Ohio State University Review:

Sputter Beam Epitaxy

Deposition of State-of-the-Art Epitaxial Films Using Off-Axis Sputtering

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Brought to you by:

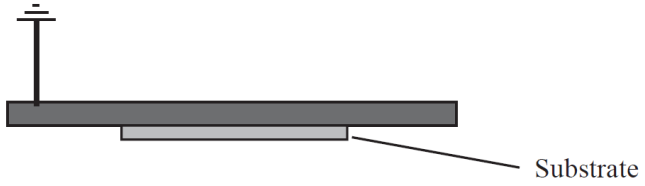
PVD PRODUCTS

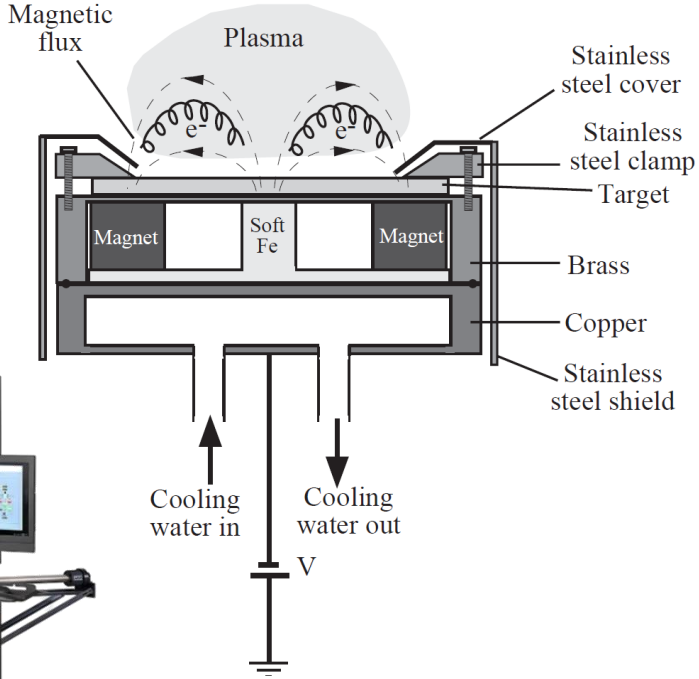
Outline

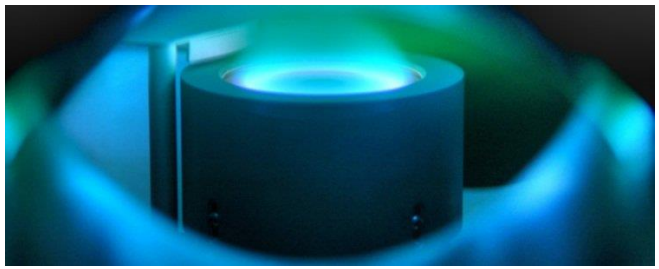
- A little history of sputtering
- Demand for high crystalline quality films
- Off-axis sputtering: important factors
- Epitaxial films grown by off-axis sputtering: structural quality
  - Perovskites and double perovskites
  - Magnetic garnets
  - Heusler compounds
  - Intermetallics, metals, alloys
  - Binary oxides
  * References to papers
- Outlook

Sputtering Techniques

- Diode sputtering
  - DC voltage of 1 - 5 kV
  - Gas pressure of 10 - 100 mtorr.
  - Very low deposition rate
- Triode sputtering
  - A hot cathode as extra electron source
- Ion beam sputtering
  - Needs a separate ion source
- Magnetron sputtering
  - Developed since 1970s

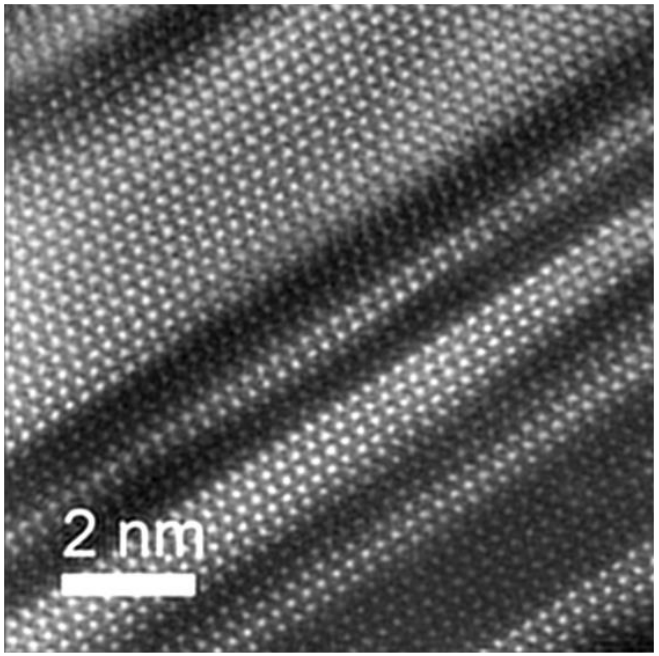




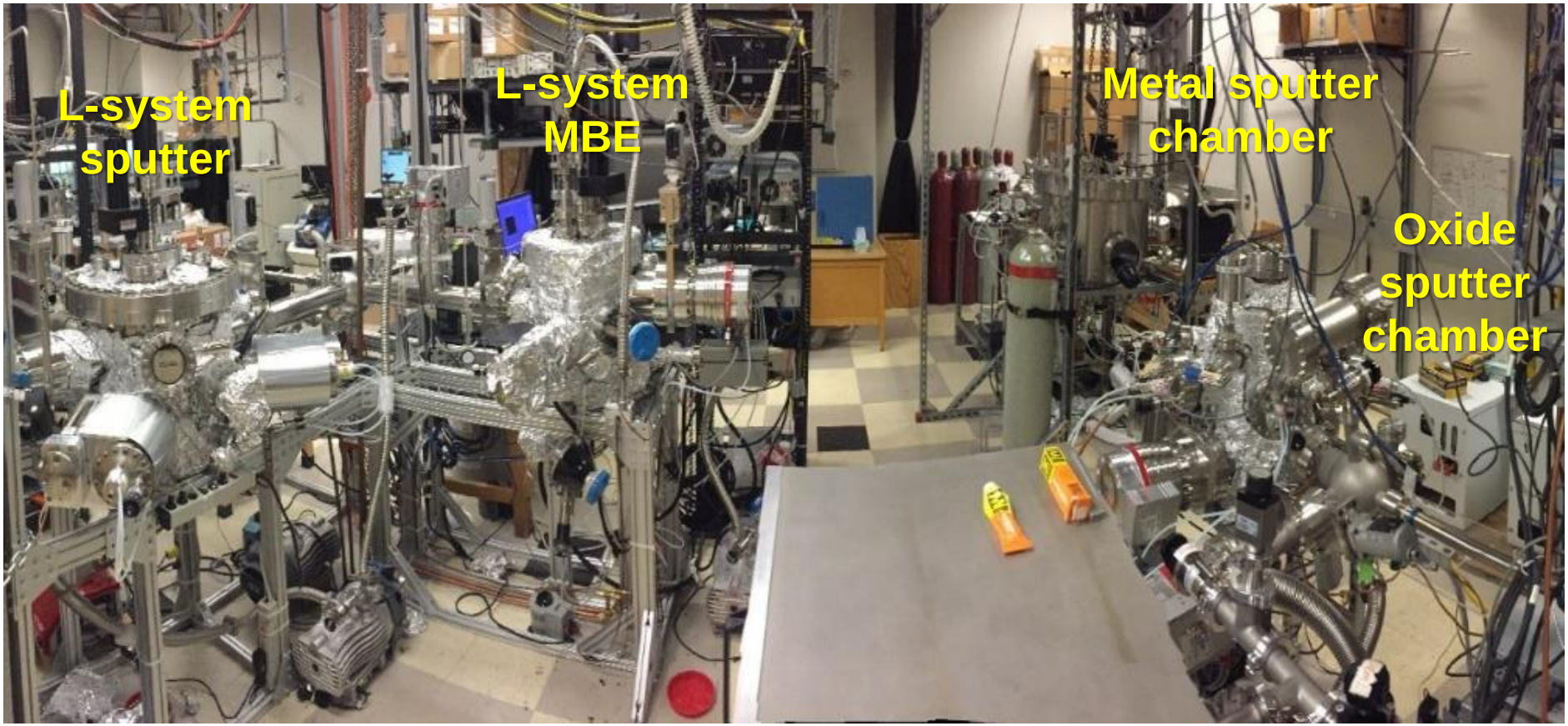


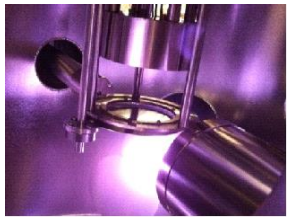
Demand for High Quality Films

- Modern condensed matter and materials research demand and start with high quality materials
- Single crystalline materials are arguably the most important class of materials for this purpose
  - Bulk single crystals
  - Single crystal films and multilayers by epitaxy



