High-Energy Phonon Confinement in Nanoscale Metal Multilayers

Observed by Nuclear Resonant Inelastic X-Ray Scattering (NRIXS)

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Phonon Confinement

Semiconductor superlattices:

____
____________________ GaAs
____________________ AlAs
____________________ GaAs
____________________ AlAs
etc.

e.g., [GaAs/AlAs] superlattices

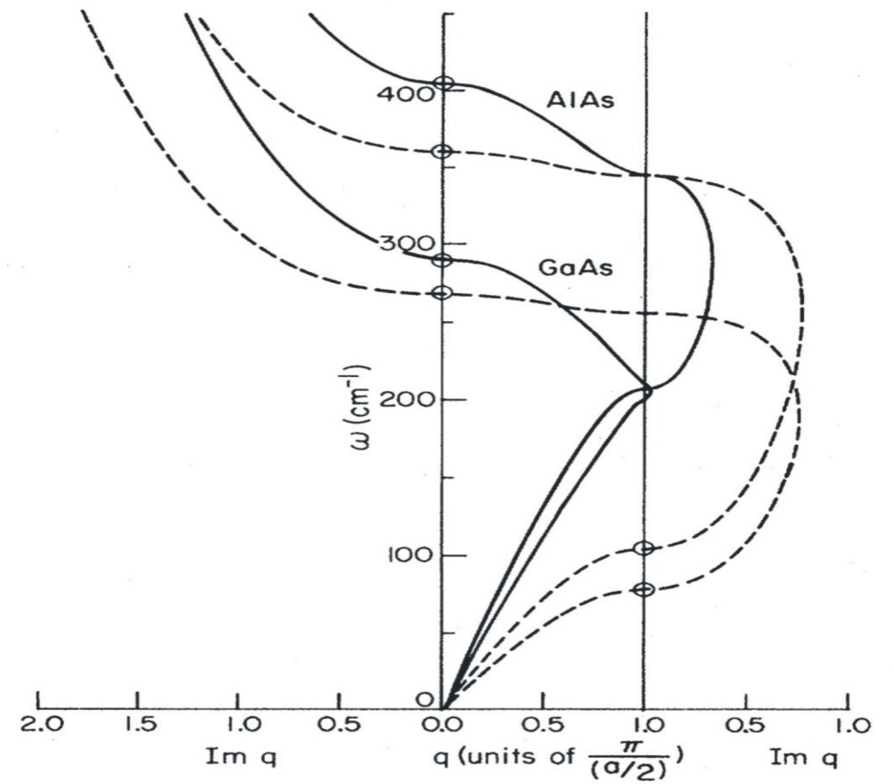
confinement of optical phonons (at k = 0) observed by Raman spectroscopy.
However: no vibrational DOS !

Metal superlattices/multilayers:
Raman spectroscopy not applicable,
only NRIXS provides vibrational DOS !

Important question:

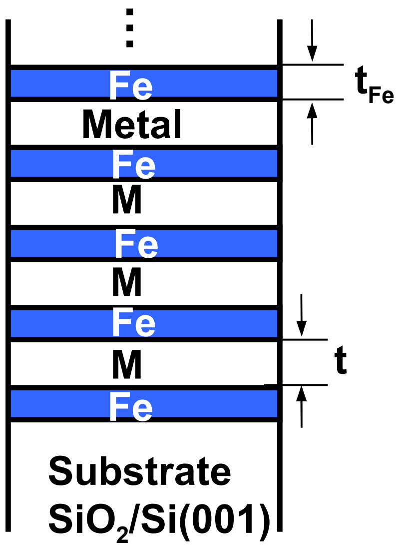
Does the vibrational (phonon) DOS change in nanoscale multilayers ?

