IEEE Magnetics Society Summer School
University of New Orleans, 24 May 2011

Carl E. Patton
Session I

Short title: Damping is not alpha.

Long title: Damping In Perpendicular Media "Like" Films

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:
C. Scott Brown, Erol Girt, Julius Hohlfeld, Misbah ul Islam, Sangita Kalarickal, Pavol Krivosik, Nan Mo, Wei Tong, Adnan Rebei, and Stella Wu.

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

Many people contributed:
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Theory **Samples**

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Session I

Three sessions:

1. Damping is not alpha.

Case-in-point: Co-Cr films

2. Precession preliminaries

(mostly stiffness fields and frequencies)

3. Phenomenological damping

(more than you ever wanted to know)

the Colorado State University program.

Global Overview

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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_u less than $4\pi M_s$.

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

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..

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.

Overview - Part I. Damping in Alloy Films

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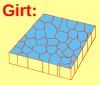
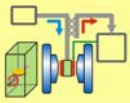
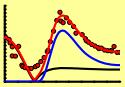
I. The films - Co-Cr-Pt sputtered alloy films made by Erol Girt:
ALLOY films, NOT granular (that's next).
Range of compositions. 17.5 nm thick.
Effective uniaxial anisotropy field H_u less than $4\pi M_s$.



II. The experiment - FMR at ~ 9.4 GHz as a function of field angle:
Huge linewidths!
Naive people would just assign a large α_{eff} ~0.02 or so.
Angle dependence NOT that expected from the Gilbert (G) equation alone.
Linewidth in terms of a "simple" Gilbert α - parameter MAKES NO SENSE.



III. Convincing three component explanation of linewidths:
Small Gilbert (G) component with α ~ 0.004.
Large inhomogeneity, $\Delta(4\pi M_s - H_u)$~ 300 - 1300.
Grain boundary two magnon scattering.
ΔH_{gbs}~ 800 - 11,000 Oe!
The ALPHA PART OF THE DAMPING IS BASICALLY NEGLIGIBLE!



The Films - ALLOY films (not granular)

6

1. Static $B_{s\text{-eff}}$ from FMR field vs. angle fits.
2. Static B_s from Erol Girt VSM data.
3. Uniaxial anisotropy effective field:
   H_u (inferred) from $B_{s\text{-eff}}$ and B_s. ($B_{s\text{-eff}} = B_s - H_u$)
   H_u (VSM) from Girt vector VSM data.

#	Co at %	Cr at %	Pt at %	$B_{s\text{-eff}}$ (G) (FMR fits)	B_s (G) (Girt)	H_u (Oe) (inferred)	H_u (Oe) (Girt)
3	90	10	0	6357	12549	6192	6704
4	85	15	0	3469	11106	7637	8155
6	87	5	8	2851	14126	11275	12175
7	82	10	8	6 ?	11878	11871?	13105

H_u values agree reasonably well.

The Films - ALLOY films (not granular) 7

1. Static $B_{s\text{-eff}}$ from FMR field vs. angle fits.
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4	85	15	0	3469	11106	7637	8155
6				2851	14126	11275	12175
7	82	10	8	6 ?	11878	11871?	13105

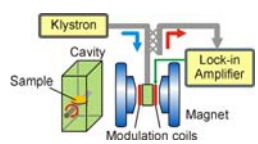
$B_{s\text{-eff}}$ values decreasing

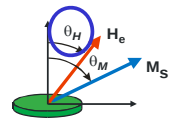
Focus here is on #6

H_u values agree reasonably well.

The FMR Field vs. Angle Response 8

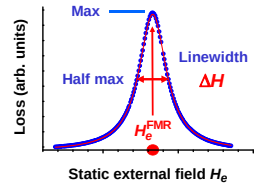
Straight FMR cavity spectrometer





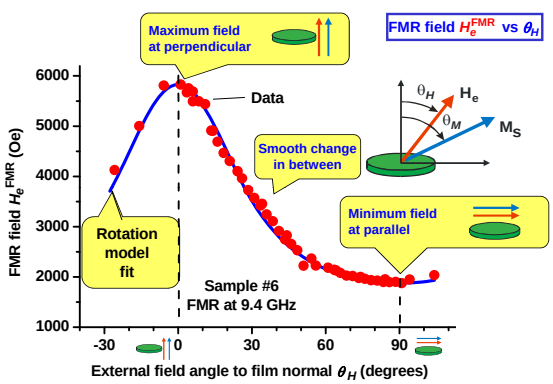
Shown for a "planar" film with $4\pi M_s > H_u$ and $\theta_M > \theta_H$