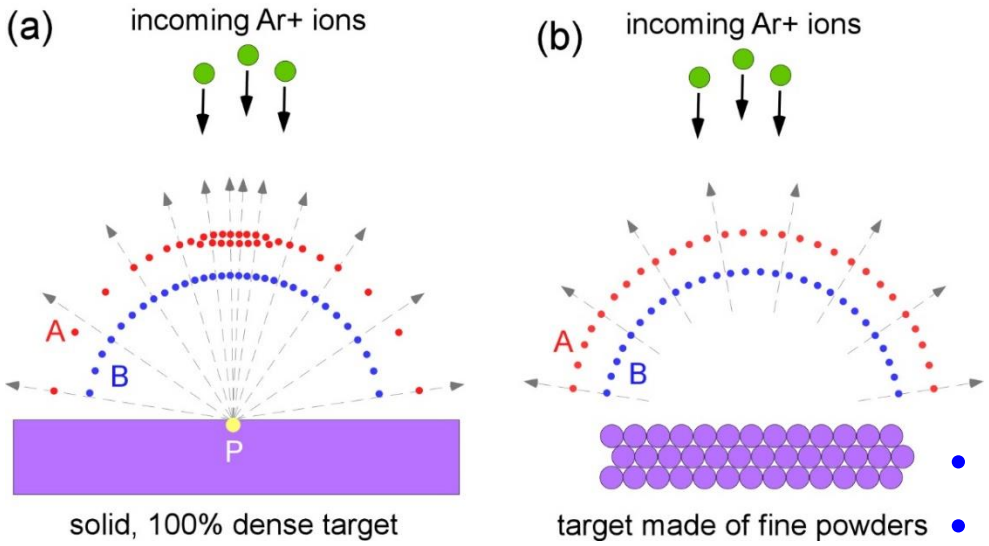
Deposition of Epitaxial Films of Wide Range of Materials: Innovative Off-Axis UHV Sputtering

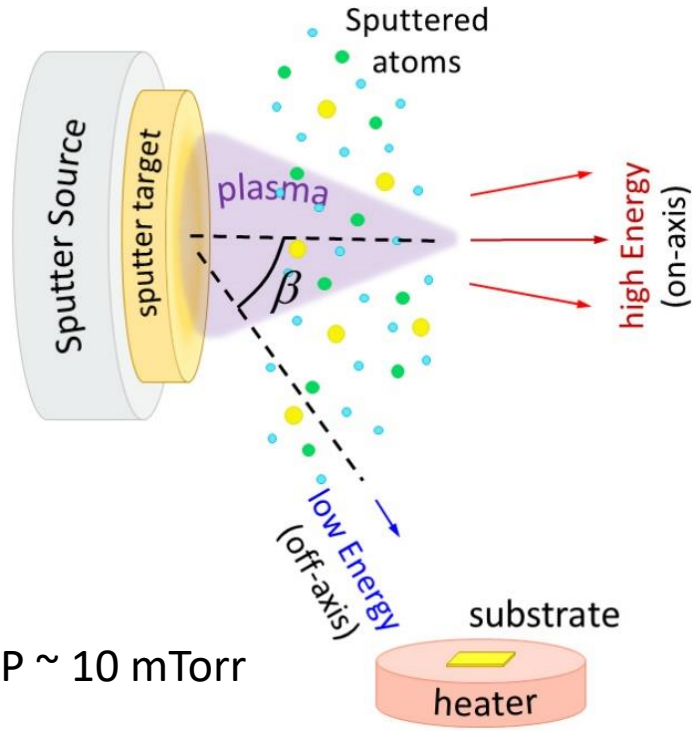




Deposition of Epitaxial Films of Wide Range of Materials: Innovative Off-Axis UHV Sputtering

- Sputtering target
  - Phase-pure, powder target
- Total pressure
- Sample position
- Deposition rate
- O_2 content





P ~ 10 mTorr

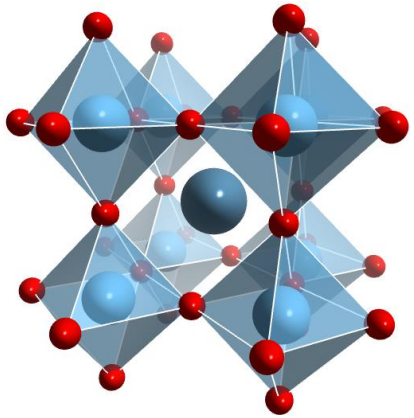
β: 50° - 60°

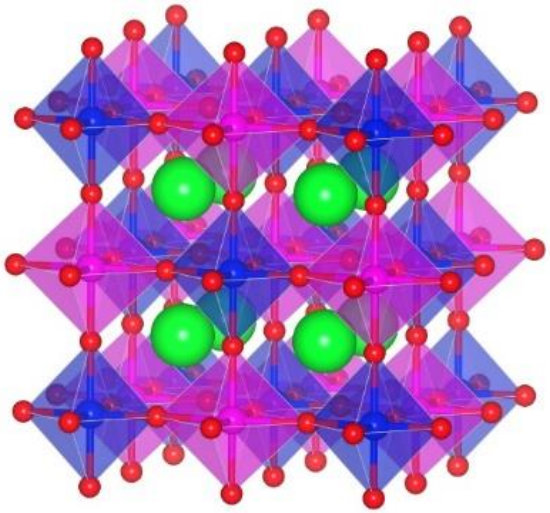
- Stoichiometry (complex materials)
- Phase purity
- Compositional uniformity
- Crystal ordering

Yang & Hammel, *J. Phys. D, Topical Review*, 51, 253001 (2018)

Perovskites & Double Perovskites

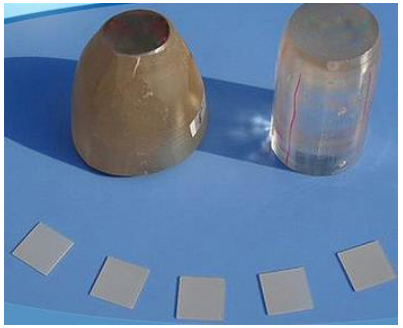
ABO_3 single perovskite & $A_2BB'O_6$ double perovskite





ABO_3 perovskites (e.g., $SrTiO_3$):

- 100s – 1000s compounds
- High T_c superconductivity
- Ferromagnetism
- Antiferromagnetism
- Ferroelectricity
- Piezoelectricity
- Multiferroics
- Solar cells



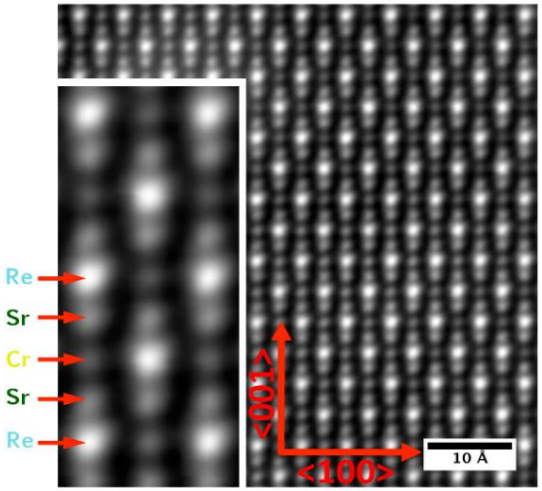
$A_2BB'O_6$ double perovskite (e.g., Sr_2CrReO_6):

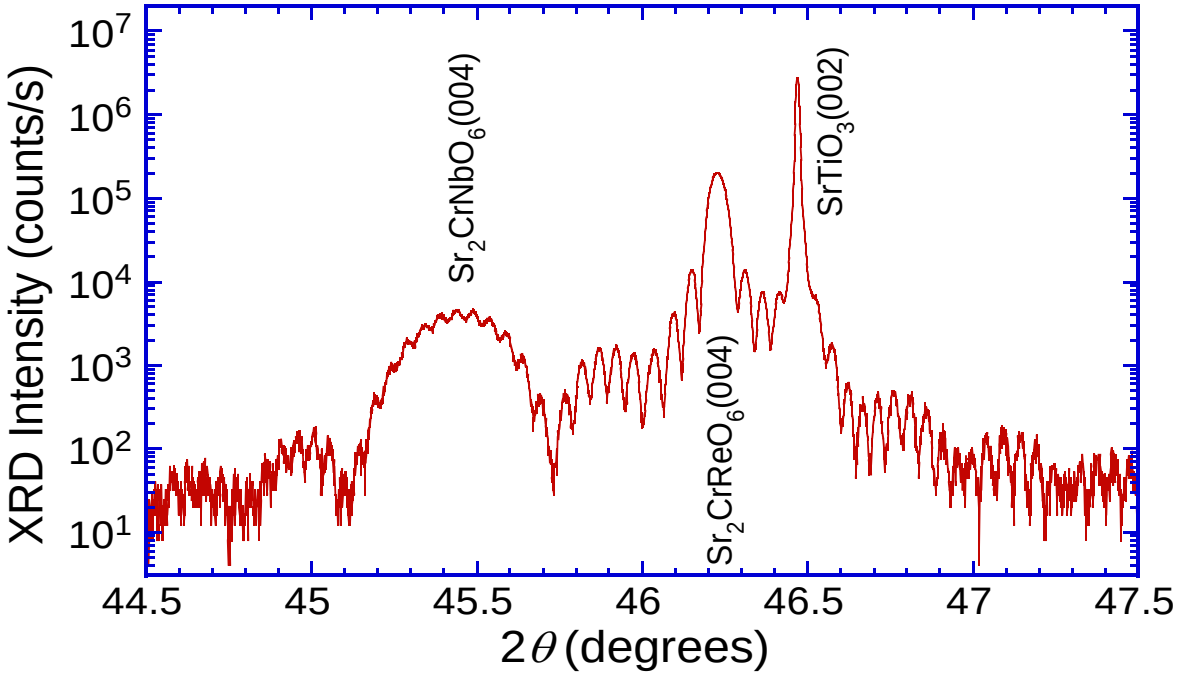
- Ferrimagnetism
- High Curie temperature
- Half-metallic (100% spin polarization)

