

Magnetic and Magnetotransport Properties of Fe-Ag Multilayers

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- Sample preparation & measuring techniques
discontinuous layers below 1 nm Fe
- Discontinuous multilayers as compared to granular composites
perpendicular anisotropy
concentration dependence of the magnetoresistance

Sample preparation

vacuum evaporation with two electron guns in a base pressure of 10^{-7} Pa
evaporation rate ≈ 0.2 nm/s

Si single crystal wafer or Al foil substrate
without cooling (~ 100 Celsius substrate temperature)

The layer thickness is controlled by a quartz oscillator
Bulk density is used to calculate the nominal thickness

Samples in the 0.1-10 nm layer thickness range

X-ray reflectivity and diffraction

SQUID magnetometry (5 Tesla)

Mössbauer spectroscopy

Magnetoresistance (12 Tesla)

$d_{\text{Fe}} > 1\text{ nm}$

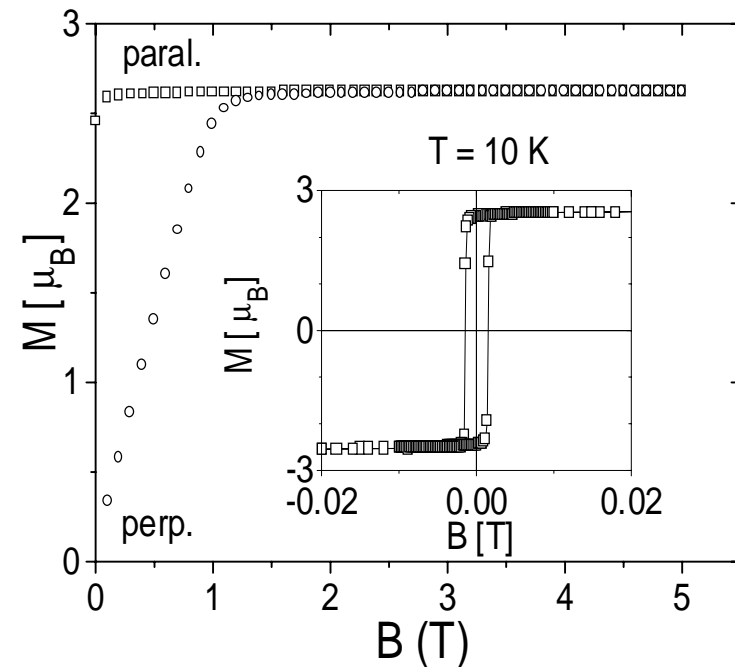
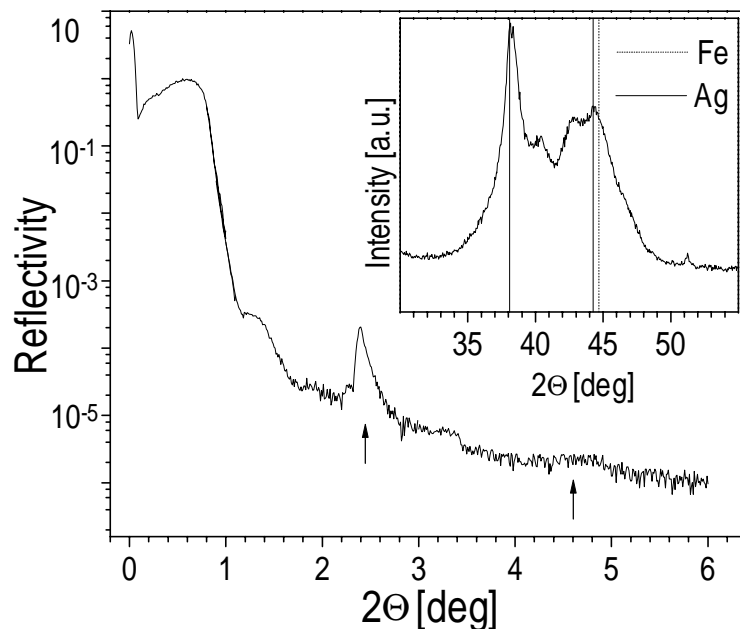
continuous ferromagnetic layers

