Resonant scattering studies of nanometer scale structure-property relationships (mostly magnetism)

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Features of scattering in the soft x-ray region

Low *q* scattering:
- structure in 1 *μm* – 1 *nm* range
- disordered & ordered structures
- “incoherent” & “coherent”
- transmission, reflection, …
- all photon technique

SXR resonances:
- *many* relevant edges in 200 – 2000 eV range
- *sharp* lines (*large* enhancements, scattering contrast)
- chemical, charge, spin sensitivity
- well-developed spectroscopies

Opportunities to extend spatially averaging spectroscopies into spatially resolving scattering techniques:

- magnetic heterogeneity
- chemical heterogeneity
- charge, orbital order
- electronic phase separation
- heterogeneous polymers

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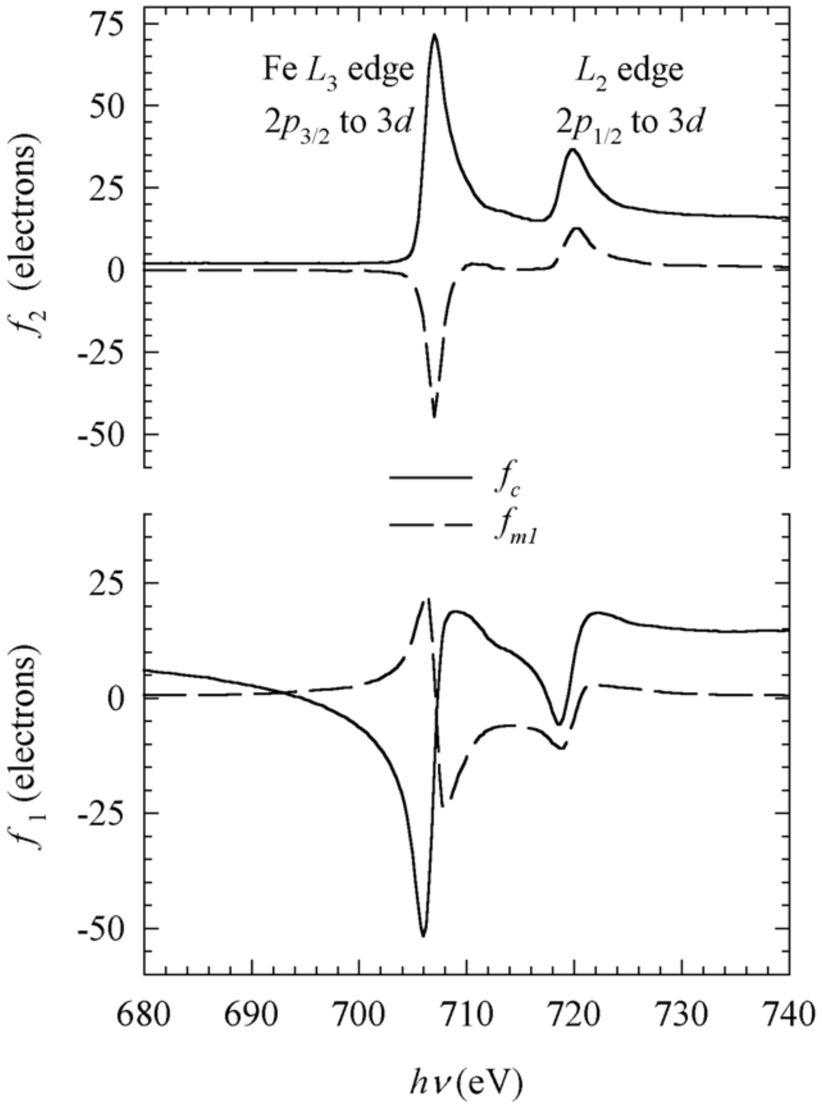
Charge & magnetic scattering factors for Fe across $L_{2,3}$ edges.