Absorption vs. field

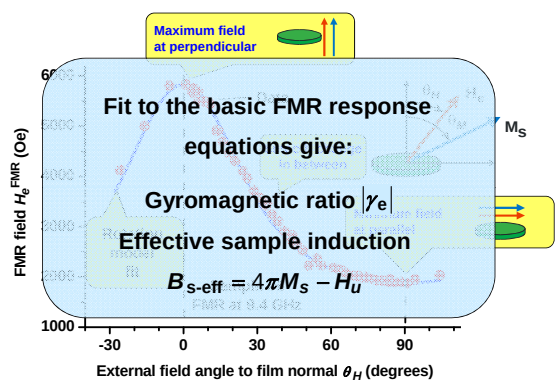


1. Measure FMR field H_e^{FMR} vs θ_H
2. Measure FMR linewidth ΔH vs θ_H

FMR Field vs. Angle - Proof of a Stoner-Wohlfarth/Kittel FMR Response 9



FMR Field vs. Angle - Proof of a Stoner-Wohlfarth/Kittel FMR Response 10

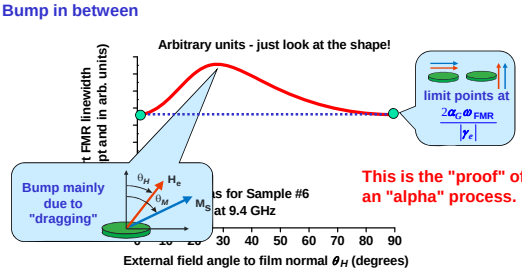


The FMR Linewidth - What would Tom Gilbert (G) say? 11

Field swept linewidth: $\Delta H_G = \frac{2\alpha_G \omega_{FMR}}{|\gamma_e|}$ From Gilbert equation

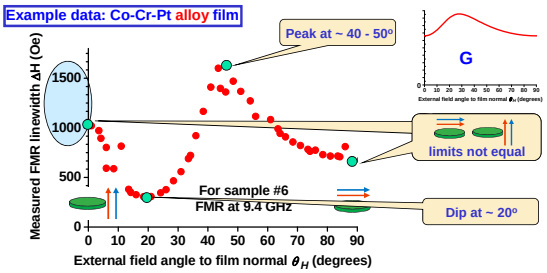
Valid in parallel and perpendicular

Bump in between



The FMR Linewidth - What do the data show? 12

Example data: Co-Cr-Pt alloy film



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

The FMR Linewidth - What do the data show? 13

Example data: Co-Cr-Pt alloy film

Peak at ~ 40 - 50°

The good news!

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

(1) A small α_G

(magnon-electron scattering)

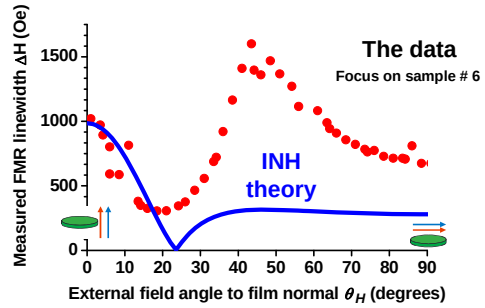
(2) Inhomogeneity line broadening.

(3) Two magnon (grain) scattering.

3. Damping has little to do with a Gilbert (G) α.

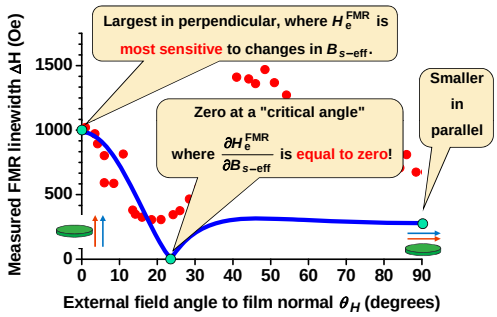
The FMR Linewidth - Inhomogeneity broadening 14

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



The FMR Linewidth - Inhomogeneity broadening 15

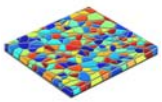
Inhomogeneity line broadening can explain the peak at perpendicular (and the dip). $\Delta B_{eff} \approx 985$ Oe

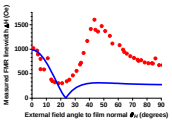


The FMR Linewidth - Inhomogeneity broadening 16

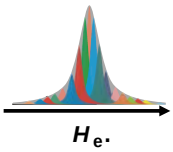
Simple origins:

Local variations in B_{s-eff}.





Change in local B_{s-eff} shifts local H_e^{FMR}.



$$\Delta H_{INH} \approx \left|\frac{\partial H_{FMR}}{\partial B_{s\text{-}eff}}\right| \cdot \Delta B_{eff}$$

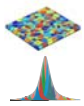
The FMR Linewidth - Critical angle effect 17

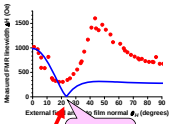
Critical angle effect:

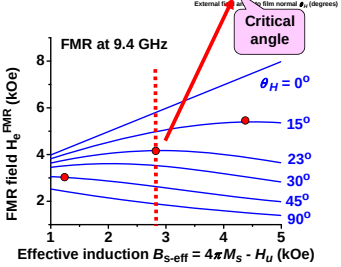
Plot H_e^{FMR} vs. $B_{s\text{-}eff}$.

Note zero slope points.

