, narrow cylindrical rod: N_X=0, N_Y=N_Z=1/2



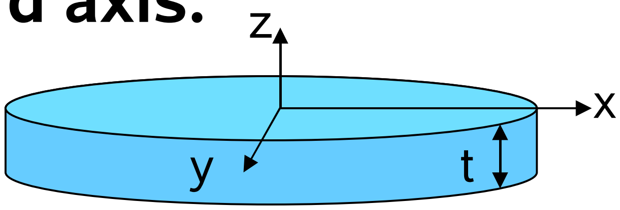
Thin, cylindrical volume z,y>>t N_Y= N_Z=0, but N_X=1

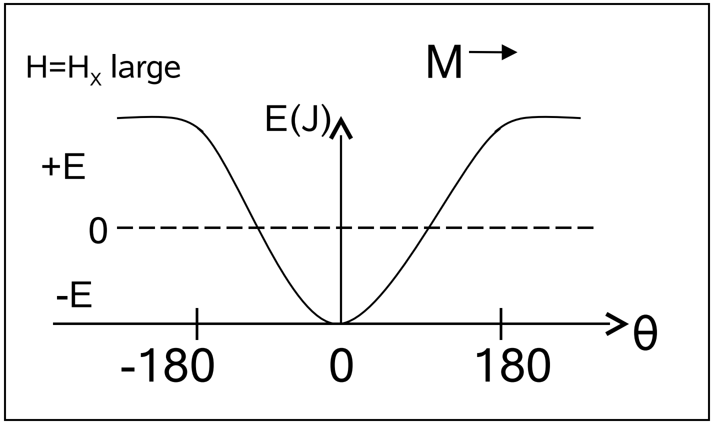


A sphere has no Shape anisotropy. N_X= N_Y=N_Z=1/3

Magnetic Anisotropy (shape)

- The film normal, $\hat{z}$,is the magnetic hard axis.
- The shape anisotropy forces the magnetization to lie in the plane of the film along the easy (longer) axis.
- Shape anisotropy minimizes magnetostatic energy (only one minimum for large, positive applied field).



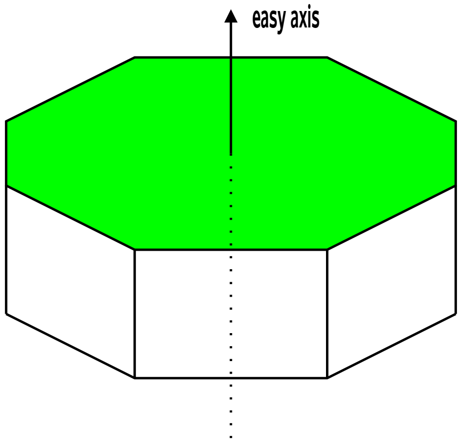


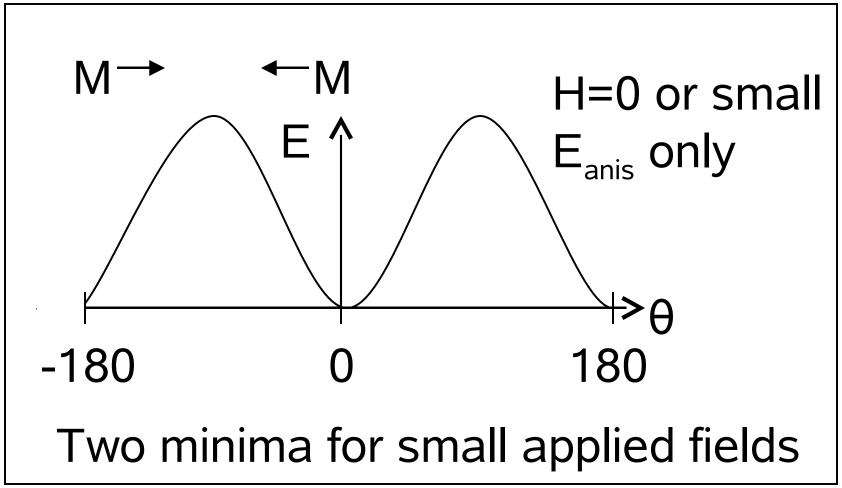
$$E_{shape} = -\mu_0 V M_S \cdot \left[H_X \cos\theta + H_Y \sin\theta \right]$$

Magnetic Anisotropy
(Uniaxial Crystalline Anisotropy)