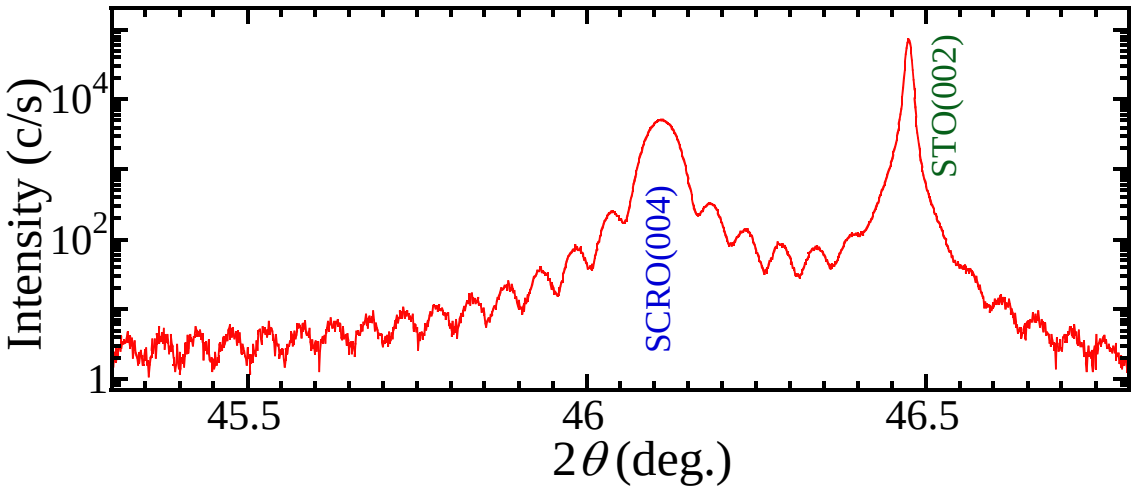
Epitaxial Films of Double Perovskites

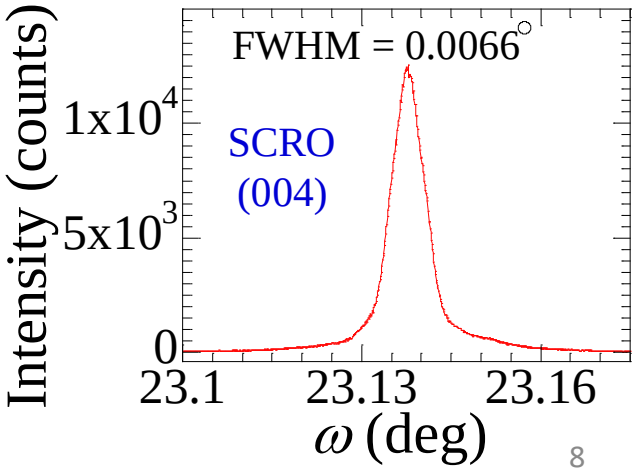
$A_2BB'O_6$ double perovskite

Sr_2CrReO_6









Extraordinary magnetic anisotropy in Sr_2CrReO_6 films

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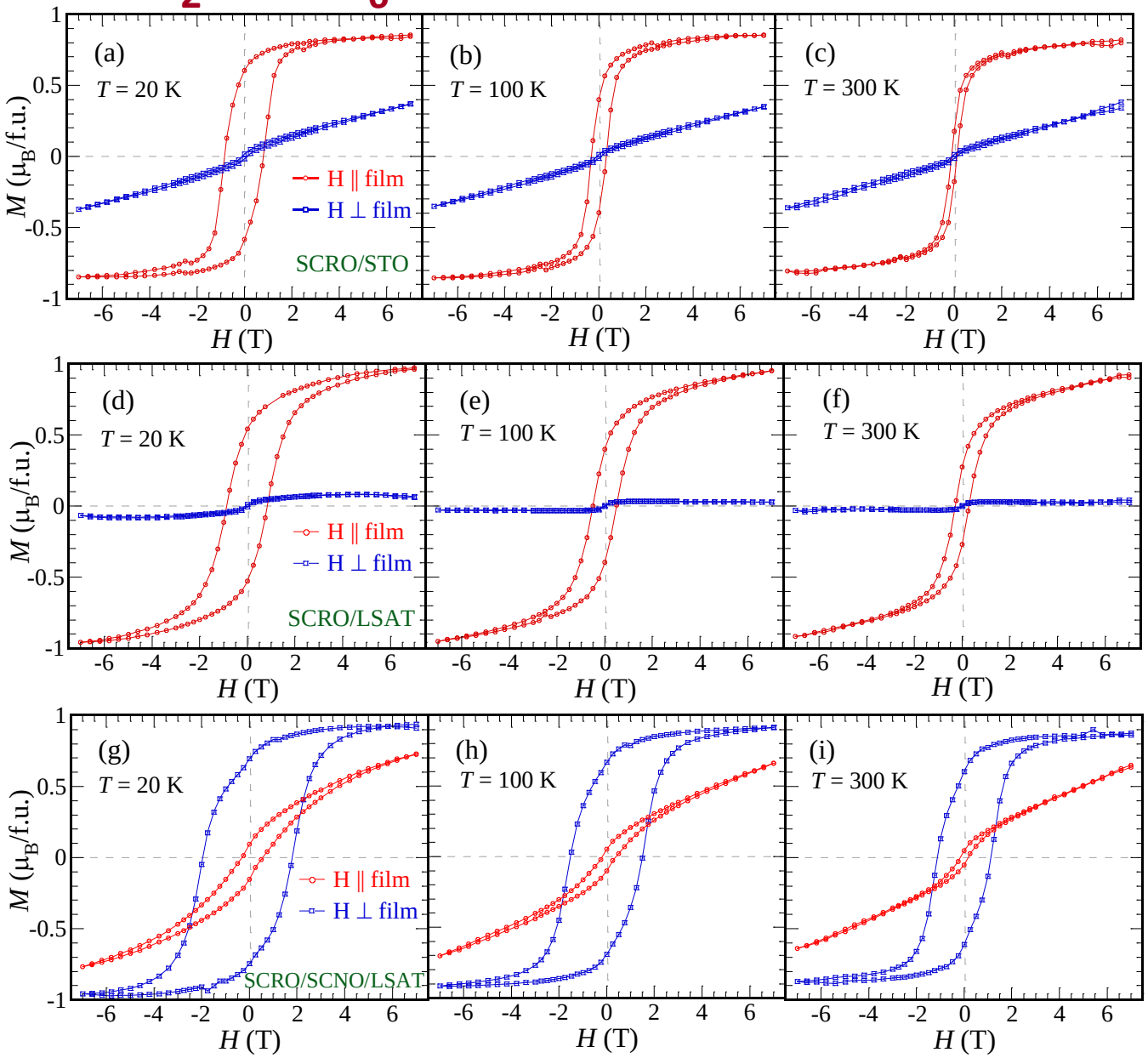

- 90-nm Sr_2CrReO_6 films as a function of strain and temperature
- Magnetocrystalline anisotropy as large as tens of Tesla
- Perpendicular magnetic anisotropy for Sr_2CrReO_6 films grown on Sr_2CrNbO_6 buffer layers on $SrTiO_3$ with tensile strain

Lucy, et al. *Phys. Rev. B* **90**, 180401(R) (2014).