PRB **62**, 12216 (2000)



$$f \cong (\mathbf{e}_f^* \cdot \mathbf{e}_0) f_c - i(\mathbf{e}_f^* \times \mathbf{e}_0) \cdot \mathbf{m} f_{m1}$$

$$= p_c f_c - p_m f_{m1}$$

$$f_{\pm} \cong f_c \mp f_{m1}$$

Assumptions (PRB **64,** 092401 (2001)):

- circular polarization basis
- small θ
- **k** || **m**
- particles scatter like big atoms

Scattered intensity (circular basis)

$$I_{\pm}(q,\omega,H) = \sum_i \sum_j f_{i\pm}^* f_{j\pm} \exp[i\mathbf{q}\cdot\mathbf{r}_{ij}]$$

$$= f_c^2 s_{c-c} + f_m^2 s_{m-m} \pm 2(f_{2c}f_{1m} - f_{1c}f_{2m})s_{c-m}$$

Intensity sum:

$$I_+ + I_- \cong f_c^2 s_{c-c} + f_m^2 s_{m-m}$$

$$I_{linear} \cong \frac{I_+ + I_-}{2}$$

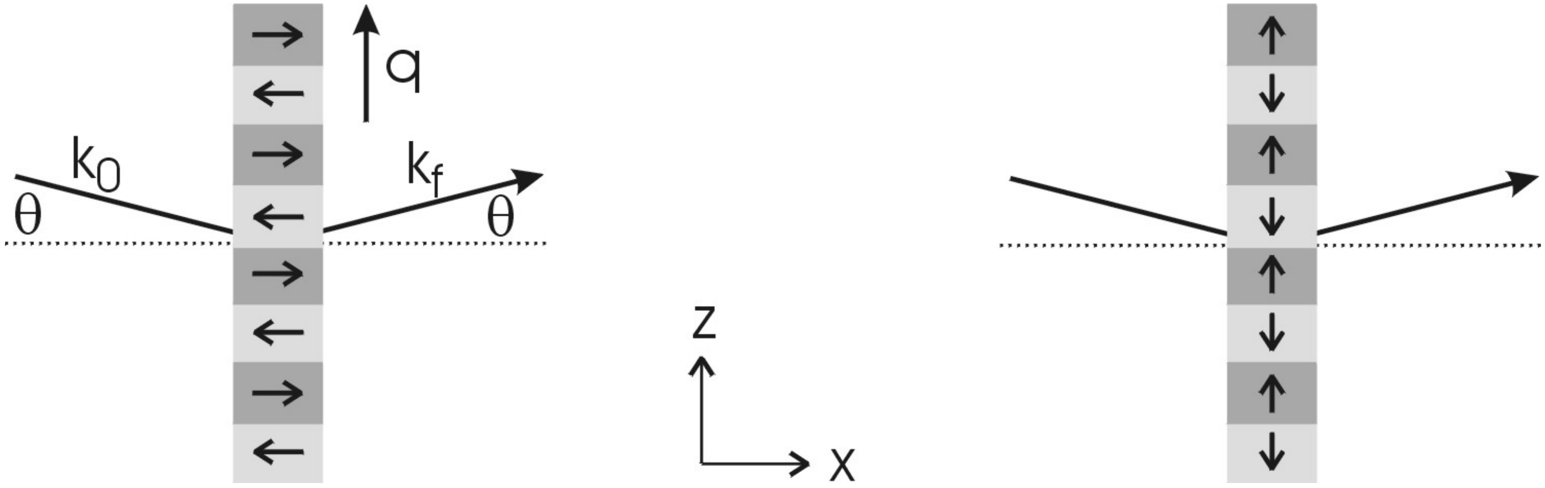
Intensity difference:

$$I_+ - I_- \propto (f_{2c}f_{1m} - f_{1c}f_{2m})s_{c-m}$$

(Osgood, et al., JMMM **198** ('99))

Correlation functions $s_{c\text{-}c}(q)$, $s_{m\text{-}m}(q,H,\omega)$, $s_{c\text{-}m}(q,H,\omega)$ describe spatial correlations of interest.