- **Indicative of a crystalline structure that has a preferred direction (like a hexagonal crystal).**
- **The crystalline anisotropy for a given material is a measured value, K_u (J/m³).**

$$E_{anis} = K_u \sin^2 \theta$$





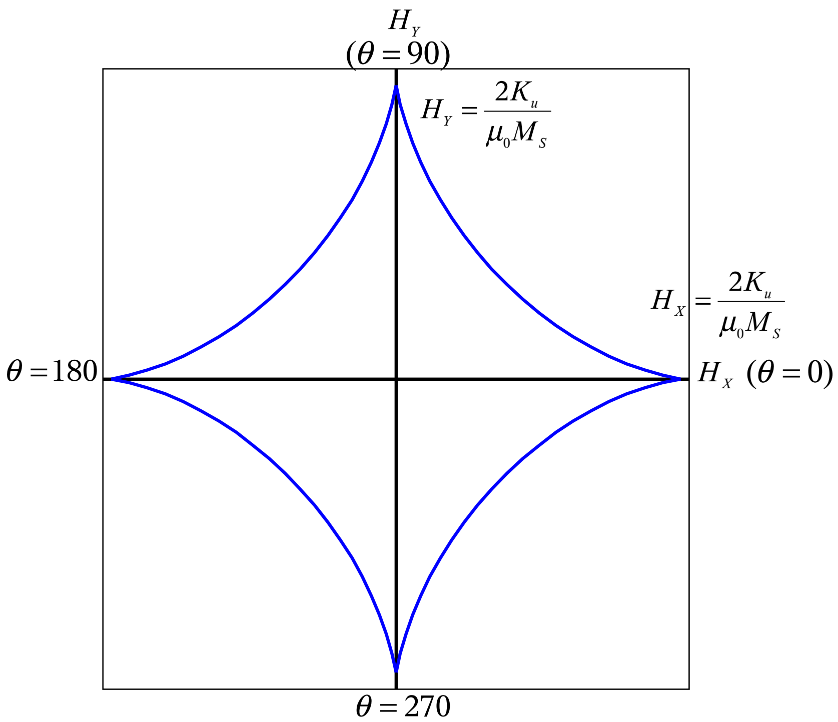
Magnetostatics/Anisotropy Summary

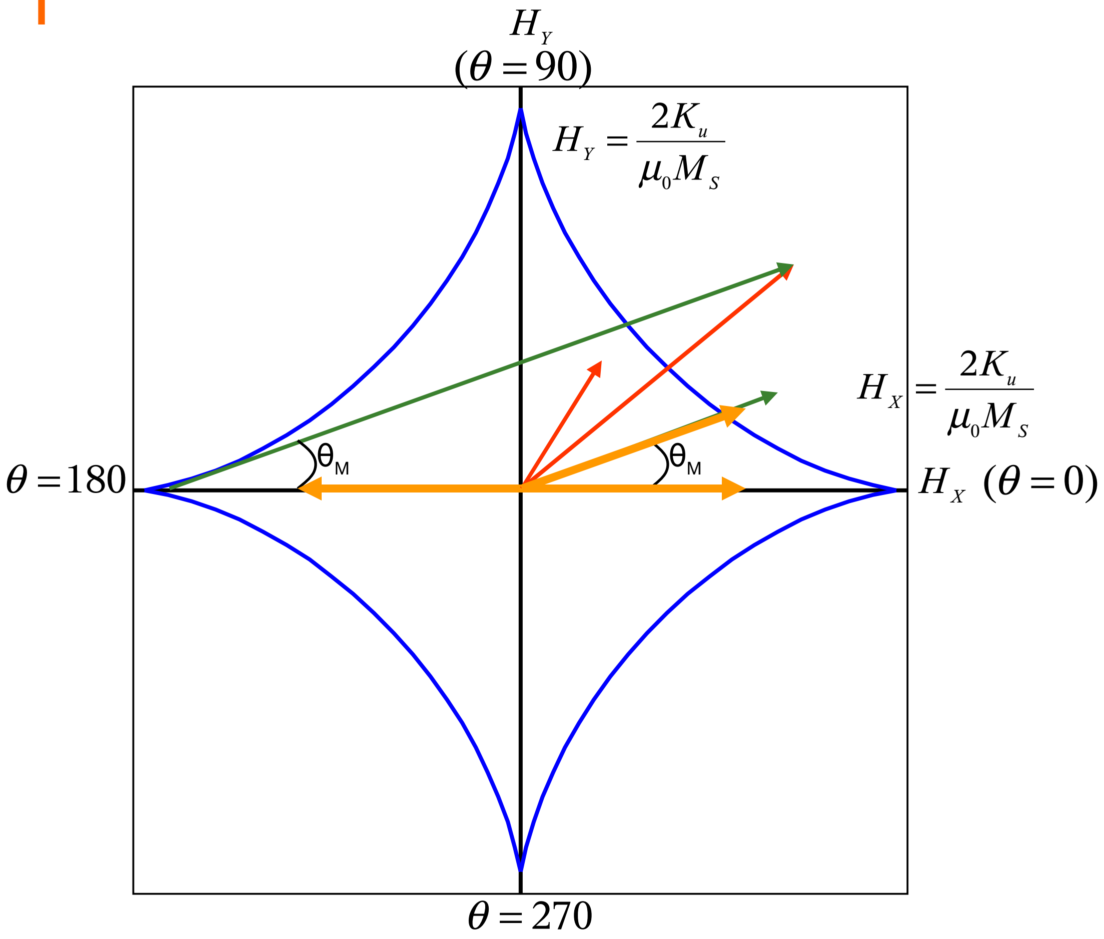
- **Shape anisotropy minimizes magnetostatic energy by coercing the direction of magnetization according to the shape of the material volume.**
- **Uniaxial anisotropy defines the preferred direction of magnetization due to the crystalline structure of the material.**
- **These two anisotropy terms are the major energy/torque contributors to the bistable (M→, ←M) operation of the spinvalve.**