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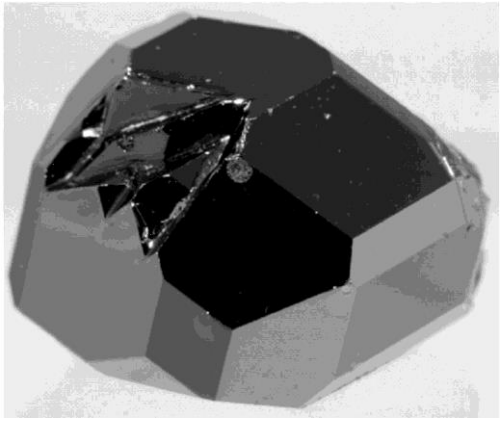
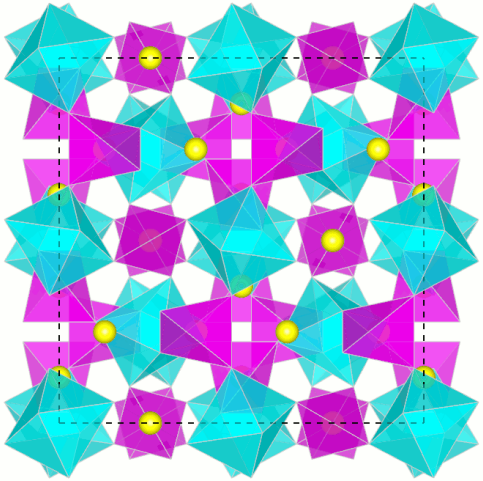
Garnets

$A_3B_5O_{12}$ garnets



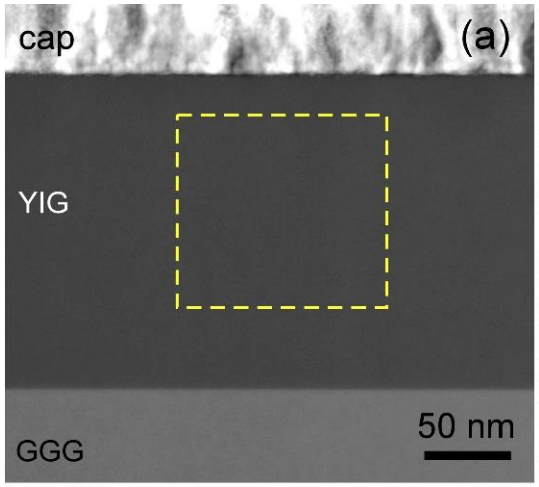


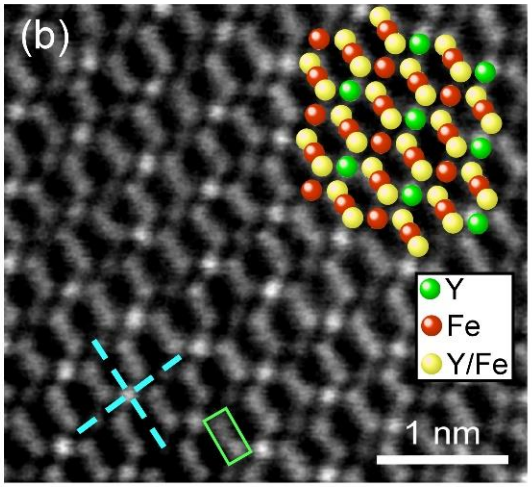
$Y_3Fe_5O_{12}$ (YIG):

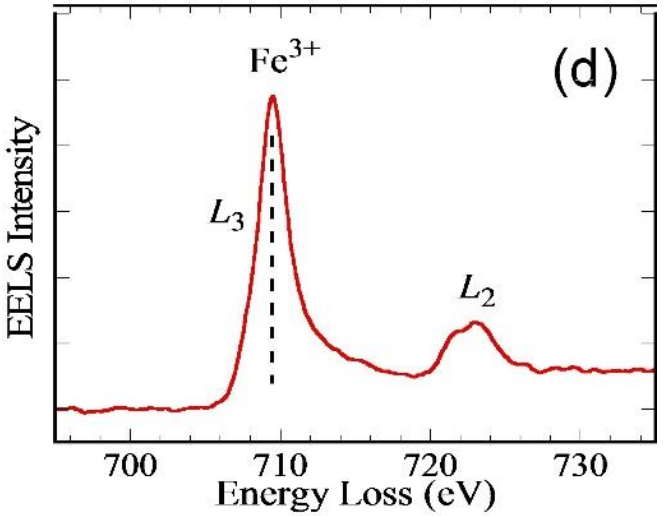
- Ferrimagnetic insulator (ferrites)
  - Extremely low damping, low loss
  - Microwave ferrites are ubiquitous in systems that send, receive, and manipulate electromagnetic signals across very high frequency to quasi-optical frequency bands
- Arguably the most important microwave material
  - Microwave filters
  - Microwave oscillators
  - Frequency synthesizers
  - Microwave circulators
  - Microwave circuits
- Radars
- Telecommunication

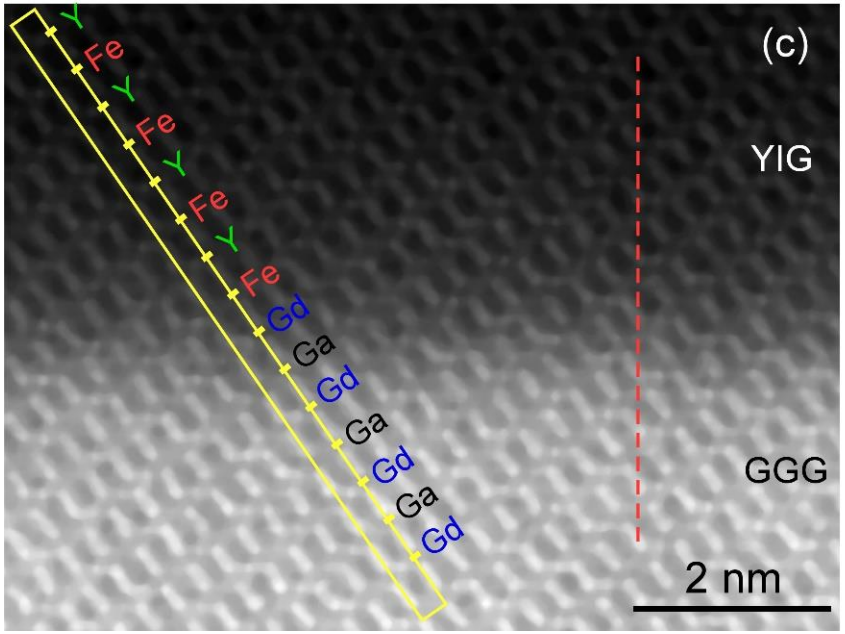
Epitaxial Films of Magnetic Garnets

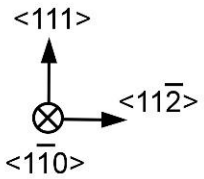
$Y_3Fe_5O_{12}$ (YIG)