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

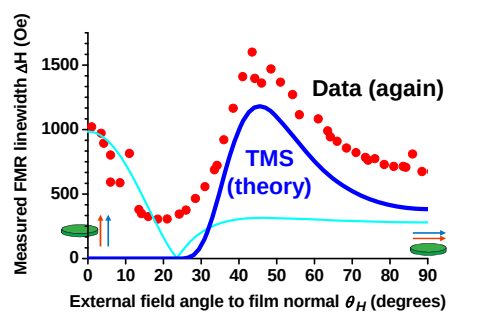


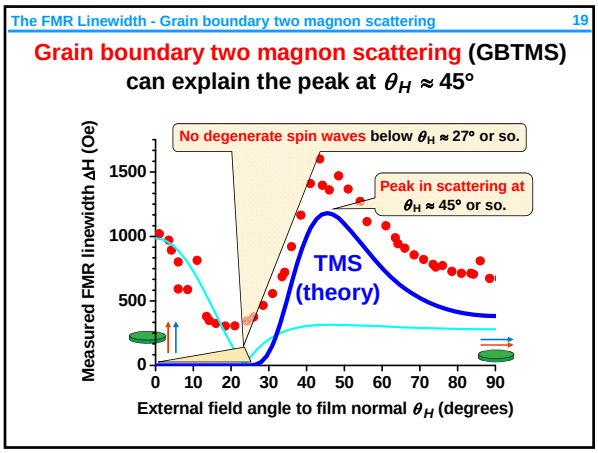


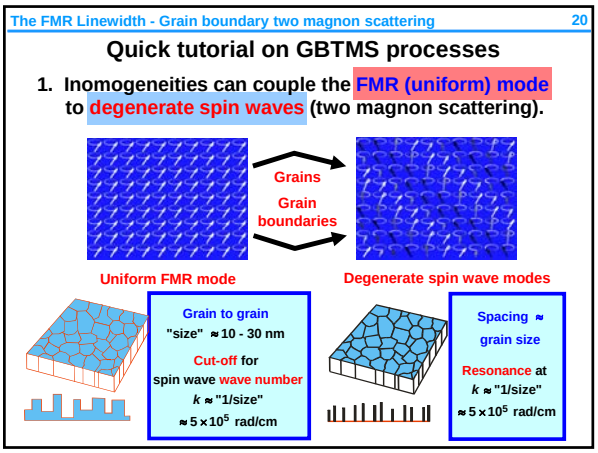


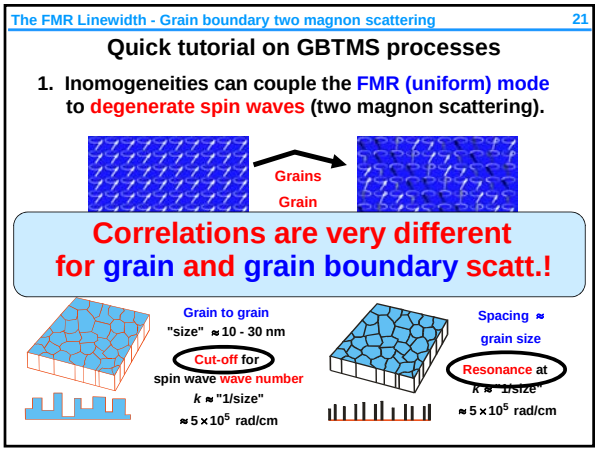
The FMR Linewidth - Grain boundary two magnon scattering 18

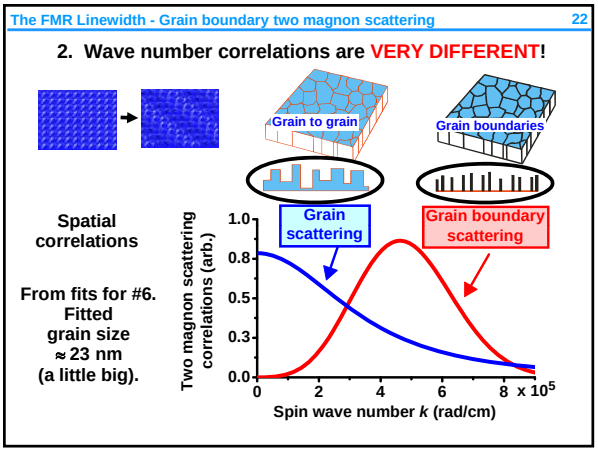
Grain boundary two magnon scattering (GBTMS) can explain the peak at $\theta_H \approx 45°$

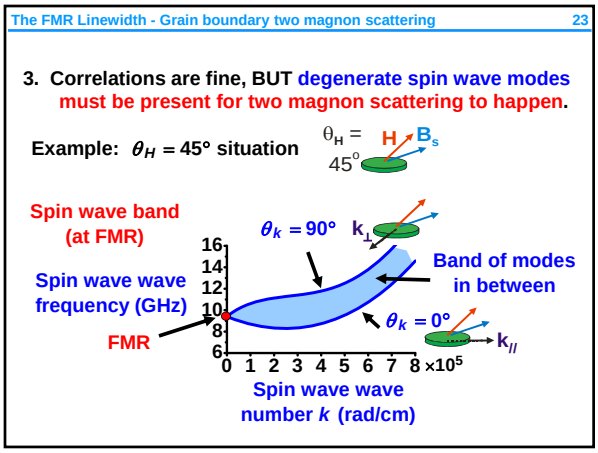


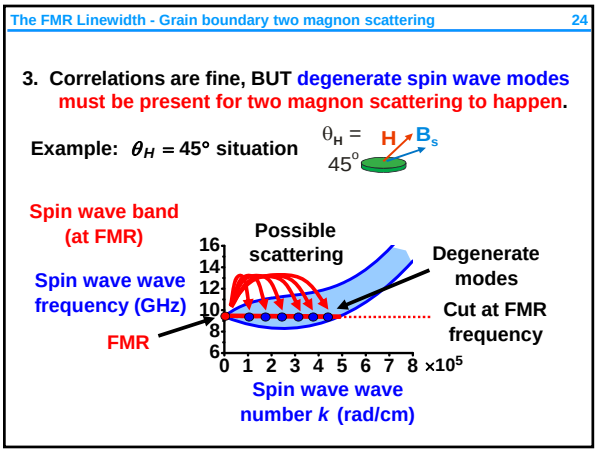

The FMR Linewidth - Grain boundary two magnon scattering
19
Grain boundary two magnon scattering (GBTMS)
can explain the peak at $\theta_H \approx 45°$
No degenerate spin waves below $\theta_H \approx 27°$ or so.
Peak in scattering at $\theta_H \approx 45°$ or so.
TMS (theory)
Measured FMR linewidth ΔH (Oe)
1500
1000
500
0
0 10 20 30 40 50 60 70 80 90
External field angle to film normal θ_H (degrees)