Magnetic Switching: Stoner-Wohlfarth switching (Magnetostatic)

- **Uniformly magnetized, single domain particles.**
- **Switching by rotation of magnetization (coherent reversal).**
- **Two stable states M$\rightarrow$, $\leftarrow$ M**
- **.**
- **The astroid is the solution to the energy minima** $\frac{d^2E}{d\theta^2} = 0$

$$\left(H_X\right)^{\frac{3}{2}} + \left(H_Y\right)^{\frac{3}{2}} = \left[\frac{2K_u}{\mu_0 M_S}\right]^{\frac{3}{2}}$$

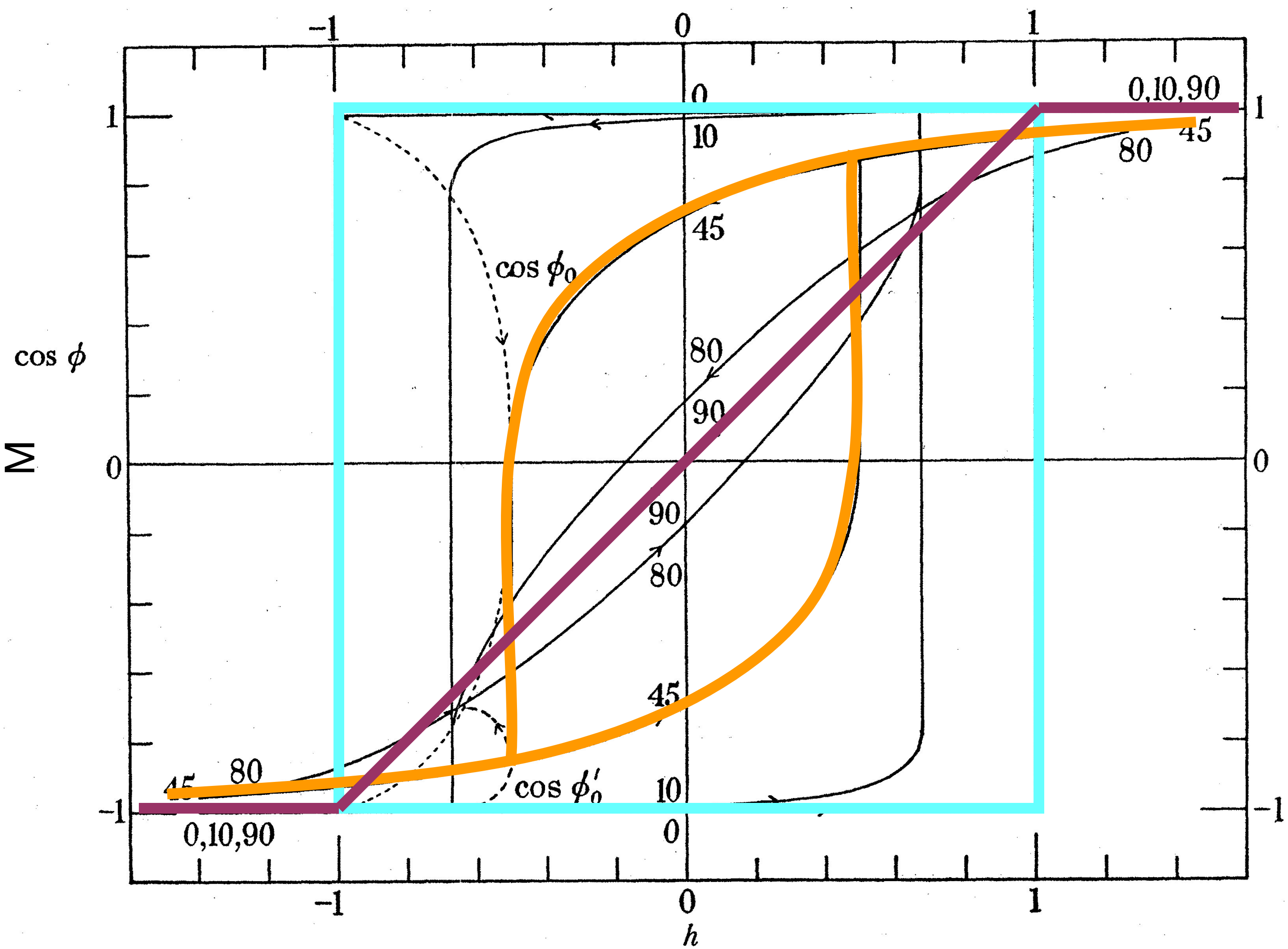




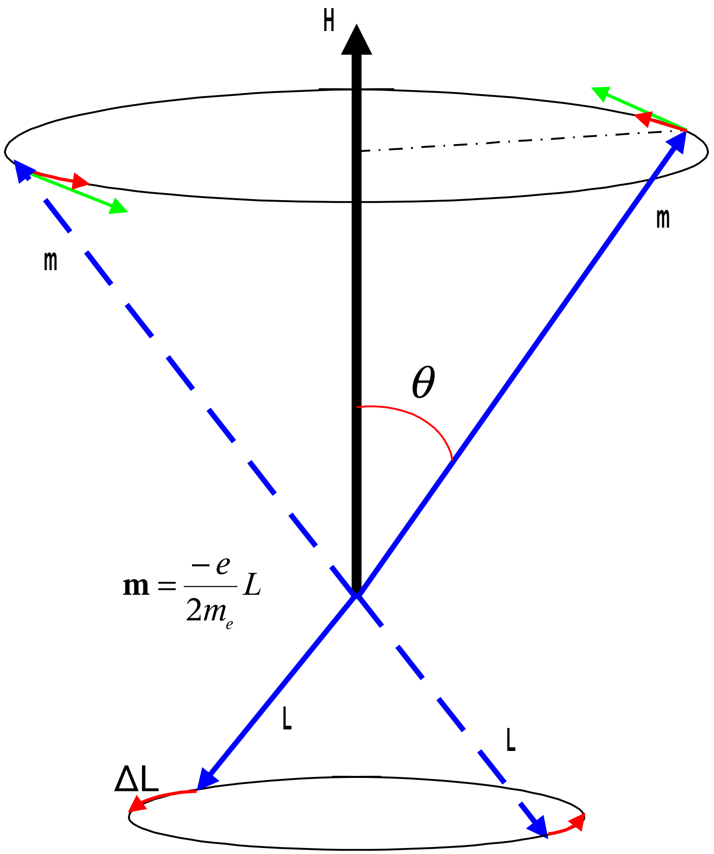