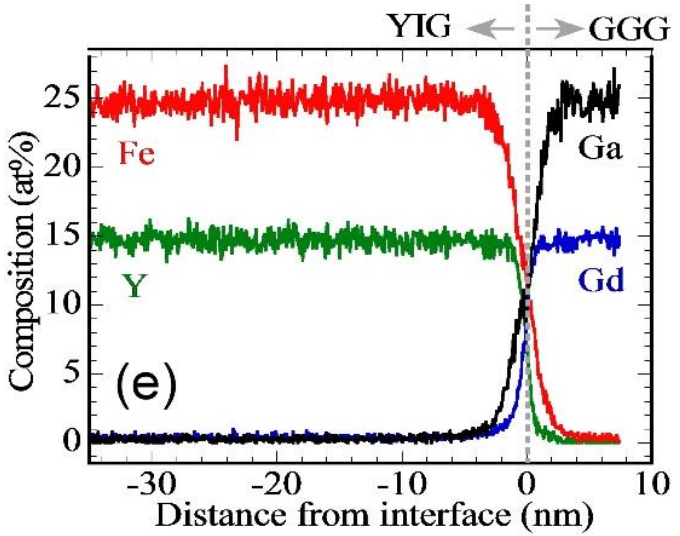






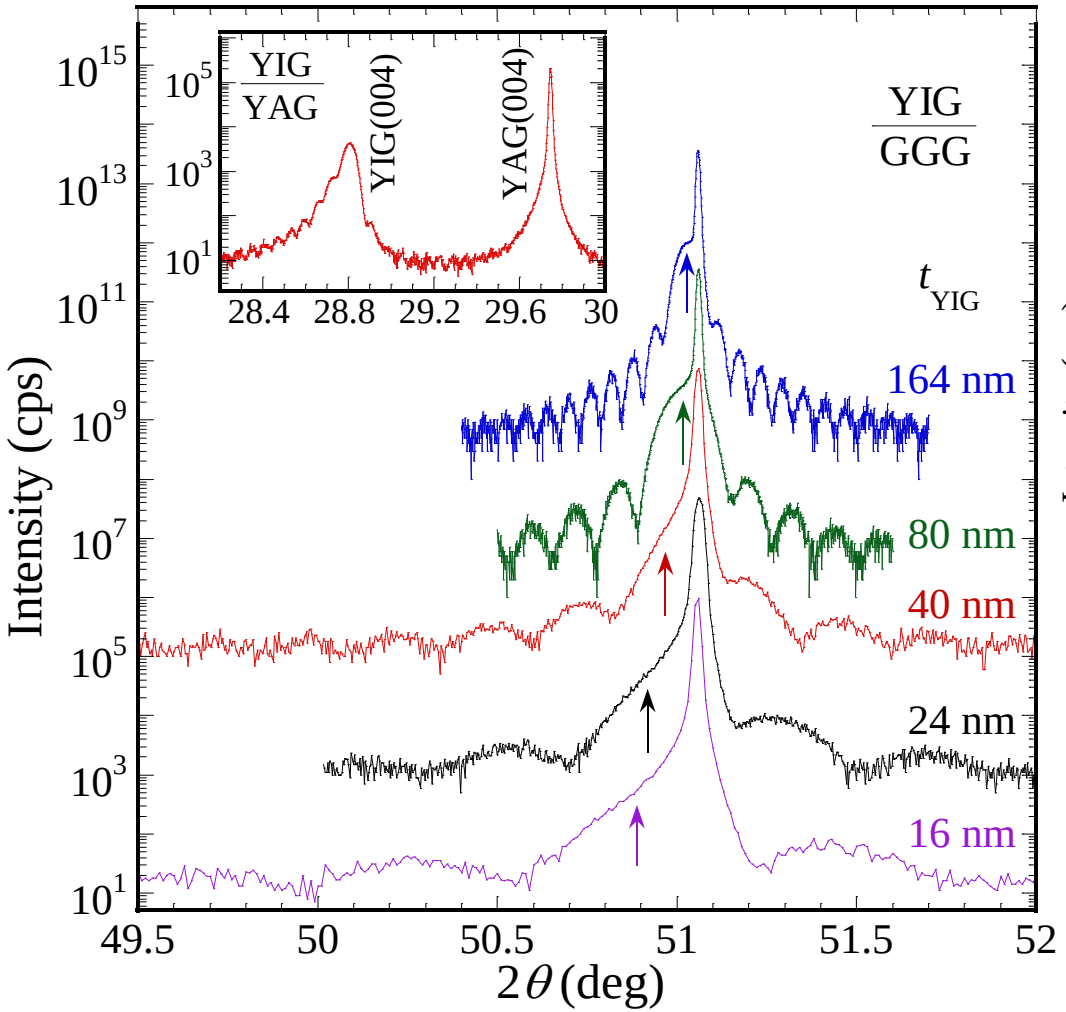


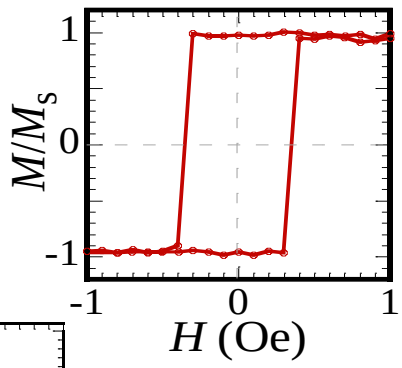


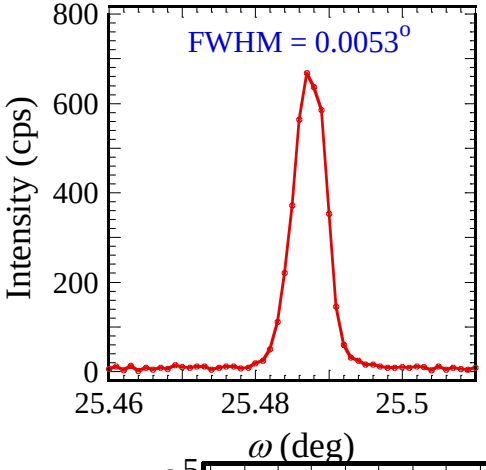


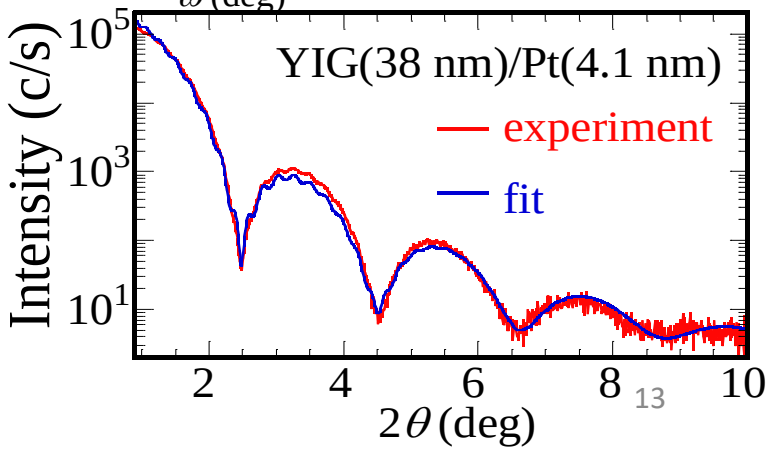
Epitaxial Films of Magnetic Garnets

$Y_3Fe_5O_{12}$ (YIG)



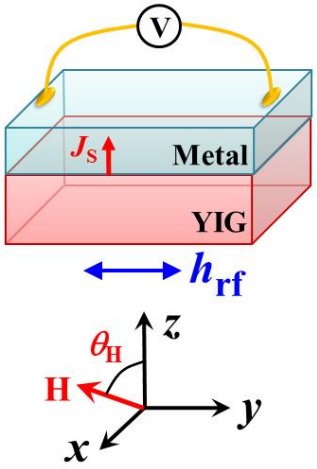




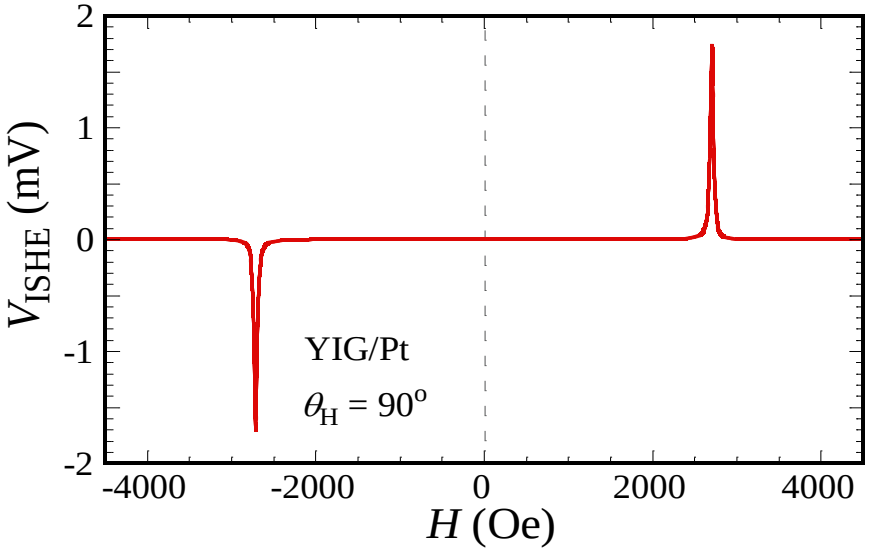


Spin pumping in YIG/metal bilayers

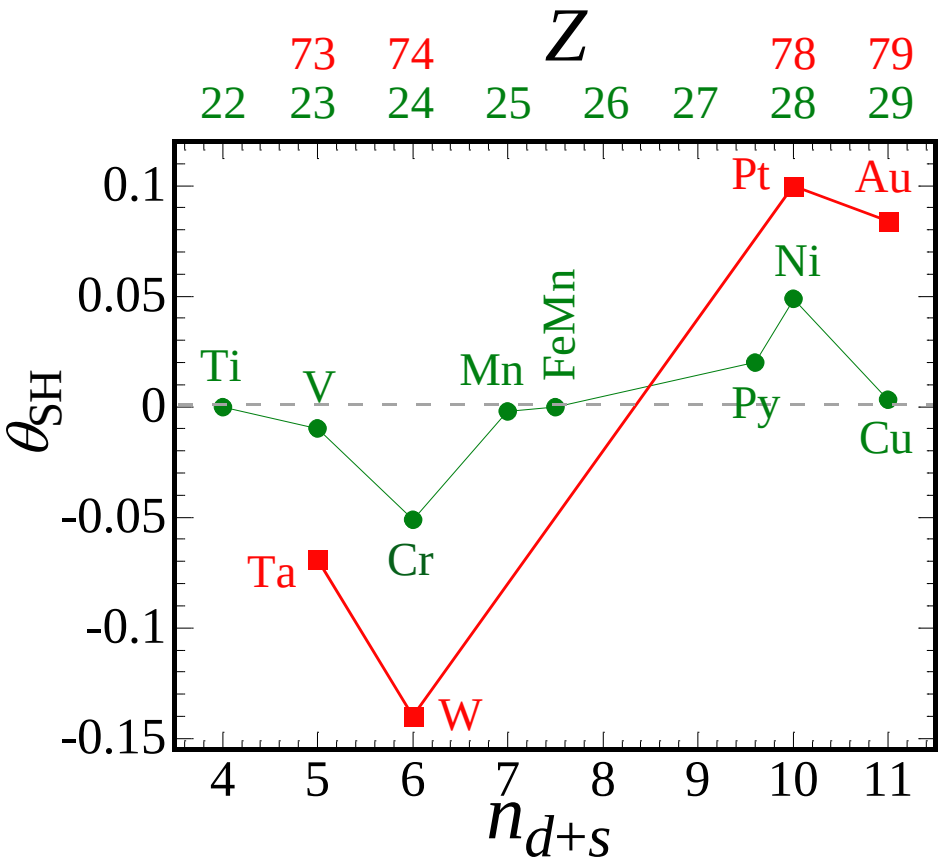
$Y_3Fe_5O_{12}$ (YIG)



Wang, et al. *Phys. Rev. Lett.* **112**, 197201 (2014).



