I. The films - Co-Cr-Pt sputtered alloy films made by Erol Girt:
- Longer title: Three Component Ferromagnetic Resonance Linewidth In Co-Cr-Pt Alloy and Co-Cr Granular Films [inhomogeneities, two magnon (in two flavors)], and (a little but not much) alpha)

Many people contributed:

Financial Support
- Seagate Technology, Information Storage Industrial Consortium (INSIC)
- Army Research Office (USA) and the Office of Naval Research (USA)

II. The experiment - FMR at ~ 9.4 GHz as a function of field angle:
- Effective uniaxial anisotropy field $H_a$ less than 4 MeV.

We think we understand the "damping" processes in these films. *Damping* does not mean "alpha.*

Part I. Damping in low anisotropy Co-Cr-Pt sputtered alloy films
- These are ALLOY films, NOT granular (that's next).
- Range of compositions. 17.5 nm thick.
- Effective uniaxial anisotropy field $H_a$ less than 4 MeV.

What is needed next: (1) FMR data on high anisotropy granular films. Not so easy. Need higher frequencies and higher fields. (2) Probably need new theory too.

Part II. Damping in ONE very low anisotropy GRANULAR film
- Some similarities with alloy film series (same small alpha).
- Some critical differences: Role of inhomogeneities. Two magnon details.

III. Convincing three component explanation of linewidths:
- Small Gilbert (G) component with $\alpha$ = 0.004.
- Large inhomogeneity. $\Delta H_{eff}$ = 300 - 1300.
- Grain boundary two magnon scattering. $\Delta H_{eff}$ = 800 - 11,000 Oe.

The ALPHA PART OF THE DAMPING IS BASICALLY NEGLIGIBLE!
1. Static $B_{s-eff}$ from FMR field vs. angle fits.
2. Static $B_s$ from Erol Girt VSM data.
3. Uniaxial anisotropy effective field:
   $H_u$ (inferred) from $B_{s-eff}$ and $B_s$ ($B_{s-eff} = B_s - H_u$)

$B_s$ (G), $B_{s-eff}$ (G), $H_u$ (Oe) (inferred) from Girt vector VSM data.

Focus here is on #6

The FMR Linewidth - What would Tom Gilbert (G) say?

Field swept linewidth:
$$\Delta H = \frac{2\gamma e\omega_{FMR}}{\alpha}$$

From Gilbert equation

Valid in parallel and perpendicular

Bump in between

Example data: Co-Cr-Pt alloy film

$B_{s-eff}$ values decreasing

$H_u$ values agree reasonably well.

The FMR Linewidth - What do the data show?

1. Huge linewidths! $\Delta H = 1000$ Oe $\Rightarrow \alpha = 0.1!$ (also huge)
2. Angle dependence NOTHING LIKE Gilbert scenario.
3. Damping has little to do with a Gilbert (G) $\alpha$. 

24 May 2011
The FMR Linewidth - What do the data show?

The entire linewidth vs. angle profile can be nicely modeled in terms of three contributions:

1. A small \( \alpha_0 \) (magnon-electron scattering)
2. Inhomogeneity line broadening.
3. Two magnon (grain) scattering.

The good news!

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For sample #6

\( B_{\text{s-eff}} \) as for Sample #6

FMR at 9.4 GHz

External field angle to film normal \( \theta_H \) (degrees)

\( \Delta H \) (Oe)

The data

Focus on sample #6

Simple origins:

1. Local variations in \( B_{\text{s-eff}} \).
2. Change in local \( B_{\text{s-eff}} \) shifts local \( H_{\text{eff}}^{\text{FMR}} \).

\( H_{\text{eff}}^{\text{FMR}} \)

\( \Delta B_{\text{eff}} \approx 985 \text{ Oe} \)

Largest in perpendicular, where \( H_{\text{eff}}^{\text{FMR}} \) is most sensitive to changes in \( B_{\text{s-eff}} \).

Smaller in parallel.

Zero at a "critical angle" where \( \frac{\partial H_{\text{eff}}^{\text{FMR}}}{\partial B_{\text{s-eff}}} \) is equal to zero.