Field points inside the Astroid do not overcome the domain's magnetostatic energy.

Field points outside the Astroid overcome the magnetostatic energy of the domain and switch the magnetization.

Classic S-W Hysteresis Loops



Magnetization Dynamics
Magnetic Precession



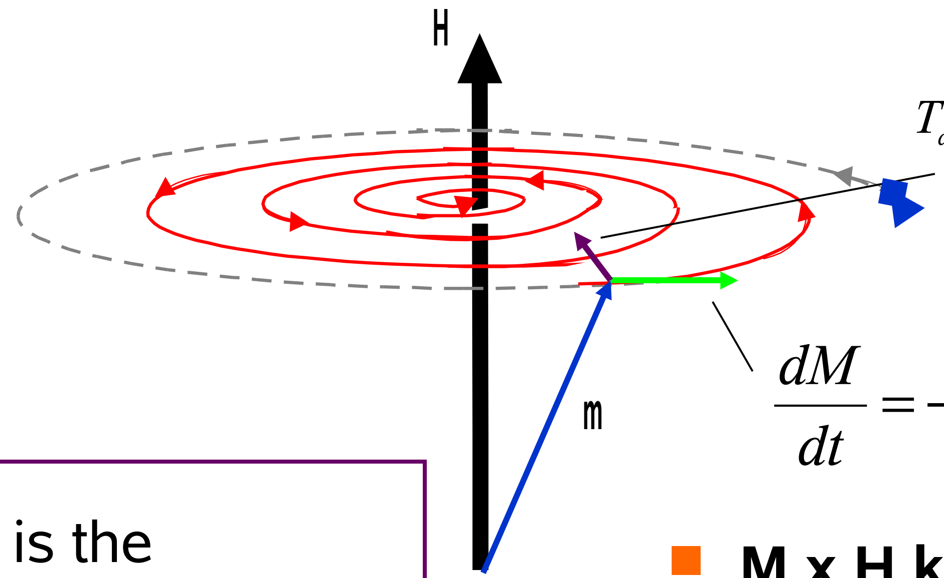
Magnetic moment, $\mathbf{m}$, in a magnetic field, B, experiences a torque: $\tau = \mathbf{m} \times B$

The torque produces a change in the angular momentum which is perpendicular to L (shown as ΔL).