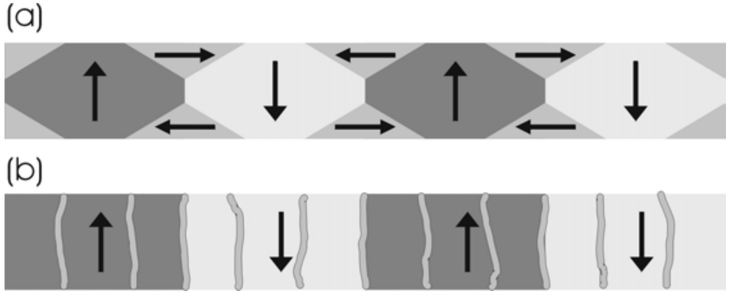
Transmission scattering geometry



$p_{m1} \sim \cos\theta$

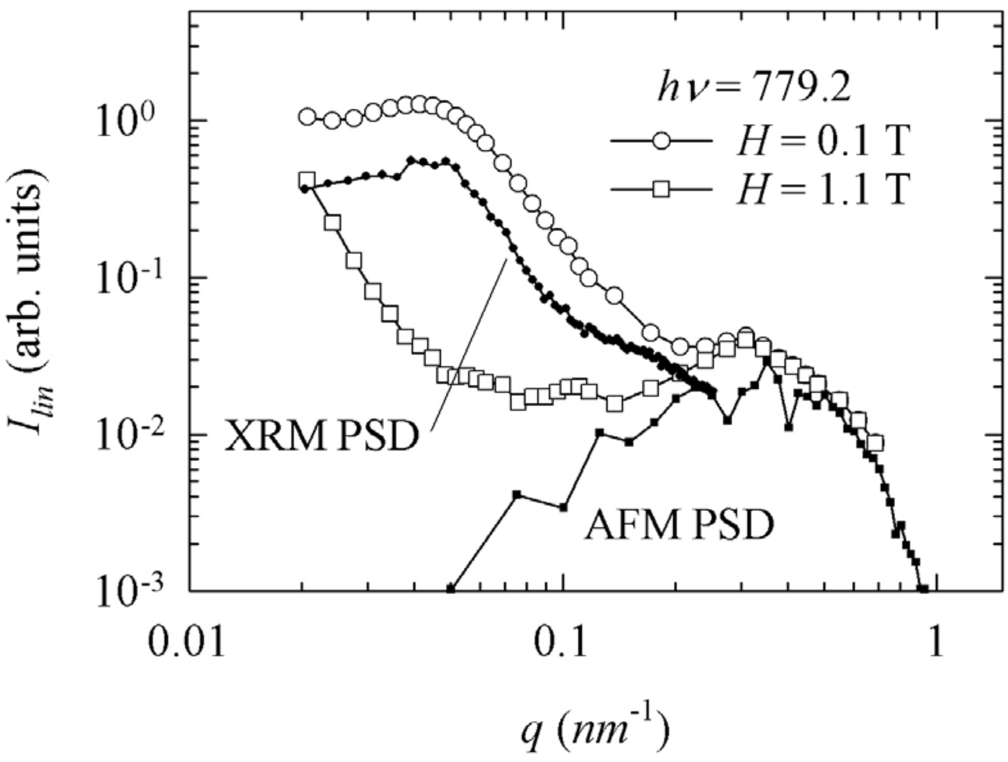
$p_{m1} \sim \sin\theta$

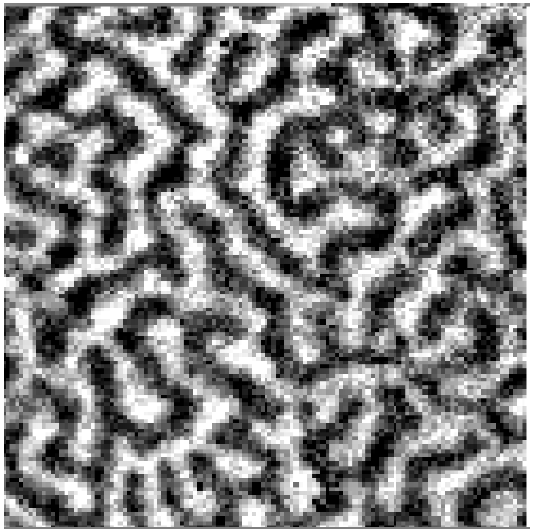
Domains in Co/Pt multilayers, *q* & *r* space