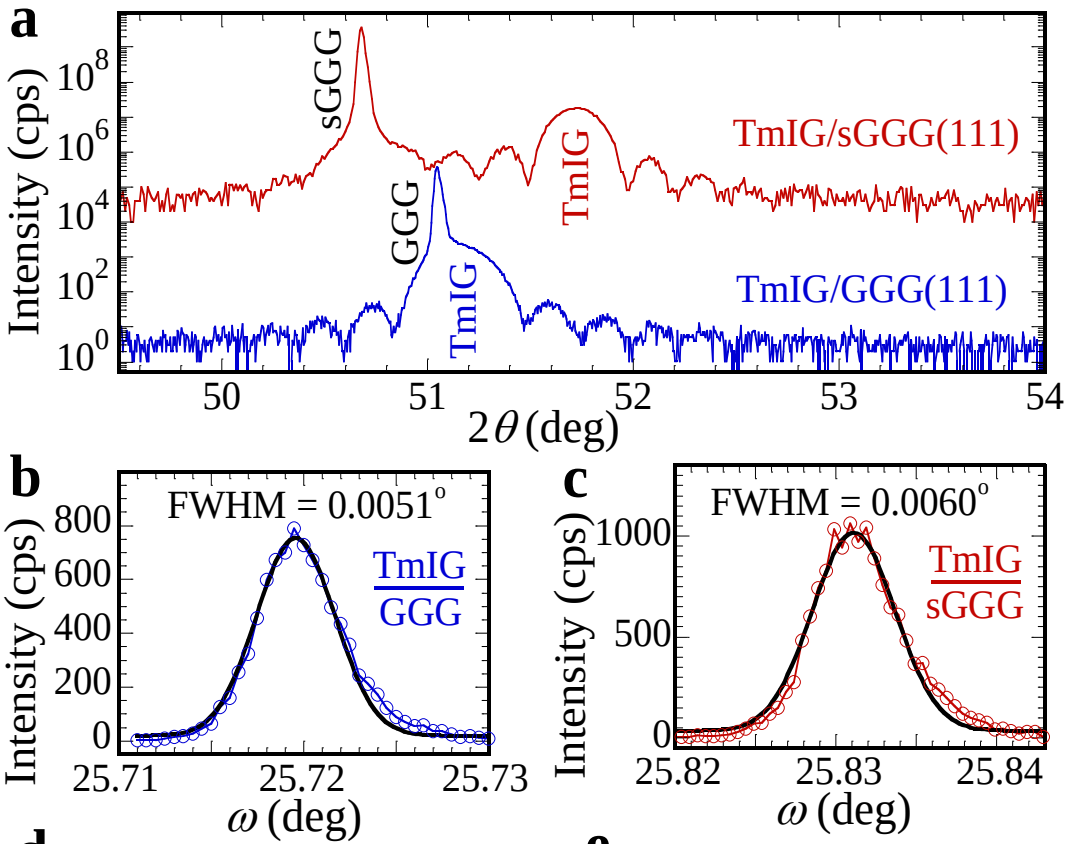
- mV inverse spin Hall voltage

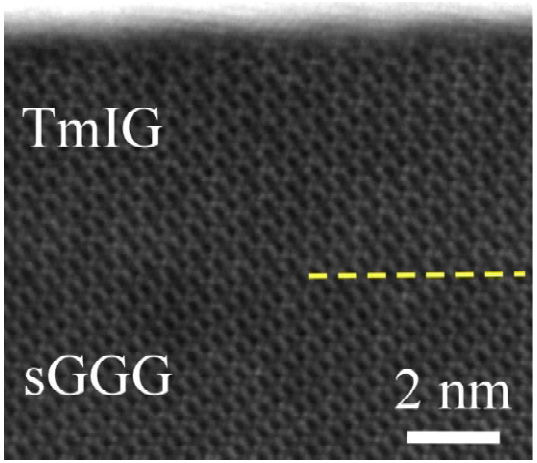


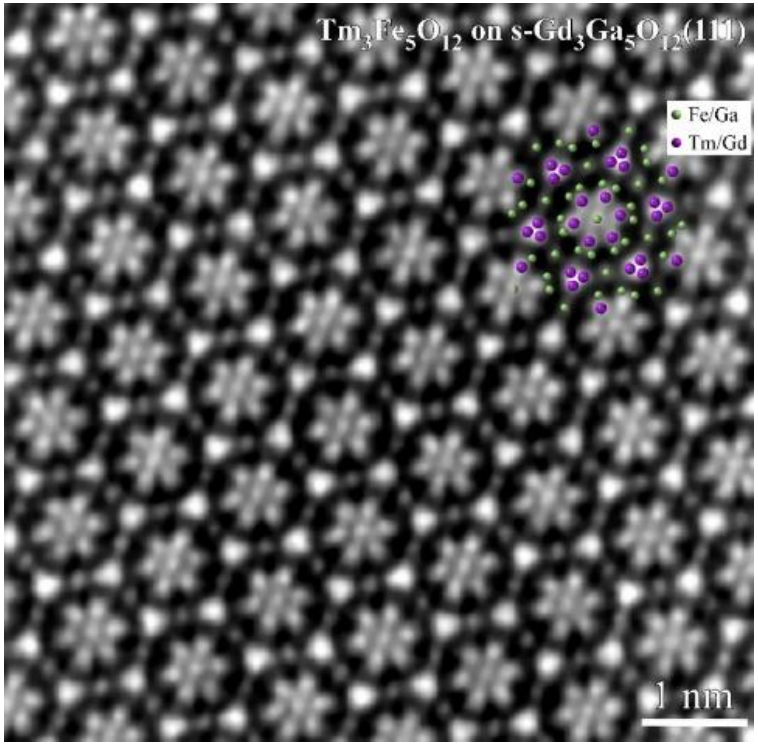
- θ_{SH} changes sign at $n_{d+s} \approx 7$
  - $n_{d+s} = 7 \rightarrow n_d = 5$: half fill
- Surprisingly large θ_{SH} for 3*d* metals

Epitaxial Films of Magnetic Garnets

$Tm_3Fe_5O_{12}$ (TmIG)