This causes m to precess around the direction of the magnetic field (called Larmor precession)

α is the Gilbert damping parameter

- **Damping causes the magnetization to precess and simultaneously relax toward the field.**



$$T_{damp} = -\frac{\alpha}{|M|}\left(M \times \frac{dM}{dt}\right)$$

$$\frac{dM}{dt} = -\gamma\mu_0 M \times H = -\gamma T$$

Gamma is the gyromagnetic ratio,

$$\gamma = \frac{\mathbf{m}}{L}$$

- **M x H keeps the same vector length, but without damping, M will precess without turning towards H. This is the gyromagnetic term due to H.**

Magnetodynamics

- **The dynamic response of the small magnetic free layer then is described by the Landau-Lifshitz-Gilbert (LLG) equation:**

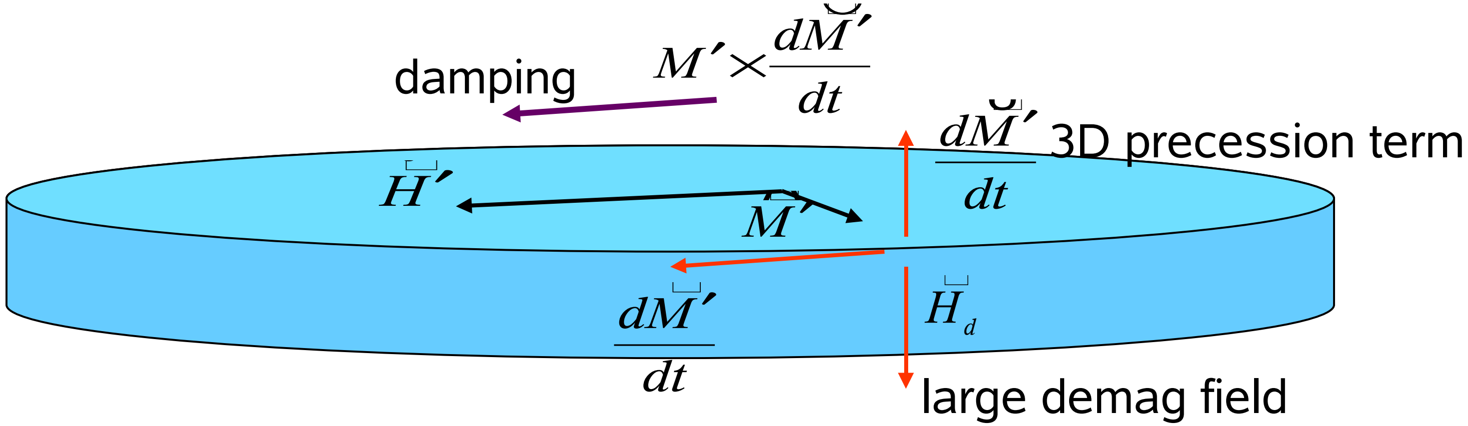
$$\frac{d\vec{M}}{dt} = \mu_0 \gamma \cdot \vec{M} \times \vec{H} - \frac{\alpha}{|\vec{M}|} \vec{M} \times \frac{d\vec{M}}{dt}$$

- **For thin films, shape anisotropy forces the magnetic moment to lie in the plane of the film so that $\vec{M}$ and $\vec{H}$ may be considered two-dimensional.**

$$\vec{M}' = (M_X, M_Y) \qquad \vec{H}' = (H_X, H_Y)$$

Magnetodynamics

- **Precession pushes $\vec{M}$ out of the plane**
- **Demag field and damping bring $\vec{M}$ back into the plane**
- **Effectively, precession becomes a damping term proportional to $\frac{1}{\alpha}$ in the thin film limit.**
- **For a thin film the 3D precessional term, $\vec{M} \times \vec{H}$, becomes a 2D damping term.**



Magnetodynamics

- **The effective in-plane magnetization dynamic is**

$$\frac{d\vec{M}'}{dt} = -\mu_0\gamma\left(\alpha + \frac{1}{\alpha}\right)\vec{M}'\times\left(\vec{M}'\times\dot{\vec{H}}'\right)$$