low PMA

high PMA



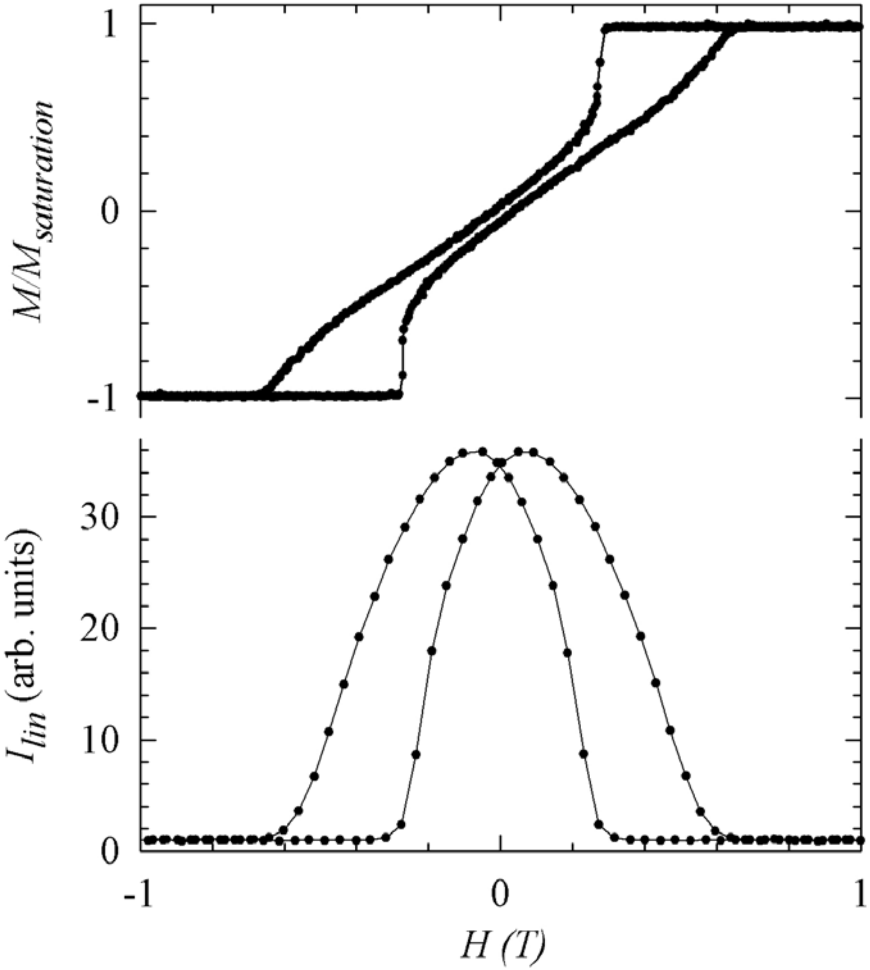


4.5 micron field

Phys. Rev. B **64**, 092401 (2001)

Different views of magnetization reversal

Phys. Rev. B **64**, 092401 (2001)