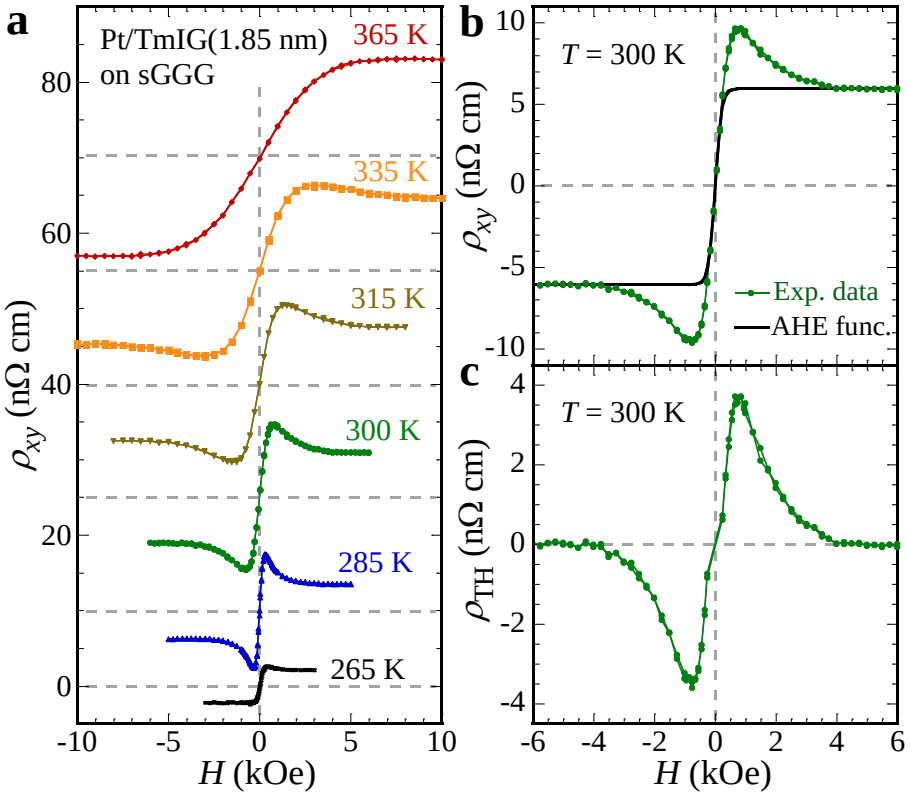


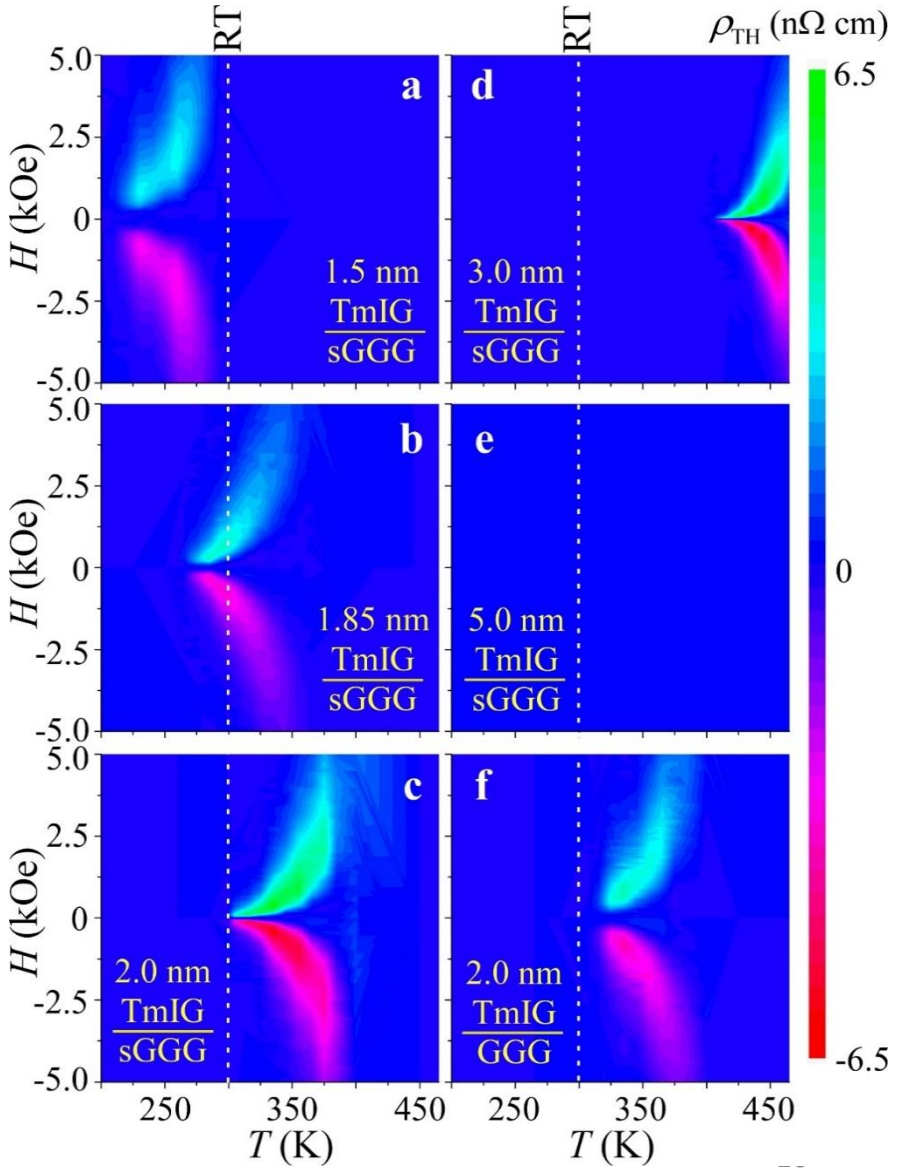




Magnetic skyrmions in TmIG/Pt thin bilayers

$Tm_3Fe_5O_{12}$ (TmIG)





Ahmed, et al. *Nano Lett.* **19**, 5683 (2019).

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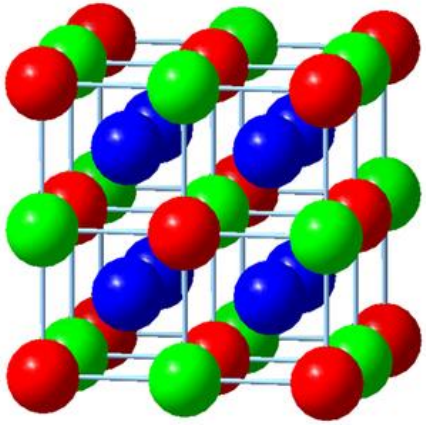
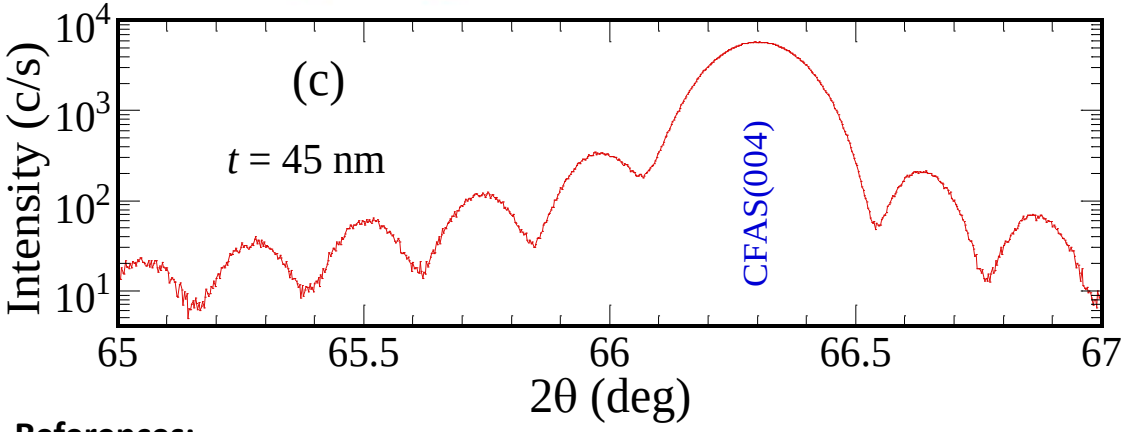
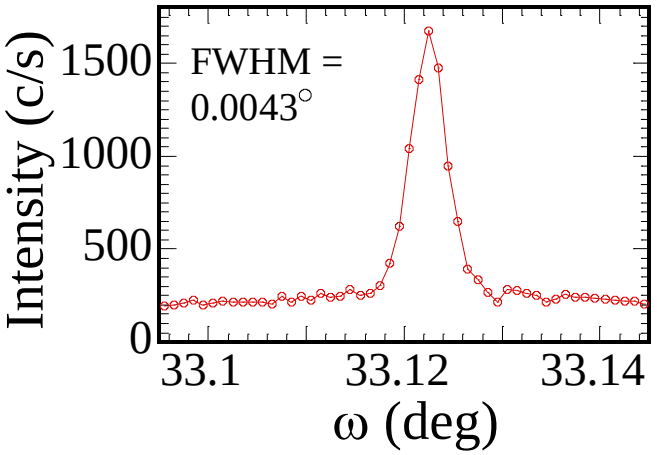
Heusler Compounds

X_2YZ Heusler



- 100s Heusler compounds
- Ferromagnetic
- 100% spin polarization
- Topological insulators
- Antiferromagnetic Weyl semimetals
- Magnetic skyrmions





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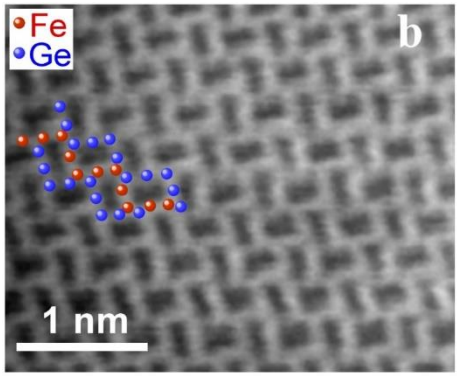
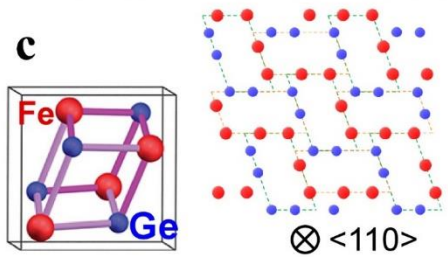
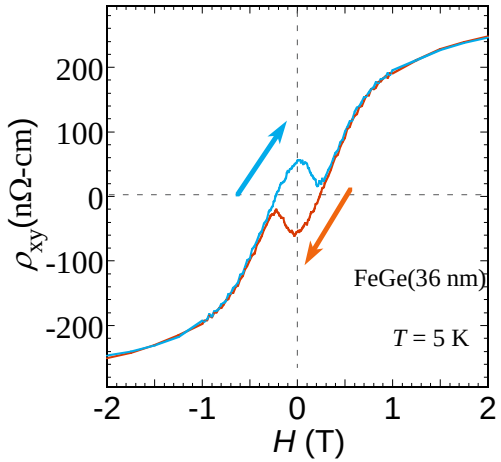
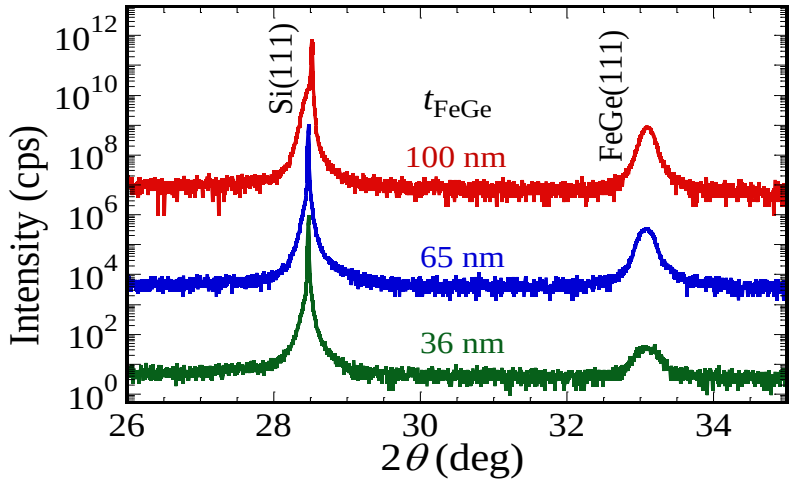
Intermetallics, Metals, and Alloys