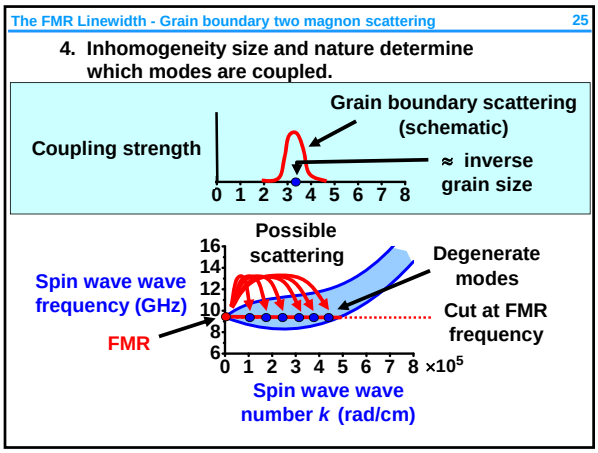

The FMR Linewidth - Grain boundary two magnon scattering
20
Quick tutorial on GBTMS processes
1. Inomogeneities can couple the FMR (uniform) mode to degenerate spin waves (two magnon scattering).
Grains
Grain boundaries
Uniform FMR mode
Degenerate spin wave modes
Grain to grain "size" ≈ 10 - 30 nm
Cut-off for spin wave wave number $k \approx$ "1/size" $\approx 5\times10^5$ rad/cm
Spacing ≈ grain size
Resonance at $k \approx$ "1/size" $\approx 5\times10^5$ rad/cm

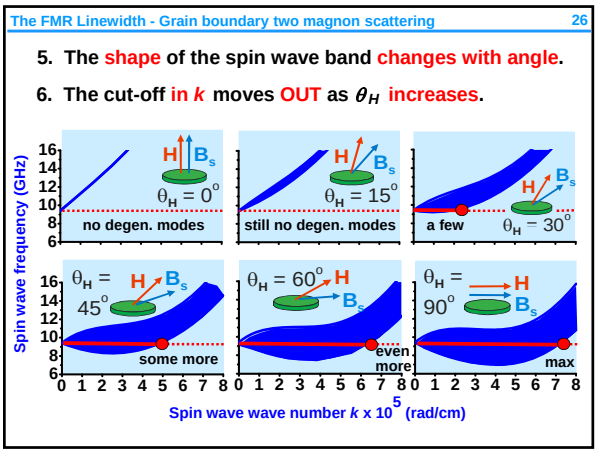

The FMR Linewidth - Grain boundary two magnon scattering
21
Quick tutorial on GBTMS processes
1. Inomogeneities can couple the FMR (uniform) mode to degenerate spin waves (two magnon scattering).
Grains
Grain
Correlations are very different for grain and grain boundary scatt.!
Grain to grain "size" ≈ 10 - 30 nm
Cut-off for spin wave wave number $k \approx$ "1/size" $\approx 5\times10^5$ rad/cm
Spacing ≈ grain size
Resonance at $k \approx$ "1/size" $\approx 5\times10^5$ rad/cm

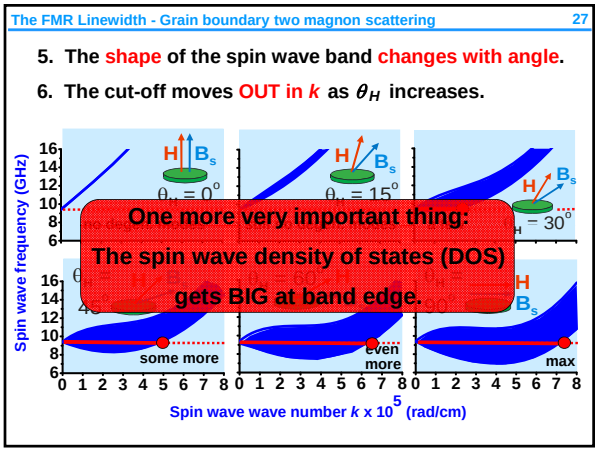

The FMR Linewidth - Grain boundary two magnon scattering
22
2. Wave number correlations are VERY DIFFERENT!
Grain to grain
Grain boundaries
Spatial correlations
From fits for #6. Fitted grain size ≈ 23 nm (a little big).
Grain scattering
Grain boundary scattering
Two magnon scattering correlations (arb.)
1.0
0.8
0.5
0.3
0.0
0 2 4 6 8 x 10^5
Spin wave number k (rad/cm)