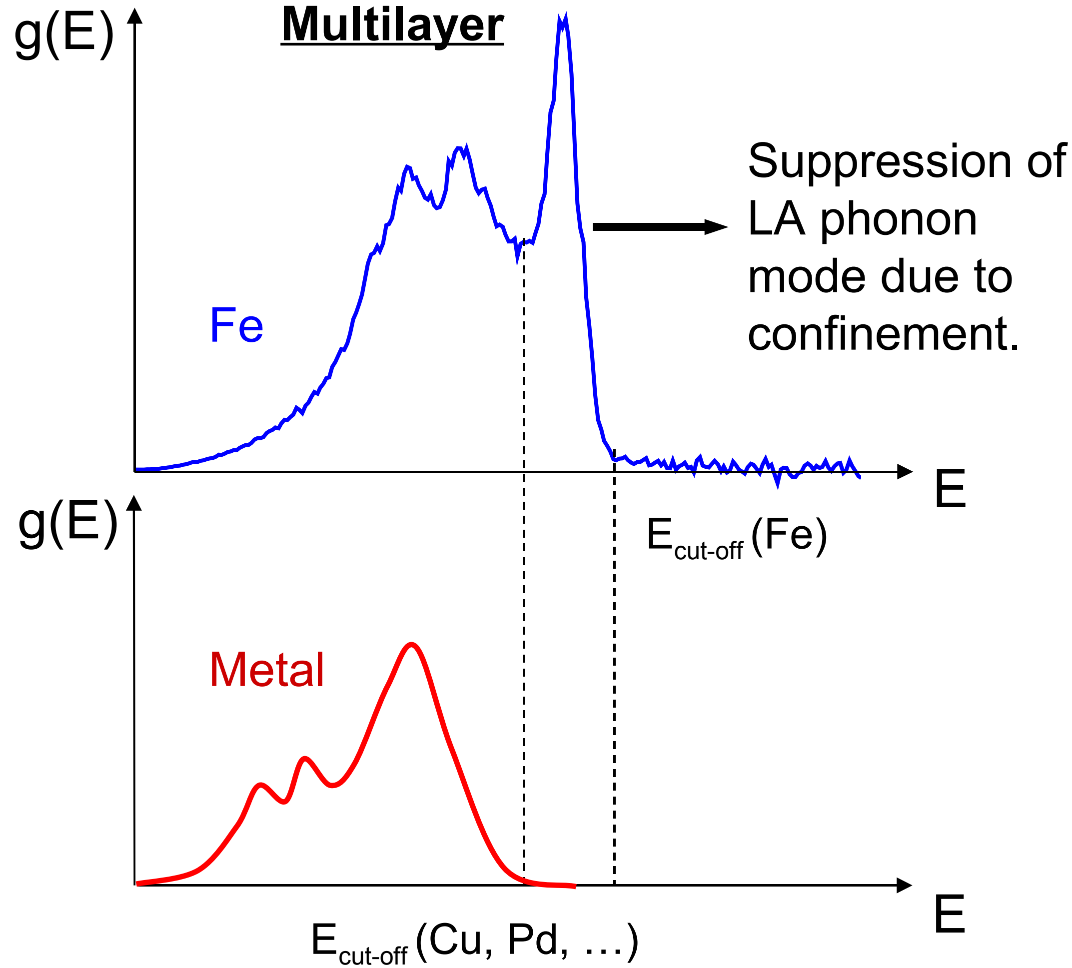
C. Colvard et al., PRB 31 (1985) 2080



LA – Phonon Confinement in bcc-Fe / Metal (M) Multilayers ?

MBE growth





LA-Phonon confinement in multilayers is a result of:

- Limited film thickness.
- Energy mismatch of g(E) of the two materials.

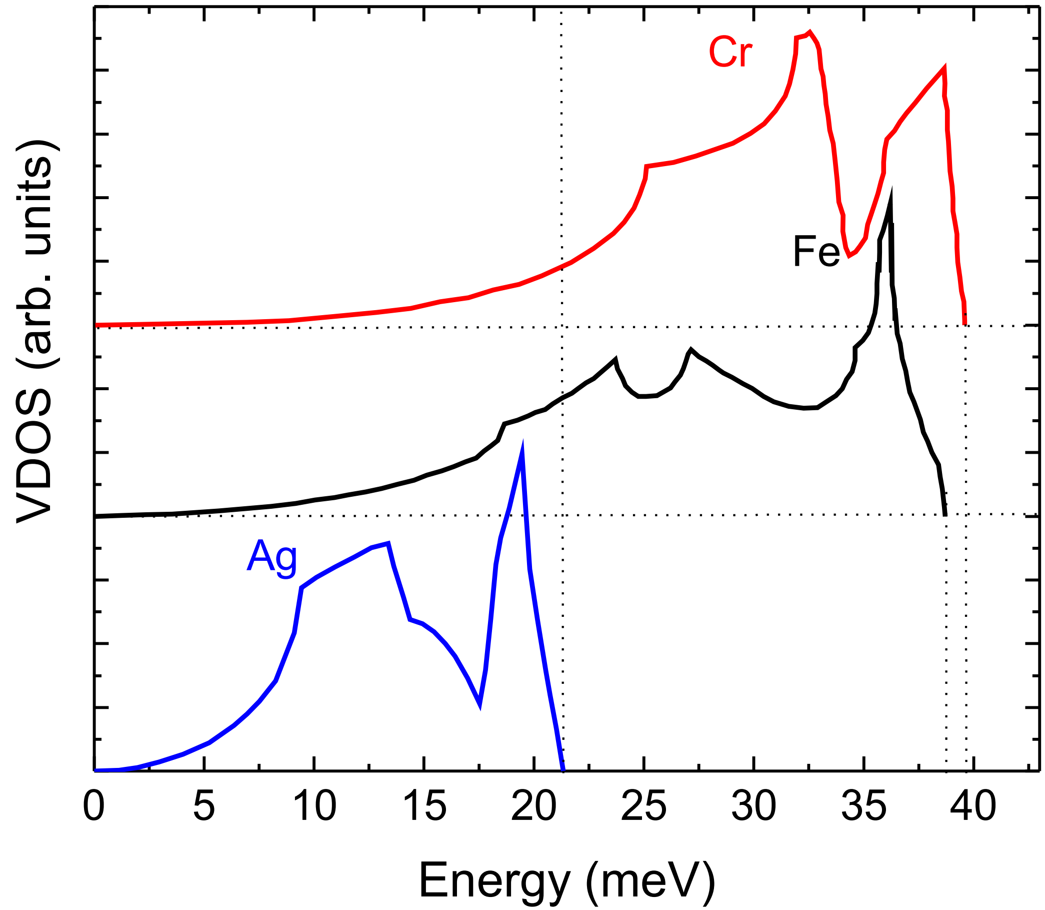
LA - Phonon confinement in bcc-Fe / Metal (M) multilayers ?