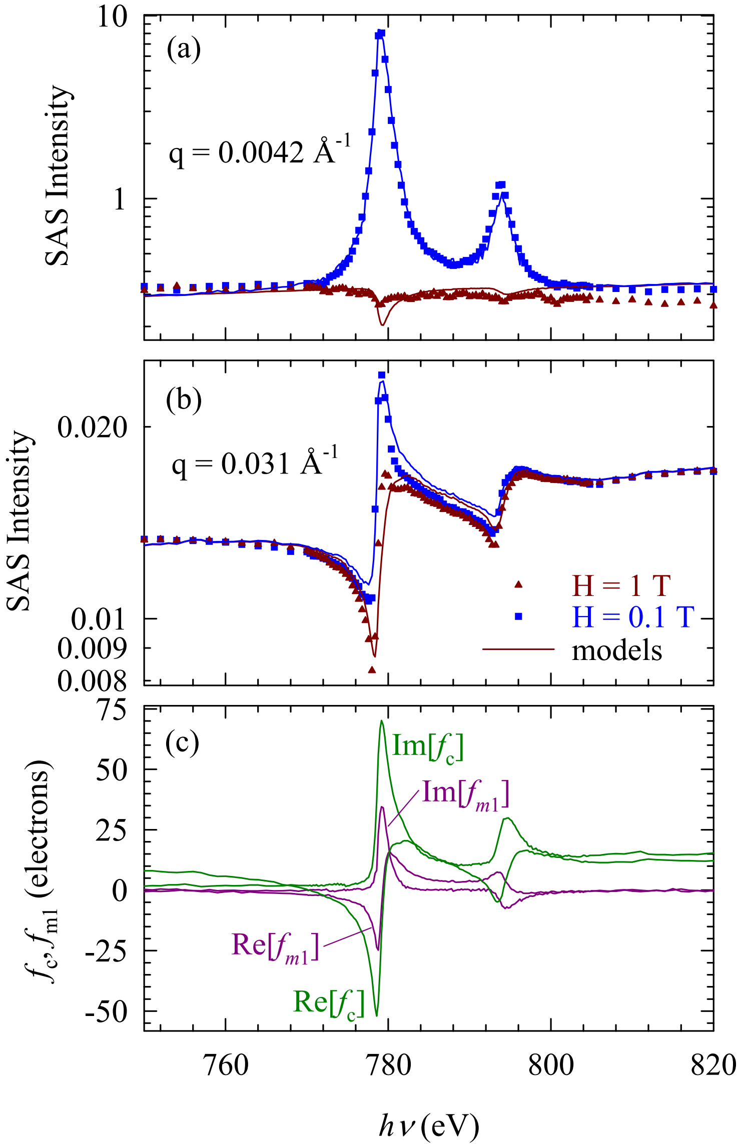


Traditional magnetometry measures *average* moment vs. H.

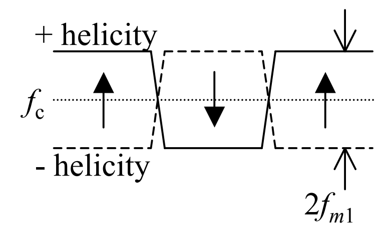
Scattering measures *deviations from average* moment vs. H

Modeling energy scans confirms pure magnetic & charge contributions, I_{lin} model.

Phys. Rev. B **64**, 092401 (2001)



Pure magnetic + non-resonant background



Pure charge at saturation, with added pure magnetic at remanence.

$$2I_{lin} = I_+ + I_- \cong f_c^2 s_{c-c} + f_m^2 s_{m-m}$$

Extensions of scattering from domains in Co/Pt films.

Speckle metrology – domain memory vs. disorder

M. S. Pierce, *et al*., Phys. Rev. Lett. **90**, 177502 (2003)

Perpendicular exchange-bias – effects on domain structure

O. Hellwig, *et al.,* Phys. Rev. B **65**, 144418 (2002)

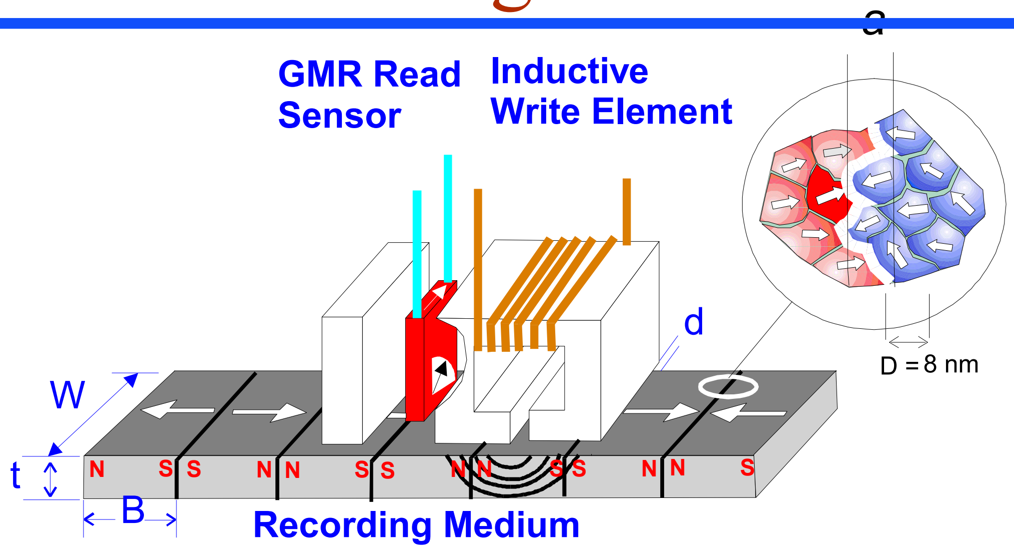
AF indirect exchange coupling – effects on domain structure

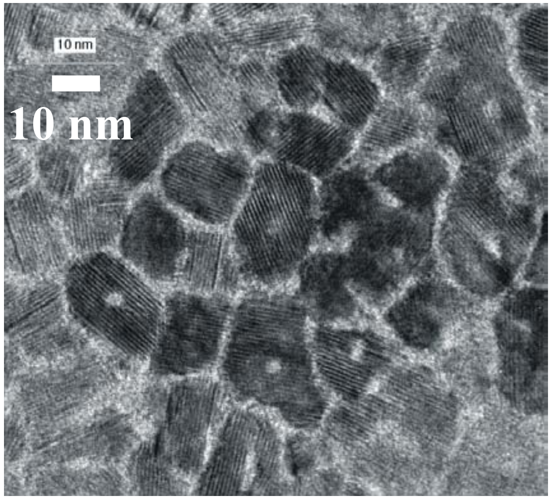
O. Hellwig, *et al*., Nature Materials, **2**, 112 (2003)

Breathing mode in aligned stripe domains

O. Hellwig, *et al*., Physica B **336**, 136 (2003)

Granular alloy recording media: what is magnetic correlation length?