- $\left|\vec{M}\right| \equiv M_S$ **and is constant.** $\vec{M}$ **is fully described by** θ_M**.**
The resultant torque for this term is due to $\frac{d\theta_M}{dt}$**:**

$$T_{damp} = -\frac{M_S}{\gamma\left(\alpha + \frac{1}{\alpha}\right)}\frac{d\theta_M}{dt}$$

Torques

- **The torque/vol. required to rotate the magnetization of the free layer in the direction of the applied field:**

$$Torque_{EXT} = \frac{d(E/V)}{d\theta} = \mu_0 M_S \left(H_Y \cos\theta_M - H_X \sin\theta_M\right)$$

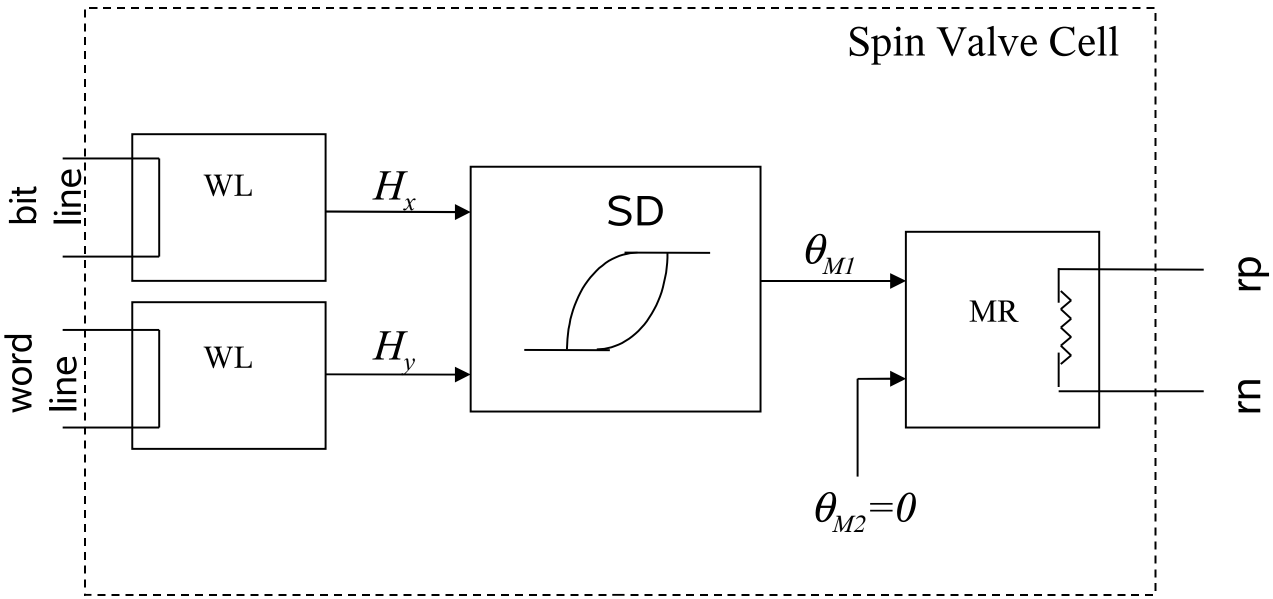
- **The torque/vol. required to rotate the magnetization of the free layer away from its axis of preferred crystalline direction:**

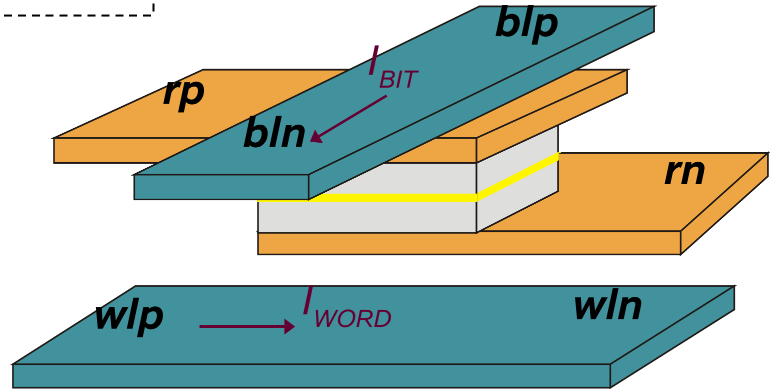
$$Torque_{ANIS} = -K_u \sin(2\theta_M)$$

- **The damping torque/vol. for precession of the magnetization of the free layer in the plane:**

$$T_{damp} = -\frac{M_S}{\gamma\left(\alpha + \frac{1}{\alpha}\right)} \frac{d\theta_M}{dt}$$

Spin Valve Model Diagram





Single Domain Model

- **Verilog-A Code allows definition of non-electrical variables "*disciplines*" that have a particular "*nature*".**

```
nature Magnetic_Field
    units = "A/m" ;
    access = H ;
    abstol = 1p ;
endnature

discipline sig_flow_H        // signal-flow discipline
        potential Magnetic_Field ;
enddiscipline
```