Material (M)	LA – Phonon Cut-off frequency (THz)
MgO ??	12
Al	10
Cr	9.5
Fe	9.4
Co	8.0
Cu	7.2
Pd	6.8
Ru	6.2 (7.7) optical
Ag	5.0
In	3.4

No confinement

Confinement

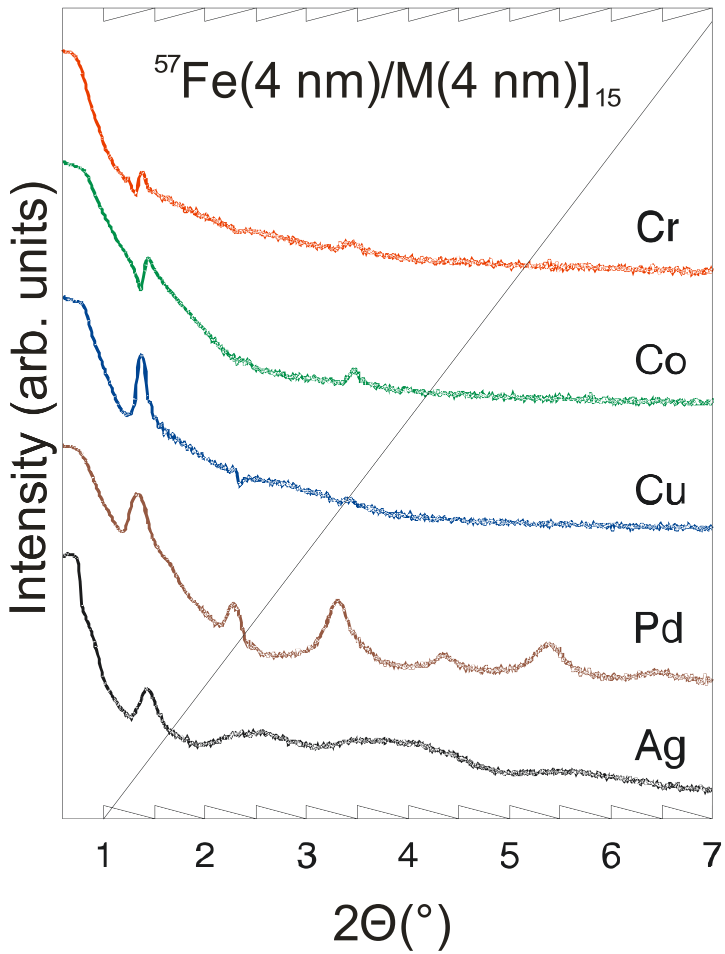
Energy mismatch



1 THz = 4.13550 meV

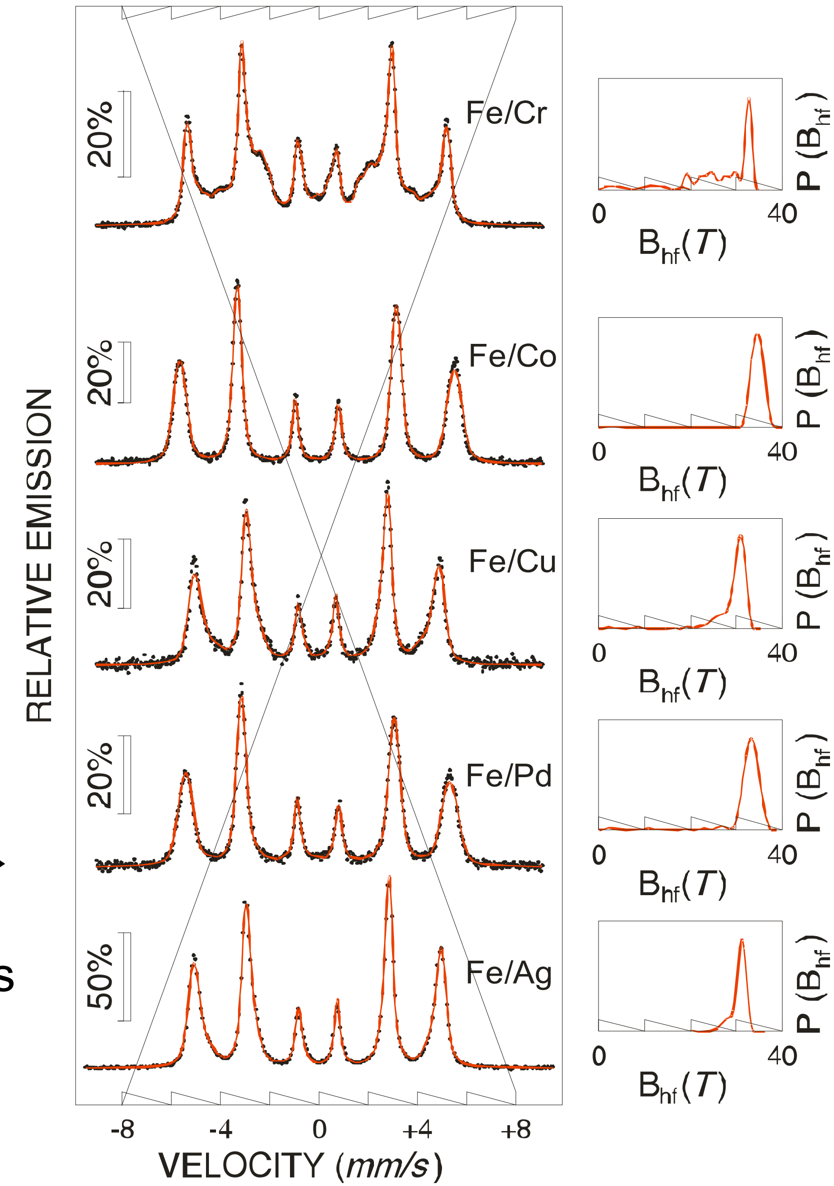
Sample Preparation and Characterization

- Substrate: SiO_2/Si(001)
- Deposition: Molecular Beam Epitaxy (MBE) at RT
- Polycrystalline films (XRD): bcc-Fe(110)