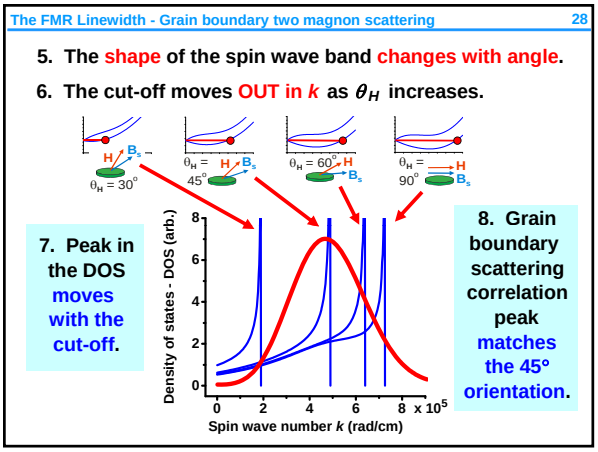

The FMR Linewidth - Grain boundary two magnon scattering
23
3. Correlations are fine, BUT degenerate spin wave modes must be present for two magnon scattering to happen.
Example: $\theta_H = 45°$ situation
$\theta_H = 45°$
H
B_s
Spin wave band (at FMR)
$\theta_k = 90°$
$k_\perp$
Band of modes in between
Spin wave wave frequency (GHz)
$\theta_k = 0°$
$k_{//}$
FMR
16
14
12
10
8
6
0 1 2 3 4 5 6 7 8 ×10^5
Spin wave wave number k (rad/cm)

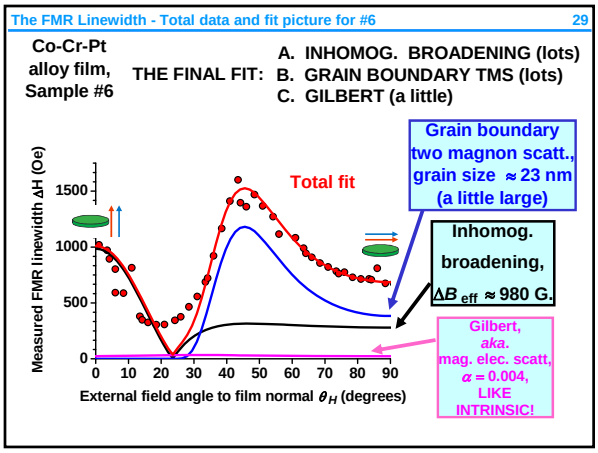

The FMR Linewidth - Grain boundary two magnon scattering
24
3. Correlations are fine, BUT degenerate spin wave modes must be present for two magnon scattering to happen.
Example: $\theta_H = 45°$ situation
$\theta_H = 45°$
H
B_s
Spin wave band (at FMR)
Possible scattering
Degenerate modes
Spin wave wave frequency (GHz)
Cut at FMR frequency
FMR
16
14
12
10
8
6
0 1 2 3 4 5 6 7 8 ×10^5
Spin wave wave number k (rad/cm)

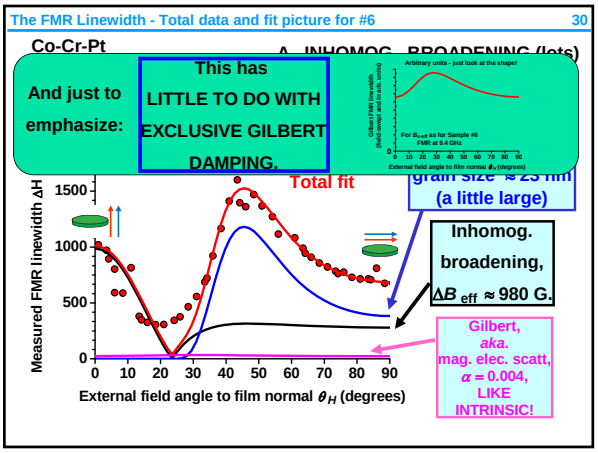

The FMR Linewidth - Grain boundary two magnon scattering
25
4. Inhomogeneity size and nature determine which modes are coupled.
Coupling strength
Grain boundary scattering (schematic)
≈ inverse grain size
Possible scattering
Degenerate modes
Spin wave wave frequency (GHz)
Cut at FMR frequency
FMR
Spin wave wave number k (rad/cm)


The FMR Linewidth - Grain boundary two magnon scattering
26
5. The shape of the spin wave band changes with angle.
6. The cut-off in k moves OUT as θH increases.
Spin wave frequency (GHz)
no degen. modes
still no degen. modes
a few
some more
even more
max
Spin wave wave number k x 10^5 (rad/cm)


The FMR Linewidth - Grain boundary two magnon scattering
27
5. The shape of the spin wave band changes with angle.
6. The cut-off moves OUT in k as θH increases.
Spin wave frequency (GHz)
One more very important thing:
The spin wave density of states (DOS)
gets BIG at band edge.
some more
even more
max
Spin wave wave number k x 10^5 (rad/cm)


The FMR Linewidth - Grain boundary two magnon scattering
28
5. The shape of the spin wave band changes with angle.
6. The cut-off moves OUT in k as θH increases.
7. Peak in the DOS moves with the cut-off.
8. Grain boundary scattering correlation peak matches the 45° orientation.
Density of states - DOS (arb.)
Spin wave number k (rad/cm)

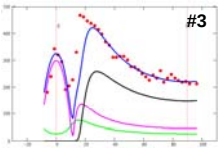

The FMR Linewidth - Total data and fit picture for #6
29
Co-Cr-Pt alloy film, Sample #6
THE FINAL FIT:
A. INHOMOG. BROADENING (lots)
B. GRAIN BOUNDARY TMS (lots)
C. GILBERT (a little)
Total fit
Grain boundary two magnon scatt., grain size ≈ 23 nm (a little large)
Inhomog. broadening, ΔB eff ≈ 980 G.
Gilbert, aka. mag. elec. scatt, α = 0.004, LIKE INTRINSIC!
Measured FMR linewidth ΔH (Oe)
External field angle to film normal θH (degrees)