Listing 2. Single Domain module

```
`define P_gamma 1.76e11   //Gyromagnetic constant [Hz/tesla]

module single_domain(hx, hy, M) ;
input hx, hy ;      // magnetic field vector components
inout M ;           // magnetization angle and torque
sig_flow_H hx, hy ;
rotational M ;

parameter real Ms = 8e5;     // saturation magnetization [A/m]
parameter real Ku = 500;     // uniaxial anisotropy [J/m^3]
parameter real alpha = 0.1;  // LLG damping factor [unitless]

analog begin
  // torque due to external field (shape anisotropy):
      Tau(M) <+ -`P_U0*Ms*(H(hx)*sin(Theta(M))-H(hy)*cos(Theta(M)));

  // anisotropy:
      Tau(M) <+ -Ku*sin(2*Theta(M)) ;

  //damping torque:
      Tau(M) <+ -ddt(Theta(M))* Ms/((alpha+1/alpha)*`P_gamma);
end
endmodule
```

Writeline Model

Listing 1. Write Line module

```
module writeline(wlp,wln,hy);
inout wlp, wln;
output hy;
electrical wlp, wln;
sig_flow_H hy;

parameter real W = 1.0u;     // write line width [m]
parameter real R = 0;        // line resistance [ohms]

analog begin
    V(wlp,wln) <+ R*I(wlp,wln);
    H(hy) <+ I(wlp,wln)/(2*W);          // H = I / 2w
end
endmodule
```