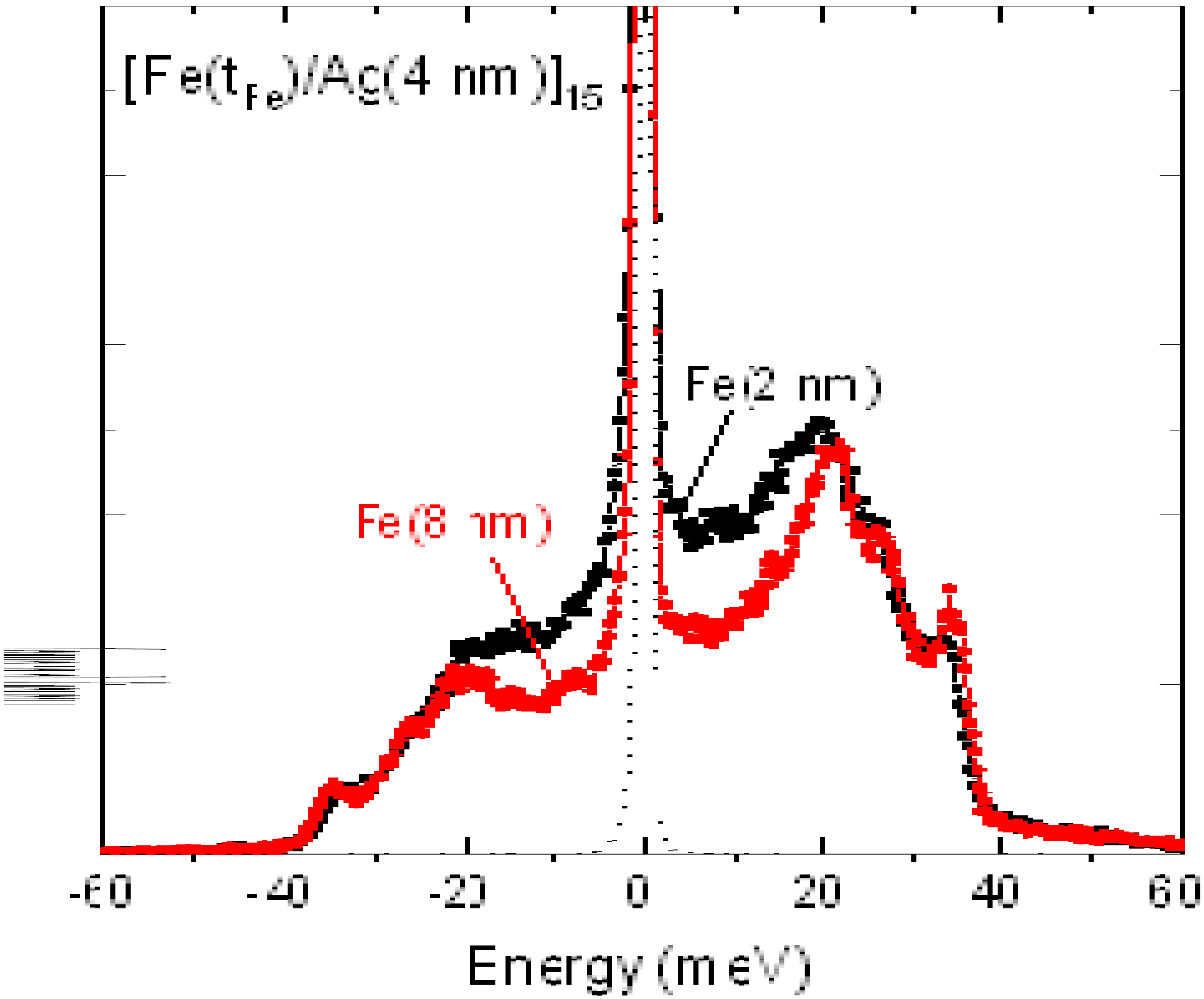


X-ray Reflectometry

Only 1-2 ML → intermixing at Fe/M interfaces

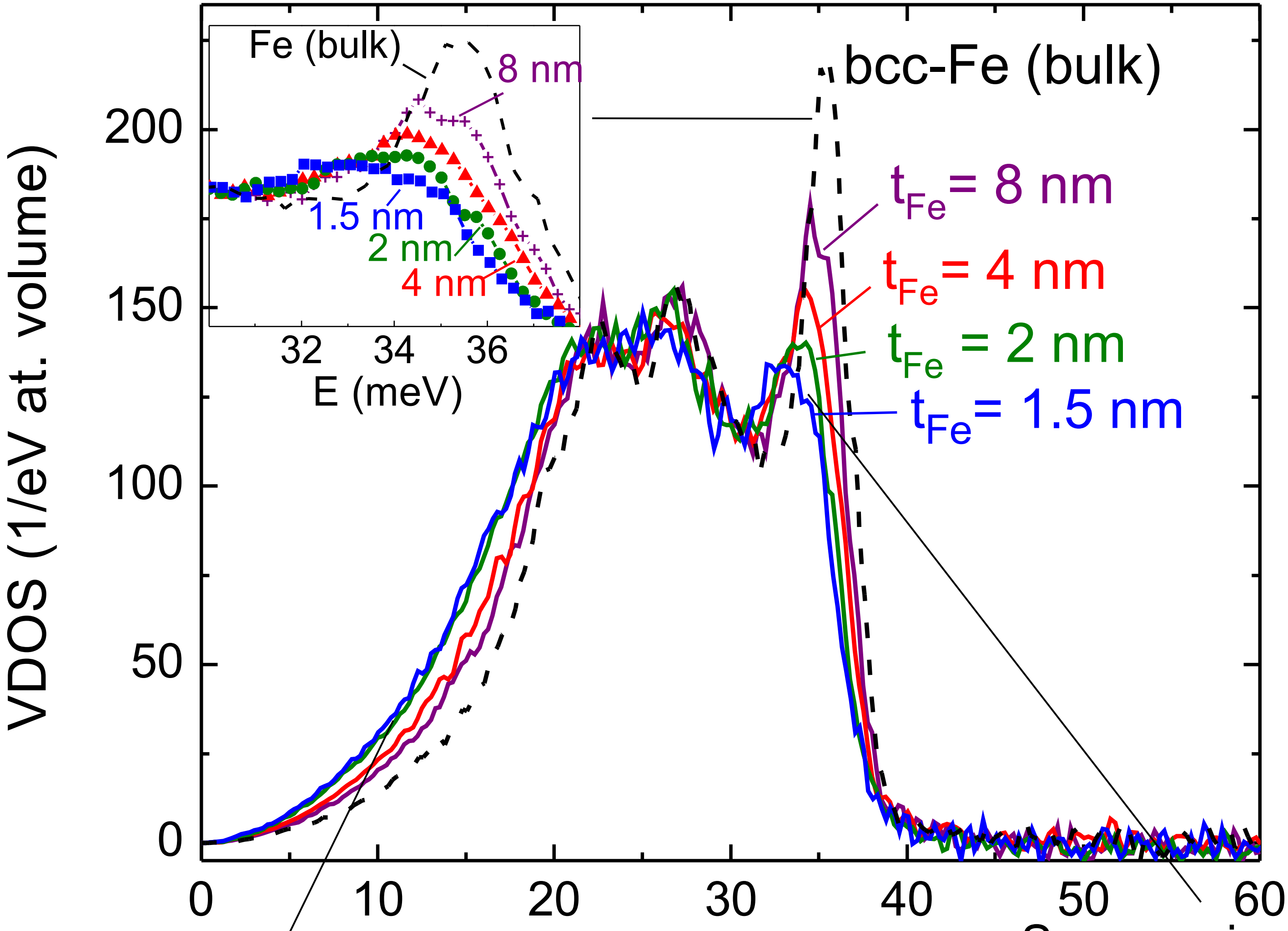


^{57}Fe CEMS: [^{57}Fe(1.5nm)/M(4nm)]$_{15}$



Size-effects!