The FMR Linewidth - Total data and fit picture for #6
30
Co-Cr-Pt
And just to emphasize:
This has LITTLE TO DO WITH EXCLUSIVE GILBERT DAMPING.
Total fit
(a little large)
Inhomog. broadening, ΔB eff ≈ 980 G.
Gilbert, aka. mag. elec. scatt, α = 0.004, LIKE INTRINSIC!
Measured FMR linewidth ΔH
External field angle to film normal θH (degrees)

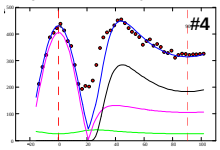
The FMR Linewidth - Grain boundary two magnon scattering (31)

Same story for all samples:
(a_0 = grain size)

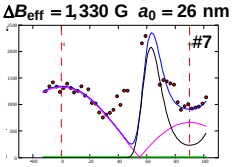
ΔB_{eff} = 300 G a_0 = 36 nm



ΔB_{eff} = 406 G a_0 = 31 nm

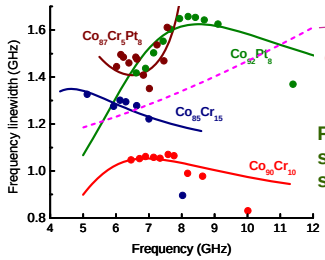


ΔB_{eff} = 1,330 G a_0 = 26 nm



Linewidth vs. frequency data tell the same story (32)

Data from: T. Clinton *et al.*, J. Appl. Phys., 103, 07F546 (2008)



Clearly, an overall α model does NOT work

Fits with a two magnon scattering model and a small α = 0.004

Fit based on theory in:
Krivosik *et al.*, J. Appl. Phys. 101, 083901 (2007)

The FMR Linewidth - Total data and fit picture for #6 (33)

Co-Cr-Pt

A. INHOMOG. BROADENING (lots)

CONCLUSIONS FOR Co-Cr-Pt ALLOY FILMS:

(1) An overall α 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, *aka* magnon - electron scatt.).

INTRINSIC!

The FMR Linewidth - Total cata and fit picture for #6 (34)

Co-Cr-Pt

A. INHOMOG. BROADENING (lots)

THE NEXT QUESTION:

WHAT HAPPENS FOR REAL PERPENDICULAR MEDIA?

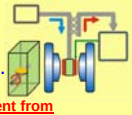
1. PERPENDICULAR ANISOTROPY
2. GRANULAR FILMS

INTRINSIC!

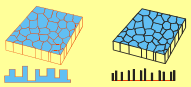
Overview - Part II. Damping in Granular Films (35)

I. The film - Co-Cr sputtered granular film from Stella Wu:
Effective uniaxial anisotropy field H_u slightly greater than $4\pi M_s$. $H_{u\text{-eff}} = H_u - 4pM_s$ is about 800 Oe.
Still not the most exciting perpendicular media film.

II. Same experiment - FMR. Two frequencies, ~ 9.4 GHz and ~ 17 GHz, as a function of field angle:
Large linewidths, but not as huge as before!
We think α is still as small as before.
Story in words is the same: Small α. Large two magnon.
Large inhomogeneity broadening.
BUT: Two magnon and inhomogeneity processes different from those for alloy films!



Remember: "Granular" means "independent" grains. Scattering correlations are very different. (Spin wave bands may also be different – skip this complication in this talk.) More questions than answers!



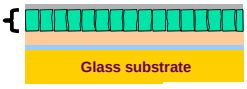
grains boundaries

Stella's M1 film: (36)

DC magnetron supttering
(same as alloy films)
$4\pi M_S$ ~ 6 kG
H_u ~ 6.9 kOe
H_u^{eff} ~ 0.9 kOe

CoCr layer thickness ~ 16 nm
Grain size ~ 8 nm
Grain boundary ~ 1 nm (?)
Intergranular exchange - unknown

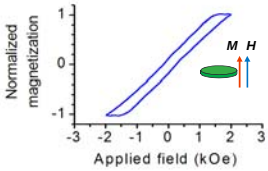
CoCr - x-oxide (with cartoon grains)



Carbon overlayer
Ru underlayer
Non magnetic seed layer
Glass substrate

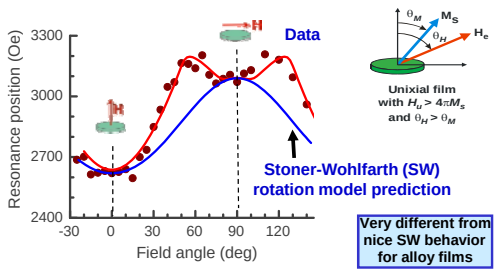
MOKE loop:
Out-of-plane field
(after Nistor and Wu)

Skewed loop likely due to grain demag



FMR field vs. angle at 9.4 GHz

37



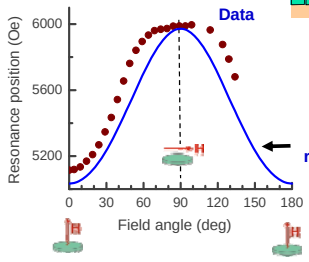
Very different from nice SW behavior for alloy films

Away from H and H, sample may not be saturated.