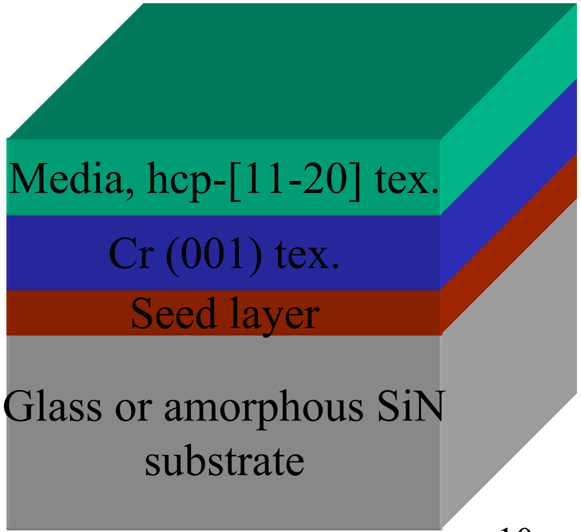




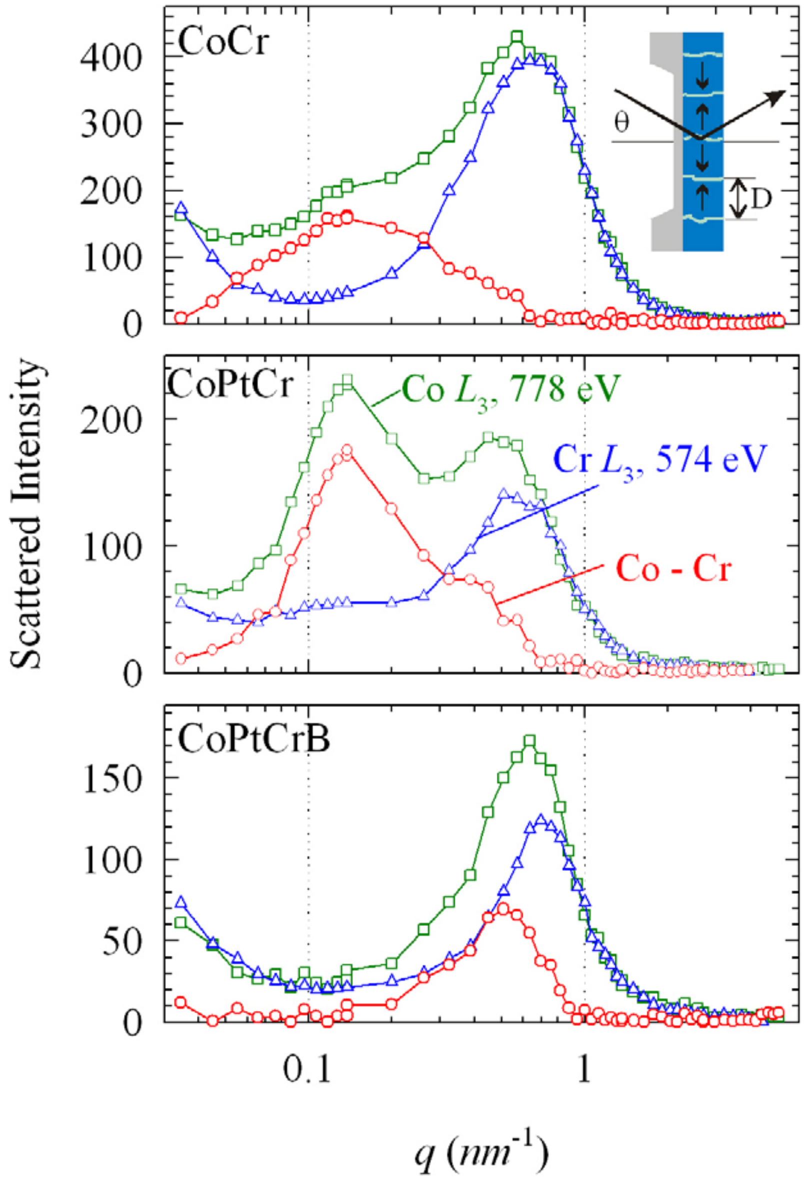
Sharpness of bit transition determines recording density.