Fe thickness dependence: $[^{57}Fe(t_{Fe})/Ag(4\ nm)]_{15}$

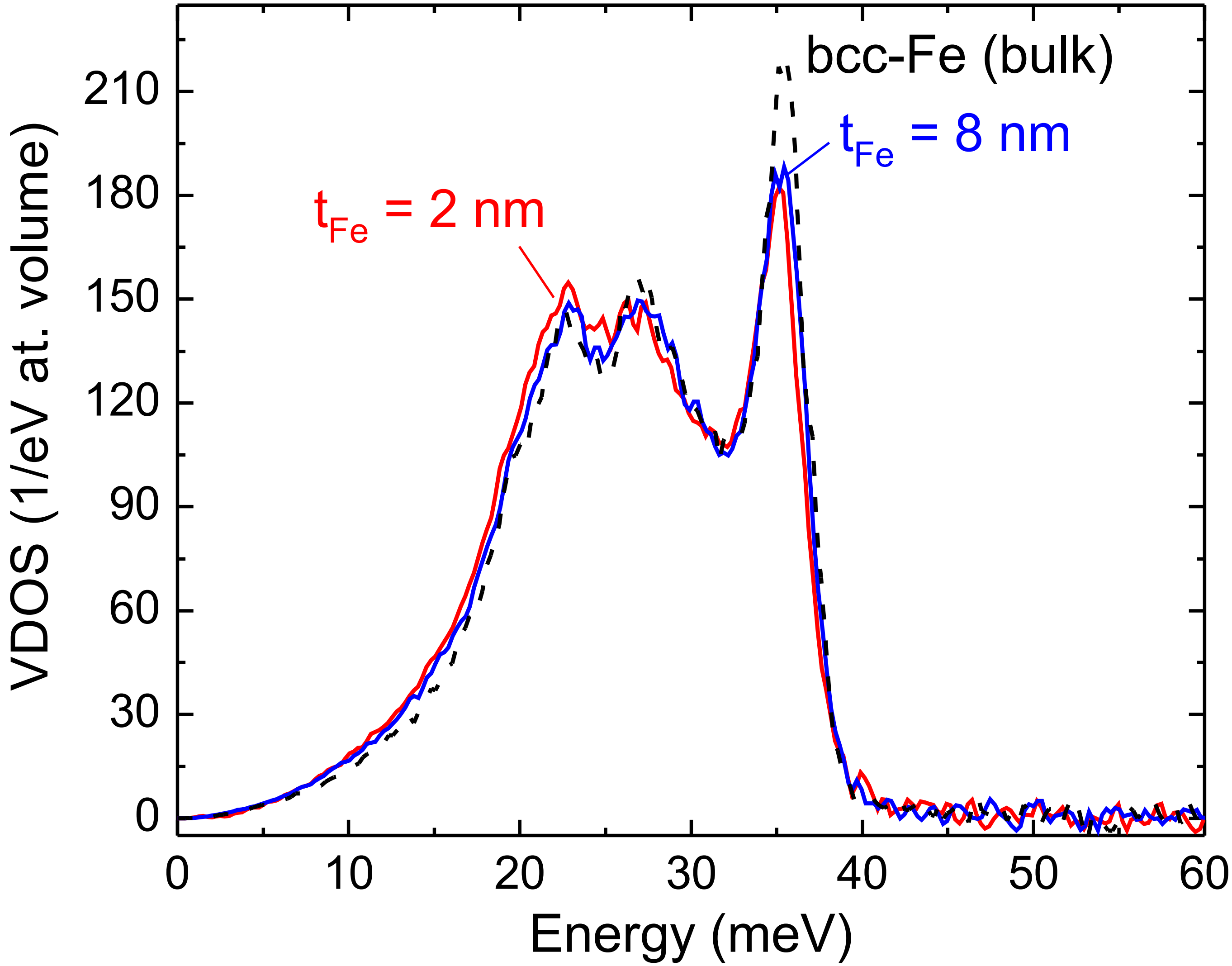


Enhancement of low energy phonons

Suppression of longitudinal acoustic phonons