Inhomogeneity line broadening can explain the peak at perpendicular (and the dip). \( \Delta B_{\text{eff}} \approx 985 \text{ Oe} \)

For sample #6

\( B_{\text{s-eff}} \approx 2850 \text{ G} \)

Critical angle effect:

Plot \( H_{\text{eff}}^{\text{FMR}} \) vs. \( B_{\text{s-eff}} \).

Note zero slope points.

For sample #6, \( B_{\text{s-eff}} \approx 2850 \text{ G} \)

Data (again)
The FMR Linewidth - Grain boundary two magnon scattering

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Grain boundary two magnon scattering (GBTMS) can explain the peak at $\theta_H \approx 45^\circ$

No degenerate spin waves below $\theta_H = 27^\circ$ or so.

Peak in scattering at $\theta_H = 45^\circ$ or so.

Quick tutorial on GBTMS processes

1. Inhomogeneities can couple the FMR (uniform) mode to degenerate spin waves (two magnon scattering).

2. Wave number correlations are VERY DIFFERENT!

3. Correlations are fine, BUT degenerate spin wave modes must be present for two magnon scattering to happen.

Example: $\theta_H = 45^\circ$ situation

Spin wave band (at FMR)

Spin wave frequency (GHz)

FMR

$\theta_k = 90^\circ$ $k$

Band of modes in between

$\theta_k = 0^\circ$

Spatial correlations

From fits for #6. Fitted grain size $\approx 23$ nm (a little big).

Two magnon scattering correlations (arb.)

Spin wave number $k$ (rad/cm)

Spin wave wave number $k$ (rad/cm)

Spin wave wave frequency (GHz)

FMR

Possible scattering

Degenerate modes

Cut at FMR frequency

TMS (theory)

Measured FMR linewidth vs $\theta_\text{H}$(Oe)

External field angle to film normal $\phi_H$ (degrees)

The FMR Linewidth - Grain boundary two magnon scattering

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Measured FMR linewidth vs $\theta_\text{H}$(Oe)

External field angle to film normal $\phi_H$ (degrees)
The FMR Linewidth - Grain boundary two magnon scattering

4. Inhomogeneity size and nature determine which modes are coupled.

Coupling strength

Spin wave wave number $k$ (rad/cm)

Possible scattering

Degenerate modes

Cut at FMR frequency

The FMR Linewidth - Grain boundary two magnon scattering

5. The shape of the spin wave band changes with angle.

6. The cut-off moves OUT in $k$ as $\theta_H$ increases.

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Density of states - DOS (arb. units)

H$B_s$

H$B_s$

H$B_s$

H$B_s$

H$B_s$

C. GILBERT (a little)

A. INHOMOG. BROADENING (lots)

Grain boundary scattering (schematic) = inverse grain size

Spin wave wave frequency (GHz)

Spin wave frequency (GHz)

Grain boundary two magnon scattering

Inhomog. broadening, $A_B^{\text{eff}} = 980$ G.

Temperature, aka, mag. elec. scatt, $\alpha = 0.004$, LIKE INTRINSIC!

Total fit

H$B_s$

H$B_s$

H$B_s$

H$B_s$

H$B_s$

H$B_s$

H$B_s$

H$B_s$

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The FMR Linewidth - Grain boundary two magnon scattering

Same story for all samples:

\( \Delta B_{\text{eff}} = 300 \, \text{G} \quad a_b = 36 \, \text{nm} \)

\( \Delta B_{\text{eff}} = 406 \, \text{G} \quad a_b = 31 \, \text{nm} \)

\( \Delta B_{\text{eff}} = 1,330 \, \text{G} \quad a_b = 26 \, \text{nm} \)

CONCLUSIONS FOR Co-Cr-Pt ALLOY FILMS:

(1) An overall \( \alpha \) model DOES NOT WORK!

(2) FMR linewidth dominated by TWO effects:
   A. inhomogeneity line broadening (not real loss).
   B. Grain boundary two magnon scattering (a real loss).