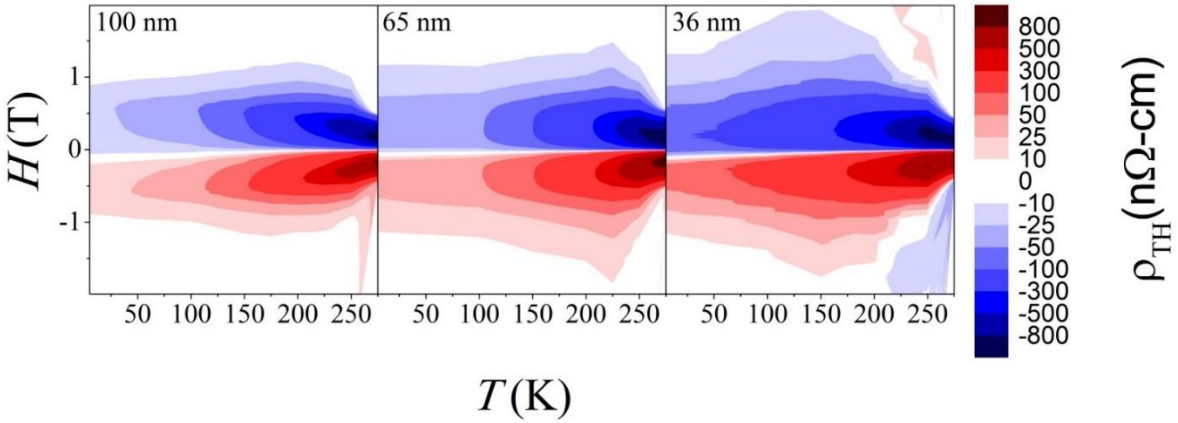
B20 compounds: Magnetic skyrmions; Novel magnetism











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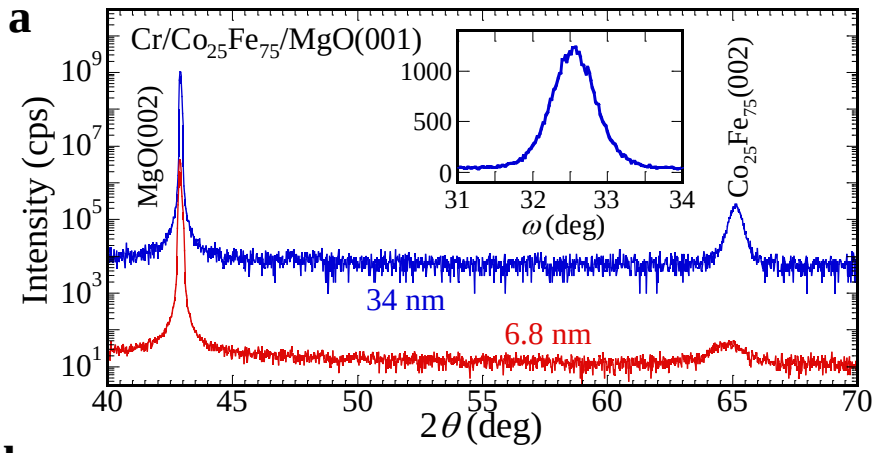
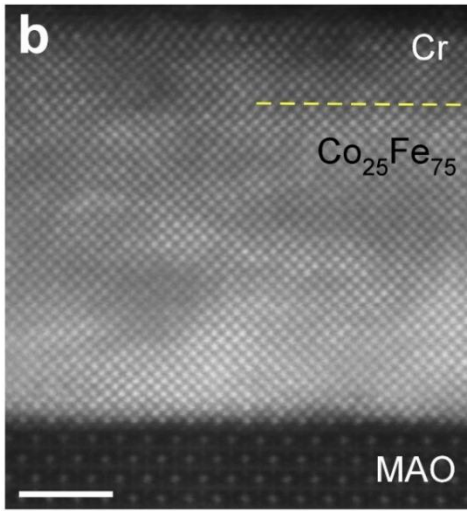
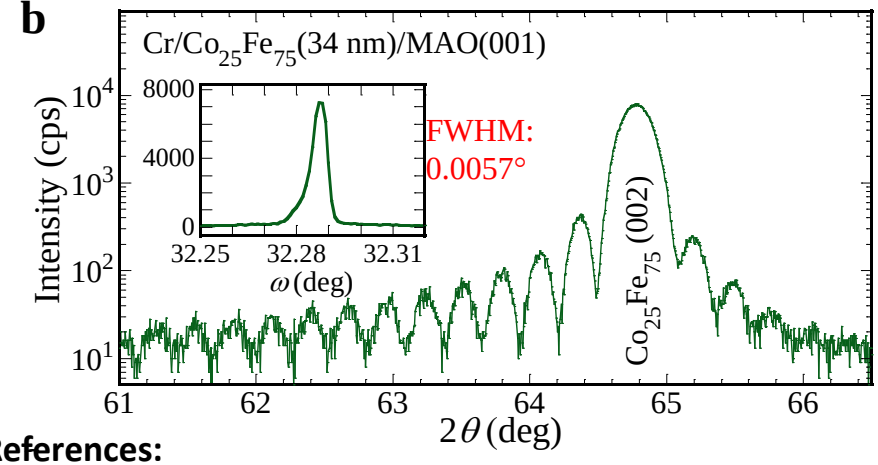
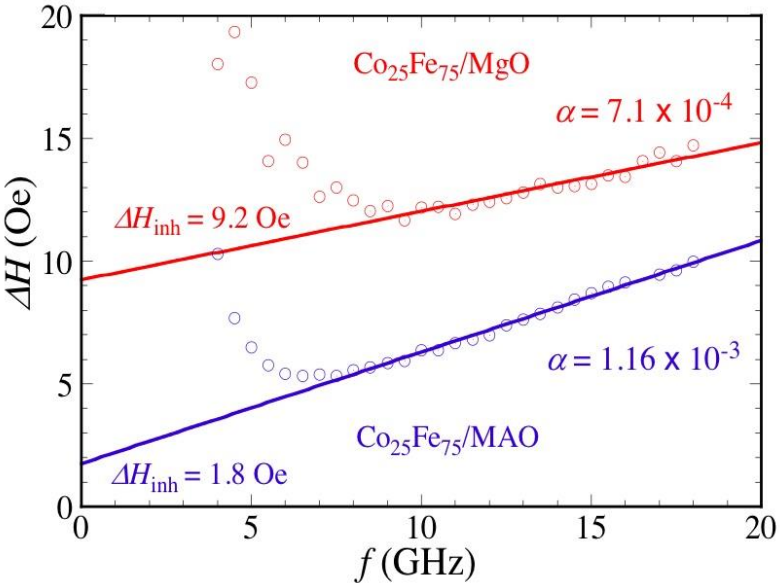
Ultralow damping in metallic ferromagnetic films



$Co_{25}Fe_{75}$







Ultralow magnetic damping

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Outlook

What materials can be grown into good epitaxial films by this technique?

- Elements
- Binary alloys and compounds
- Ternary alloys and compounds
- Quaternary alloys and compounds
- More complex compounds possible
- Non-volatile
- Atomically homogeneous, single phase targets

Ohio State University Review:

Deposition of State-of-the-Art Quality Epitaxial Films Using Off-Axis Sputtering

Q&A

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THE OHIO STATE UNIVERSITY

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Ohio State University Review:

Deposition of State-of-the-Art Quality Epitaxial Films Using Off-Axis Sputtering

Thank you!

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