with respect to bulk bcc-Fe

Confinement !

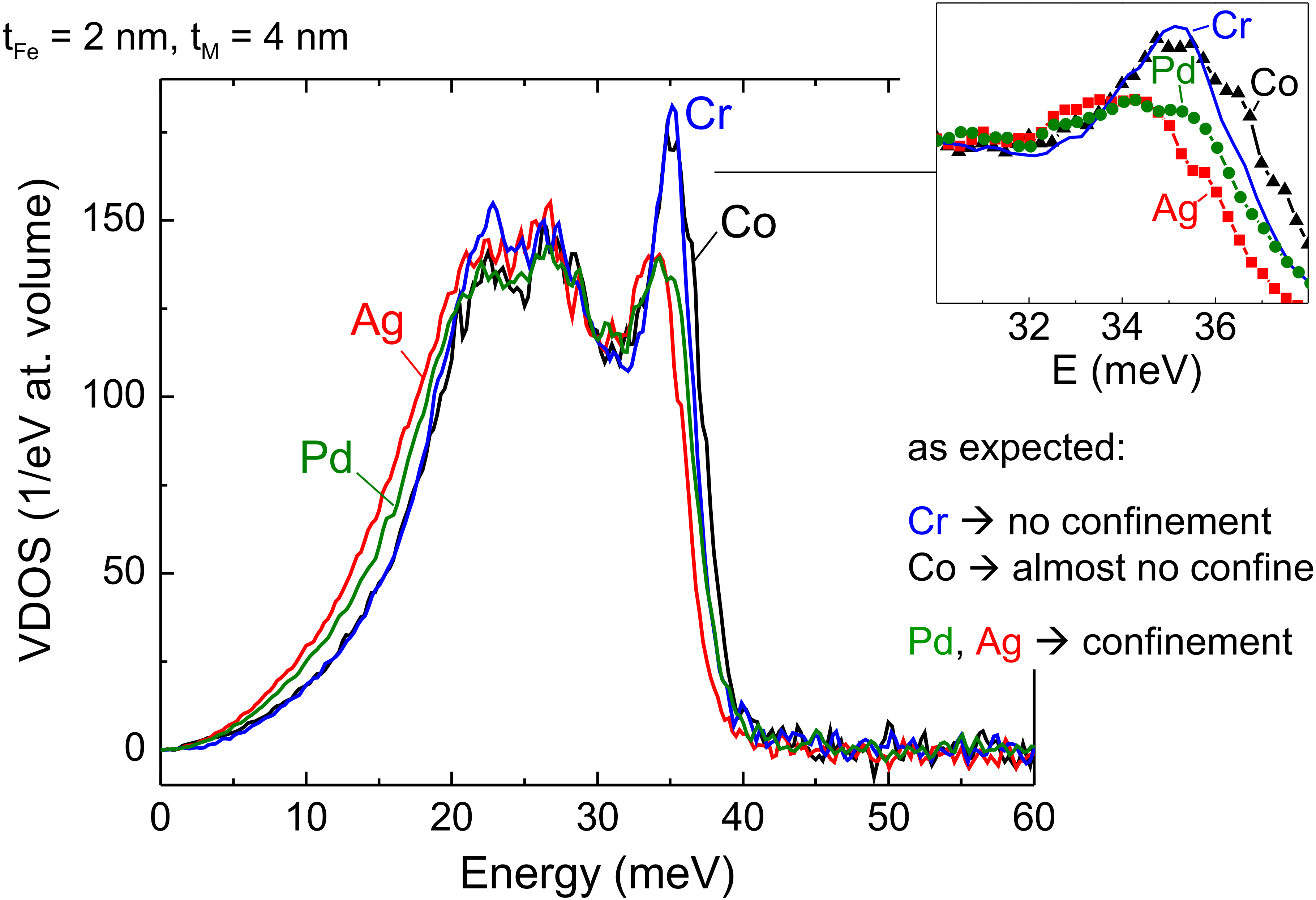
Fe thickness dependence: $[^{57}Fe(t_{Fe})/Cr(4\ nm)]_{15}$ Multilayers



Lack of Confinement !