Go to a higher frequency - 17 GHz

FMR field vs. angle at ~17 GHz

38

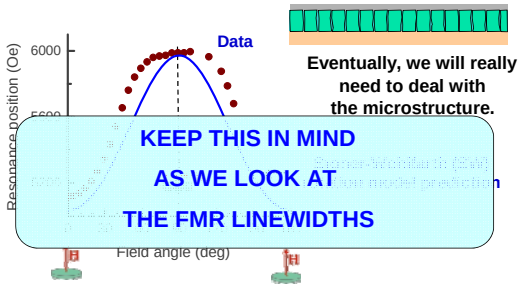


Eventually, we will really need to deal with the microstructure.

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

FMR field vs. angle at ~17 GHz

39



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

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)

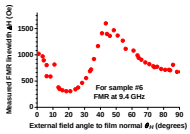
Move on to linewidth results

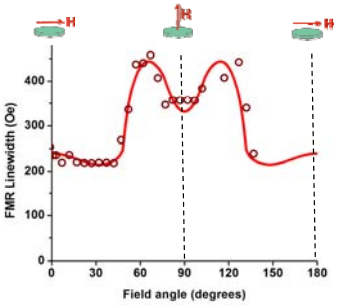
40

17.3 GHz M1 data

For now, take the red line as a "guide to the eye."

Very different from alloy film results!





1. Somewhat narrower
2. Much different angle dependence

Move on to linewidth results

41

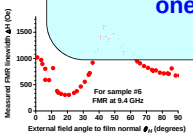
17.3 GHz M1 data

For now, take the red line as a "guid

Very from alloy film resul

What is the origin of this linewidth response?

I will show you one possible scenario.



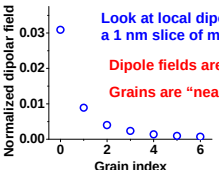
1. Somewhat narrower
2. Totally different angle dependence

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

42

A simple square grain model

1. Random variation in grain sizes (all three directions)



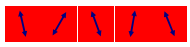
Look at local dipole field in a 1 nm slice of material

Dipole fields are localized.

Grains are "near-sighted"!

This gives a random variation in demagnetizing factors and the grain resonance field - Inhomogeneity line broadening

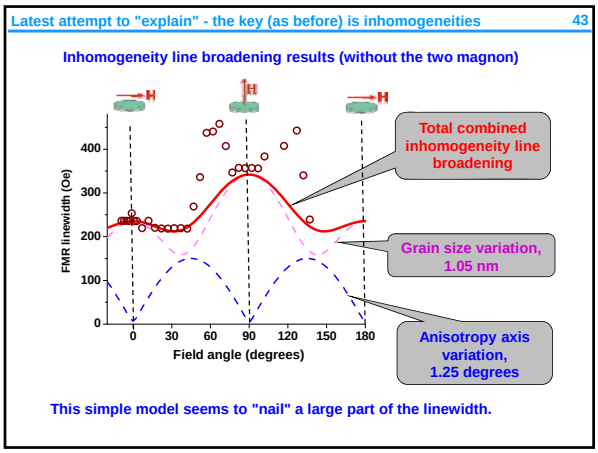
2. Next: random variation in uniaxial anisotropy axis orientation