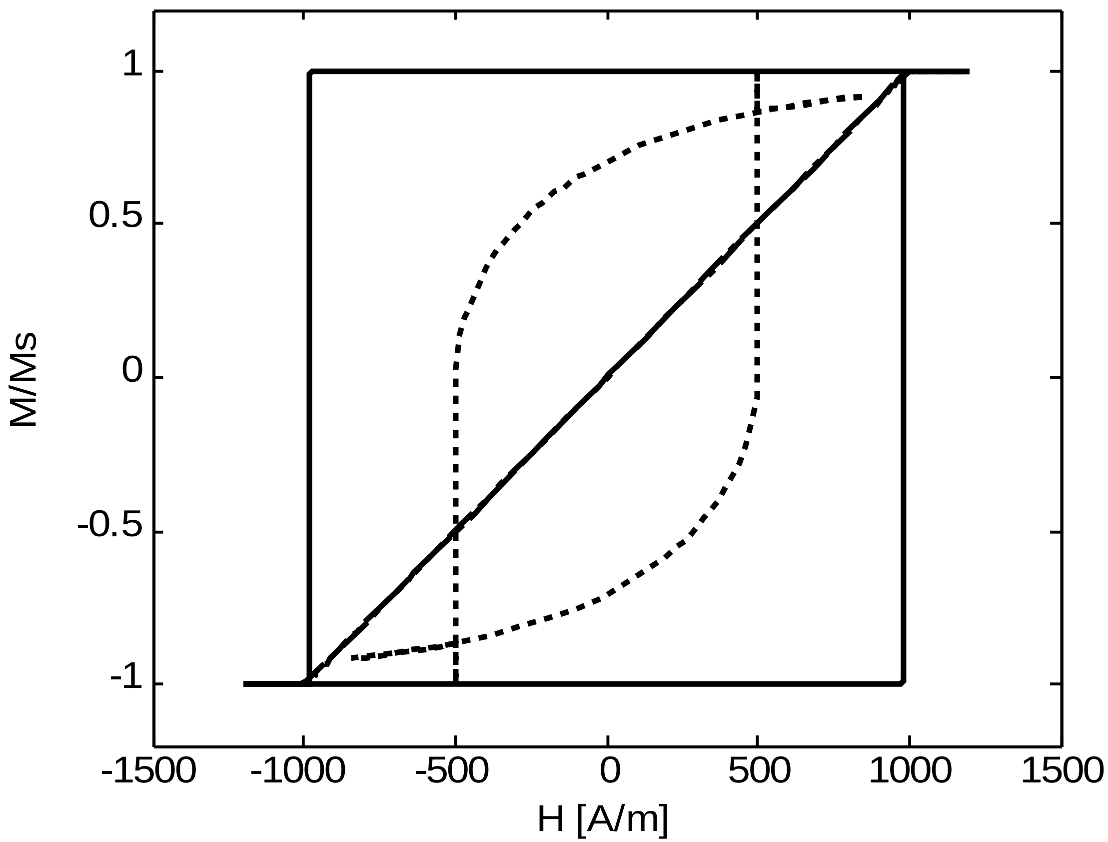
Magnetoresistance Model

Listing 3. Magnetoresistance module

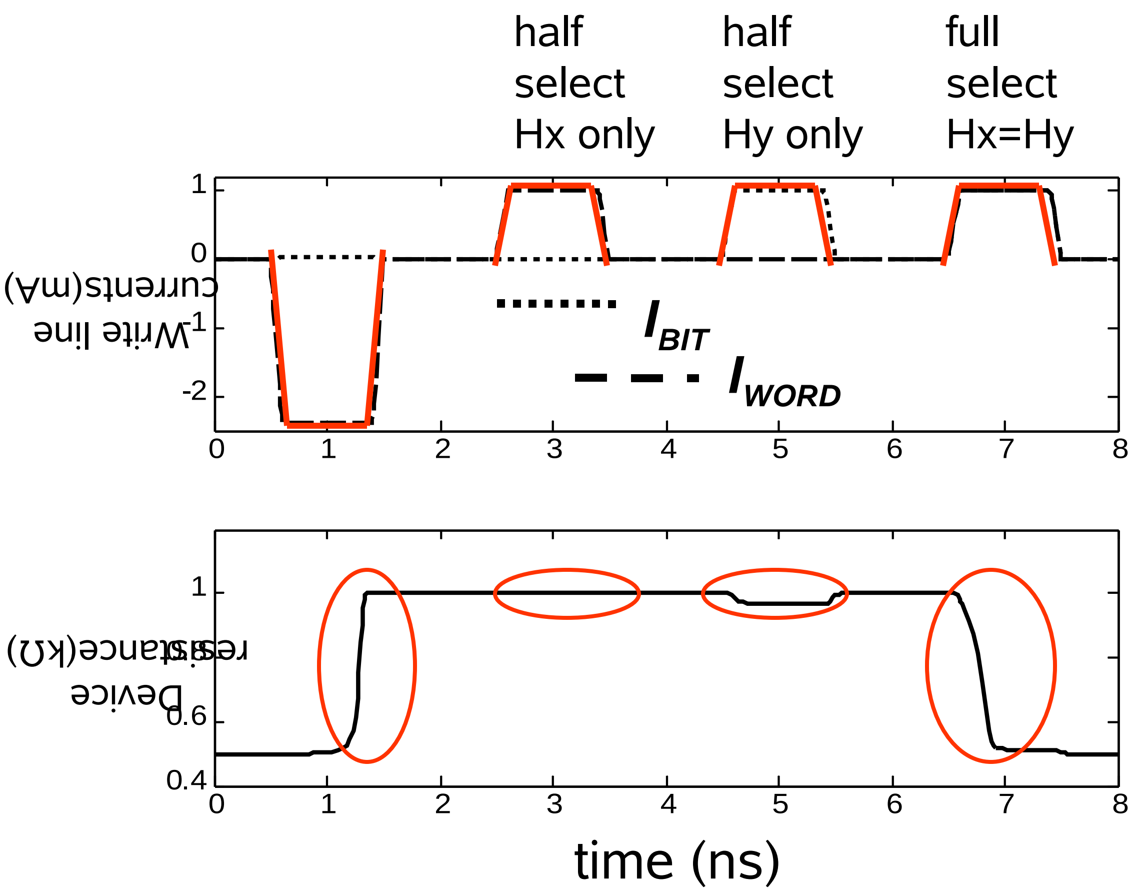
```
module magnetoresistance(M1,M2,rp,rn) ;
inout M1,M2,rp,rn ;
rotational M1,M2 ;
electrical rp,rn ;

parameter real R_max = 1000 ;  // High resistance  [ohm]
parameter real R_min = 500 ;   // Low resistance [ohm]

analog begin
        V(rp,rn) <+ I(rp,rn)*(R_min+ 0.5*(R_max-R_min)*
            (1-cos(Theta(M1)-Theta(M2)))) ;
end
endmodule
```

Results: Stoner-Wohlfarth hysteresis loops generated (dynamic term present)

- Square loop for H_x applied only
- Diagonal (hard axis "loop" for H_y applied only
- eye loop for H_x=H_y applied for a 45deg field



Results: Simulation of Spin Valve cell writing showing resistance changes in response to current pulses on the bit and word lines



- **Switching occurs for fields that equal or exceed $2K_u/\mu_0 M_S$**
- **MR changes when Hy (hard axis) tries to rotate magnetic moment.**

Concluding Remarks

- The spin valve has been successfully modeled in Verilog-A with simple code. However,….
- The results show fairly complex behavior – timing delays, hysteresis, and nonlinearity.
- The model is parameterized for use with different magnetic materials.
- A toggle MRAM model is under construction, and more physical effects for the current model are to be modeled.