Dependence on metal M: [^{57}Fe(2 nm)/Metal(4 nm)]$_{15}$ Multilayers

t_{Fe} = 2 nm, t_M = 4 nm



as expected:

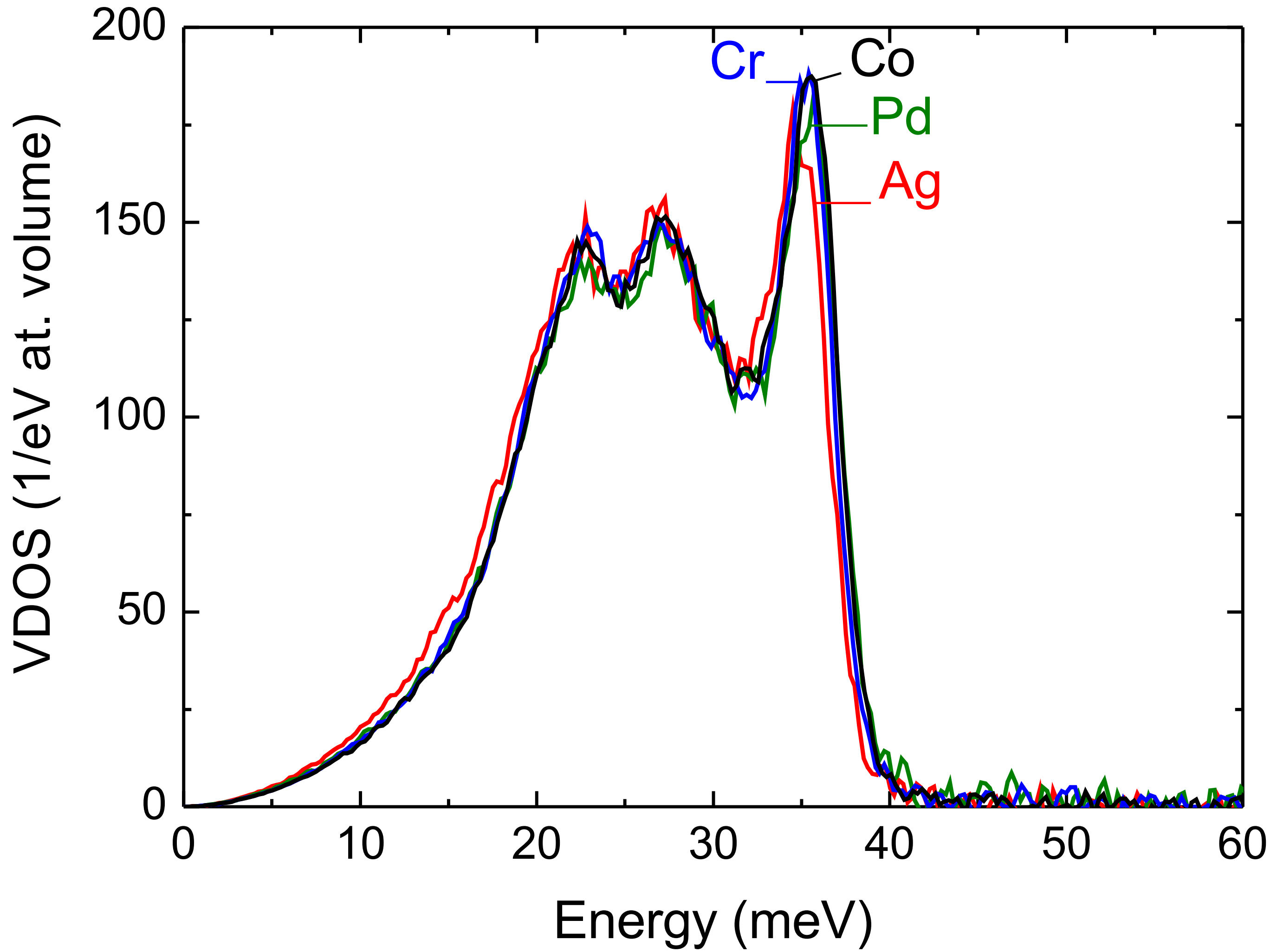
Cr → no confinement

Co → almost no confinement

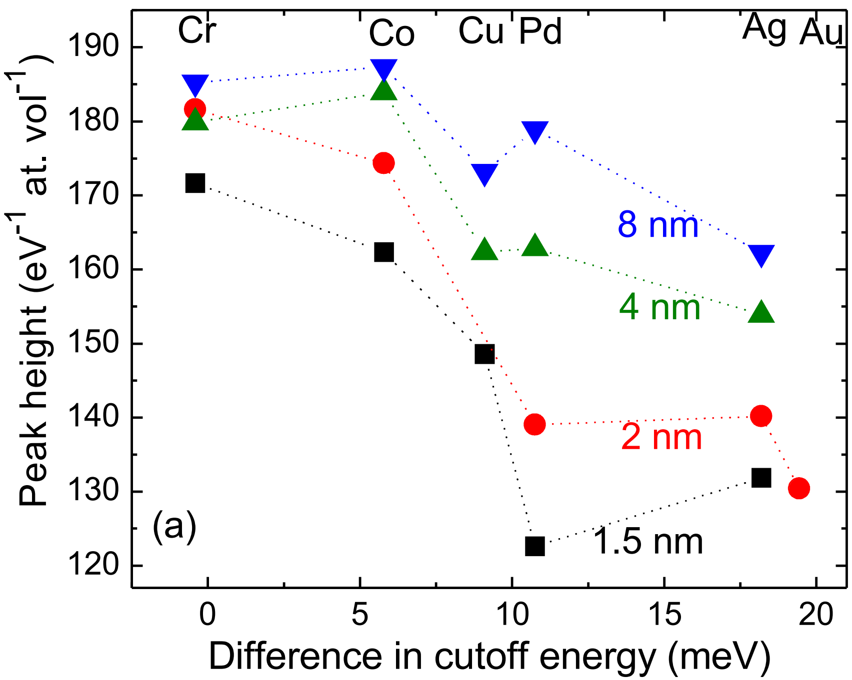
Pd, Ag → confinement

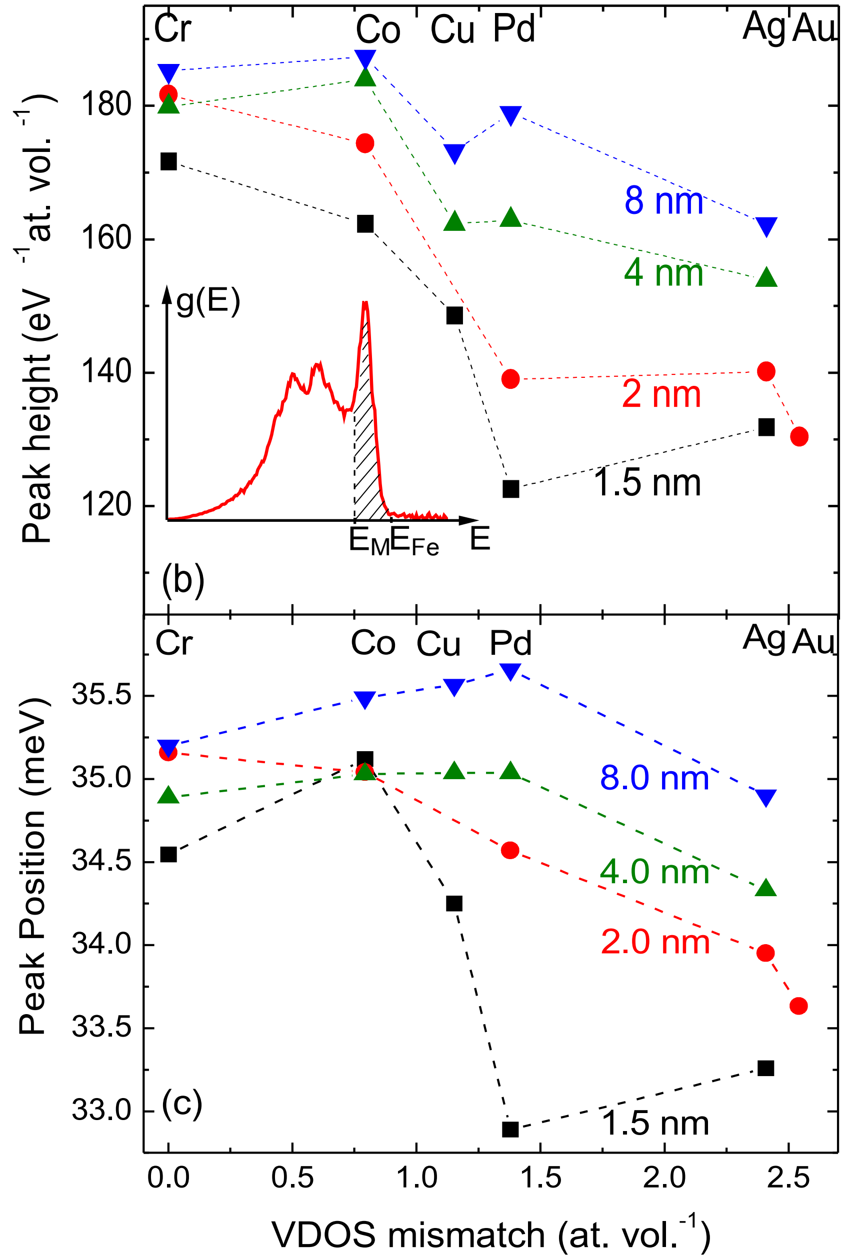
Fixed Fe Thickness: [^{57}Fe(8 nm)/Metal(4 nm)]$_{15}$ Multilayers

Negligible or weak phonon confinement for t_{Fe} = 8 nm



LA-Phonon Peak Height / Peak Position vs. VDOS Mismatch





- Thickness dependent phonon confinement: Cu, Pd, Ag, Au.

Roldan et al, PRB 77 (2008) 165410

Conclusions

Phonon Spectrum in [$^{57}Fe(t_{Fe}/M(4nm)]_{15}$ Multilayers by NRIXS:

(1) $t_{Fe} < 4$ nm : -Thickness dependent suppression and shift of the LA phonon peak near 36 meV for M = Ag, Pd, Cu ("soft metals")
→ Phonon confinement due to energy mismatch in g(E)

- Lack of phonon confinement for Cr, Co ("hard metals") due to energy matching

(2) $t_{Fe} = 8$ nm : - Negligible or weak confinement

(3) ^{57}Fe probe layers:
- Interface effects on the 36-meV LA-phonons disappear a few MLs (1-3 ML) away from the Fe/M interface

Roldan et al., PRB 77 (2008) 165410
Ruckert et al., Hyperfine Int. 126 (2000) 363

Open questions:

- Is the measured g(E) a „layer projected“ VDOS ?
  → Angular-dependent NRIXS, e.g., with the beam close to the surface normal

- Why are the TA modes of Fe hardly affected by the layered structure ?