Intergranular exchange interactions limit sharp bit transitions.

Magnetic correlation length should be a measure of intergranular exchange.



Co, Cr resonant scattering for 3 recording alloys



Appl. Phys. Lett. **80**, 1234 (2002)

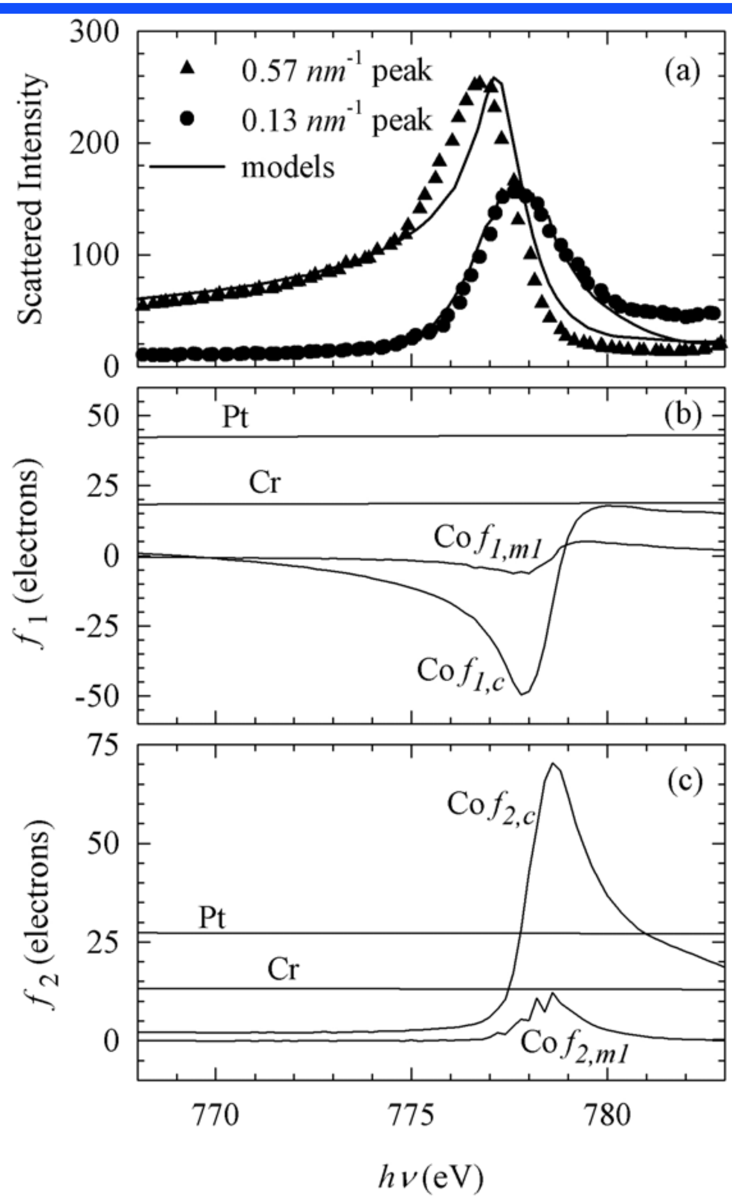
Cr ~ non-magnetic:
predominantly charge

Co magnetic:
magnetic + charge

Co – Cr:
magnetic correlations

Sample	Chemical grain size (nm)	Magnetic correlation length (nm)
CoCr	9.5	42
CoPtCr	10.5	45
CoPtCrB	8.8	~12

Modeling energy scans for CoPtCr alloy



J. Magn. and Magn. Mater. **240**, 325 (2002)

Low *q* peak pure magnetic.

High *q* peak pure charge. Charge spectra very sensitive to composition of grain-boundary (Co:Cr = 1:1) magnetic grain phases (Co:Pt:Cr = 20:2:1).

Conclusions/Directions

Resonant scattering very sensitive to magnetic and chemical structure down to $\lambda/2$.

Generally applicable to broad range of magnetic and other materials where nanometer scale structure is of interest.

q, energy, field scans all provide useful information.

Rich potential for applications across the entire soft x-ray spectral region.