(3) There is “a little bit” of “real” alpha
   \( \alpha \approx 0.004, \text{aka magnon - electron scatt.} \).

THE NEXT QUESTION:

WHAT HAPPENS FOR REAL PERPENDICULAR MEDIA?

1. PERPENDICULAR ANISOTROPY
2. GRANULAR FILMS

Stella’s M1 film:

DC magnetron sputtering (same as alloy films)

CoCr layer thickness \( \approx 16 \, \text{nm} \)
Grain size \( \approx 8 \, \text{nm} \)
Grain boundary \( \approx 1 \, \text{nm} (?) \)
Intergranular exchange - unknown

MOKE loop:
Out-of-plane field (after Nistor and Wu)
Skewed loop likely due to grain demag
Stoner-Wohlfarth (SW)
rotation model prediction

Away from $\mathbf{M}_r$ and $\mathbf{M}_s$, sample may not be saturated.

Go to a higher frequency - 17 GHz

Eventually, we will really need to deal with the microstructure.

At these fields, rotation model should be reasonably ok (?).
But data still do not fit SW model.
(closer, but still well off)

KEEP THIS IN MIND
AS WE LOOK AT
THE FMR LINEWIDTHS

At these fields, rotation model should be reasonably ok (?).
But data still do not fit SW model.
(closer, but still well off)

What is the origin of this linewidth response?
I will show you one possible scenario.

1. Somewhat narrower
2. Totally different angle dependence

Latest attempt to "explain" - the key (as before) is inhomogeneities

- A simple square grain model
  - 1. Random variation in grain sizes (all three directions)
    - Look at local dipole field in a 1 nm slice of material
      - Dipole fields are localized.
      - Grains are "near-sighted"!
  - 2. Next: random variation in uniaxial anisotropy axis orientation
    - MORE inhomogeneity line broadening
  - 3. Combine 1 and 2 - Assume exchange coupled grains
    - This leads to a total inhomogeneous line broadening response.
Latest attempt to "explain" - the key (as before) is inhomogeneities

Inhomogeneity line broadening results (without the two magnon)

Total combined inhomogeneity line broadening

Grain size variation, 1.05 nm

Anisotropy axis variation, 1.25 degrees

This simple model seems to "nail" a large part of the linewidth.

Anisotropy two magnon scattering
(variation in anisotropy c-axis between grains)

Granular CoCr film
4 degree uniaxial axis variation

We have a bonus result!

Total linewidth picture (as of today)

Similar to (but different from) alloy films:

1. More complicated inhomogeneity analysis
2. Grain-to-grain scattering (not grain boundary)
3. Very small "intrinsic" Gilbert \( \alpha \) (as before)

Inhomogeneous line broadening

Grain size variation=0.9 nm
Grain axis variation=1 deg
Anisotropy Two Magnon Scattering
Total axis variation=4 deg

Gilbert damping (mag. elec. scatt) \( \alpha = 0.003 \)

Total linewidth picture (as of today)

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The non-Stoner-Wohlfarth FMR field response explained!

Two magnon shift

Grain size variation=0.9 nm
Grain axis variation=1 deg
Anisotropy Two Magnon Scattering
Total axis variation=4 deg

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The non-Stoner-Wohlfarth FMR field response explained!

Two magnon shift

Grain size variation=0.9 nm
Grain axis variation=1 deg
Anisotropy Two Magnon Scattering
Total axis variation=4 deg

Based on one film with a modest net uniaxial anisotropy.

We need to be able to look at higher anisotropy films (higher frequency and higher field).

This all looks pretty "tidy."

Not easy!
Next up.
What about $\alpha$?
Where does it come from?
Is it good for anything?

There is no $\alpha$!

Lev Landau was 27 years old

The actual equation from the 1935 paper by Landau and Lifshitz

\[ \frac{d\mathbf{s}}{dt} = \mathbf{f(s)} + \lambda \left( \mathbf{f} - \frac{(\mathbf{f} \cdot \mathbf{s}) \mathbf{s}}{s^2} \right) \]

First we need some grounding in basic precession. Session II