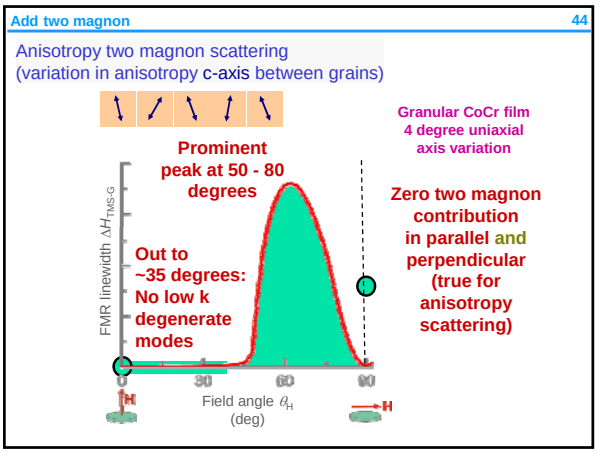


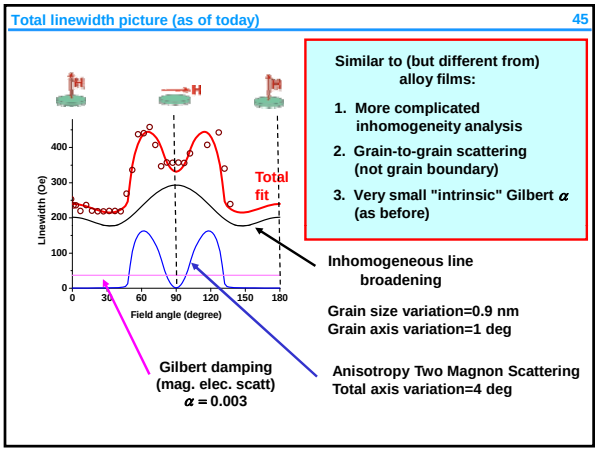
MORE inhomogeneity line broadening

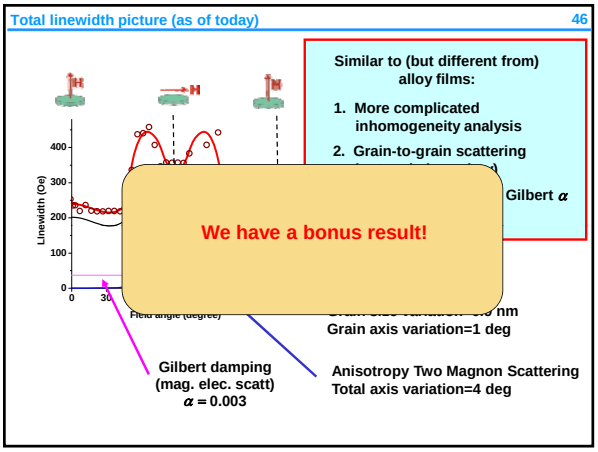
3. Combine 1 and 2 - Assume exchange coupled grains

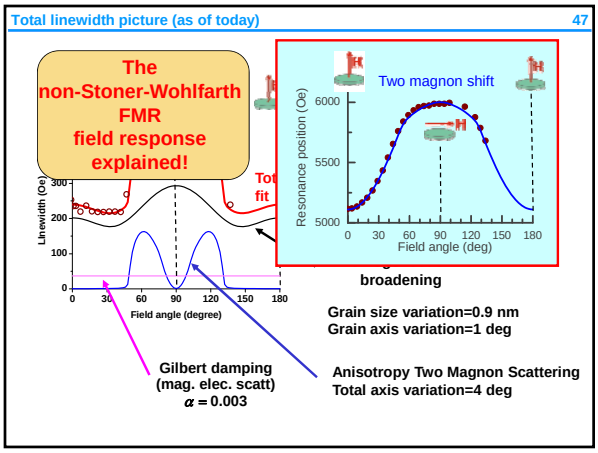
This leads to a total inhomogeneous line broadening response.

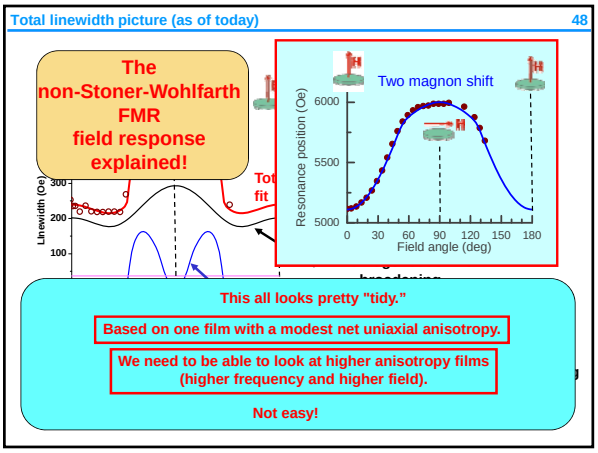

Latest attempt to "explain" - the key (as before) is inhomogeneities
43
Inhomogeneity line broadening results (without the two magnon)
FMR linewidth (Oe)
Field angle (degrees)
Total combined inhomogeneity line broadening
Grain size variation, 1.05 nm
Anisotropy axis variation, 1.25 degrees
This simple model seems to "nail" a large part of the linewidth.


Add two magnon
44
Anisotropy two magnon scattering
(variation in anisotropy c-axis between grains)
Granular CoCr film
4 degree uniaxial
axis variation
Prominent peak at 50 - 80 degrees
Out to ~35 degrees: No low k degenerate modes
Zero two magnon contribution in parallel and perpendicular (true for anisotropy scattering)
FMR linewidth ΔH_{TMS-G}
Field angle θ_H (deg)


Total linewidth picture (as of today)
45
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 α (as before)
Total fit
Linewidth (Oe)
Field angle (degree)
Inhomogeneous line broadening
Grain size variation=0.9 nm
Grain axis variation=1 deg
Gilbert damping (mag. elec. scatt) α = 0.003
Anisotropy Two Magnon Scattering
Total axis variation=4 deg


Total linewidth picture (as of today)
46
Similar to (but different from) alloy films:
1. More complicated inhomogeneity analysis
2. Grain-to-grain scattering
We have a bonus result!
Grain axis variation=1 deg
Gilbert damping (mag. elec. scatt) α = 0.003
Anisotropy Two Magnon Scattering
Total axis variation=4 deg


Total linewidth picture (as of today)
47
The non-Stoner-Wohlfarth FMR field response explained!
Two magnon shift
Resonance position (Oe)
Field angle (deg)
Grain size variation=0.9 nm
Grain axis variation=1 deg
Gilbert damping (mag. elec. scatt) α = 0.003
Anisotropy Two Magnon Scattering
Total axis variation=4 deg


Total linewidth picture (as of today)
48
The non-Stoner-Wohlfarth FMR field response explained!
Two magnon shift
Resonance position (Oe)
Field angle (deg)
This all looks pretty "tidy."
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).
Not easy!

Next up.
What about α?
Where does it come from?
Is it good for anything?

The actual equation from the 1935 paper by Landau and Lifshitz

$$\dot{\mathbf{s}}/\mu_0 = [\mathbf{f}\mathbf{s}] + \lambda\left(\mathbf{f} - \frac{(\mathbf{f}\mathbf{s})\,\mathbf{s}}{s^2}\right)$$

There is no α!

Lev Landau was 27 years old

First we need some grounding in basic precession. Session II