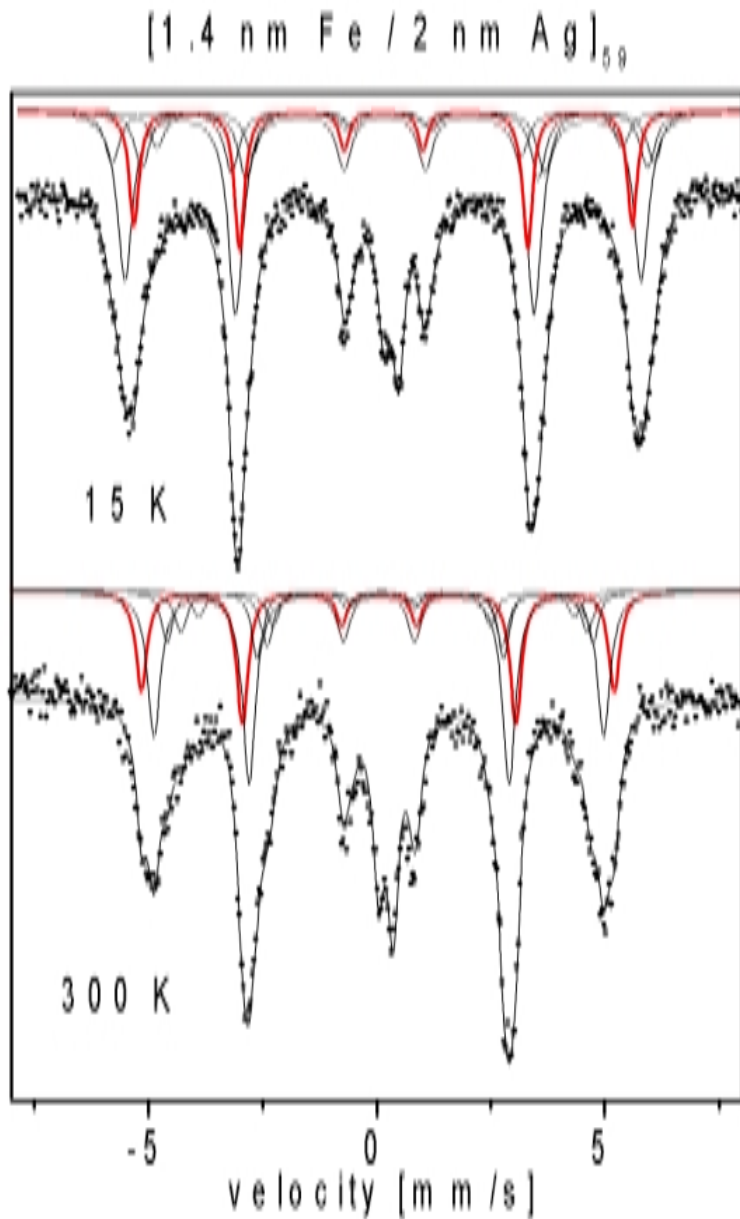
in-plane magnetization

non-equilibrium alloying by interface mixing

(increased magnetic moments, lower Curie temperature,
broadening of the Mössbauer linewidth)

$[\text{Ag}(2\text{ nm})/\text{Fe}(1.4\text{ nm})]_{60}$ multilayer





in-plane magnetic moments
 $(I_{2-5} = 4 \sin^2\Theta / (1 + \cos^2\Theta))$

hyperfine field distribution

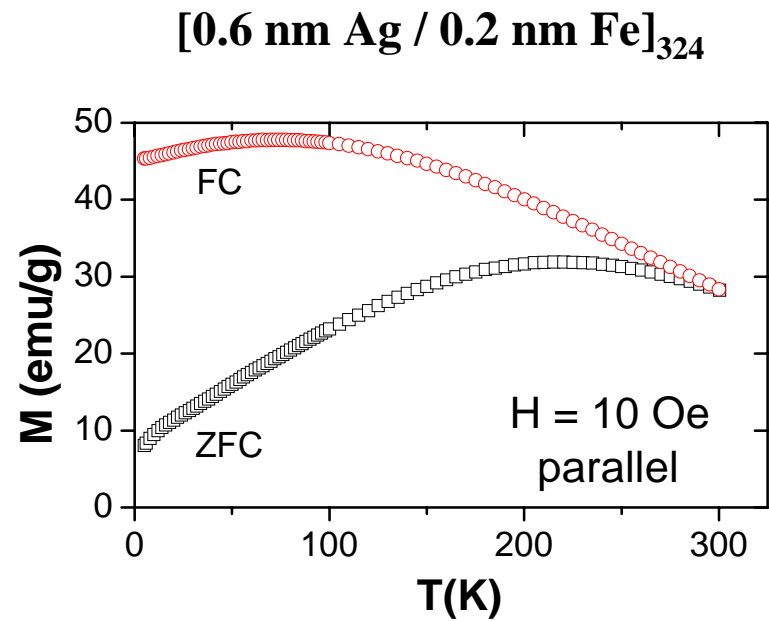
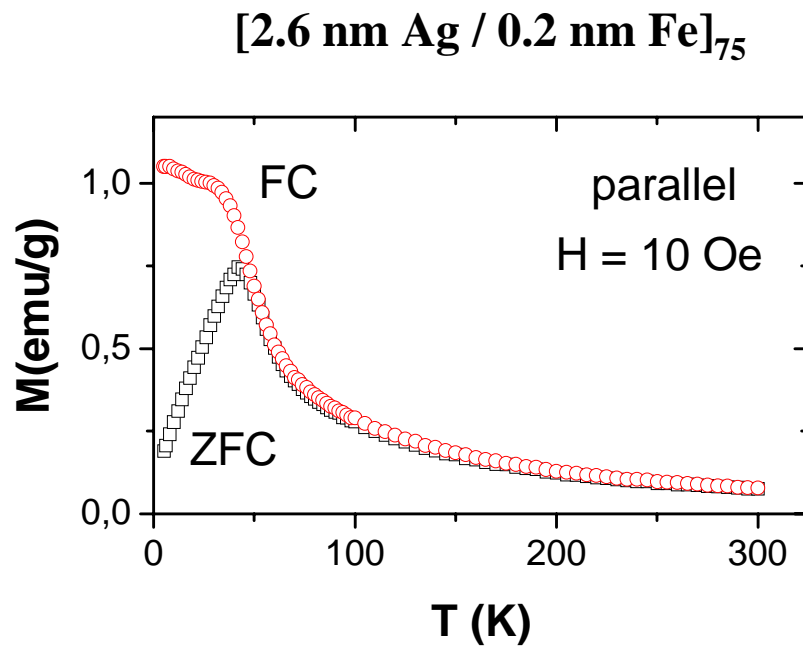
Sharp interface and atomic terraces
 or rough interface and atomic mixing ?

P. J. Schurer et al. Phys Rev. B 51, 2506 (1995)

Systematic comparison of
 polycrystalline and epitaxial layers

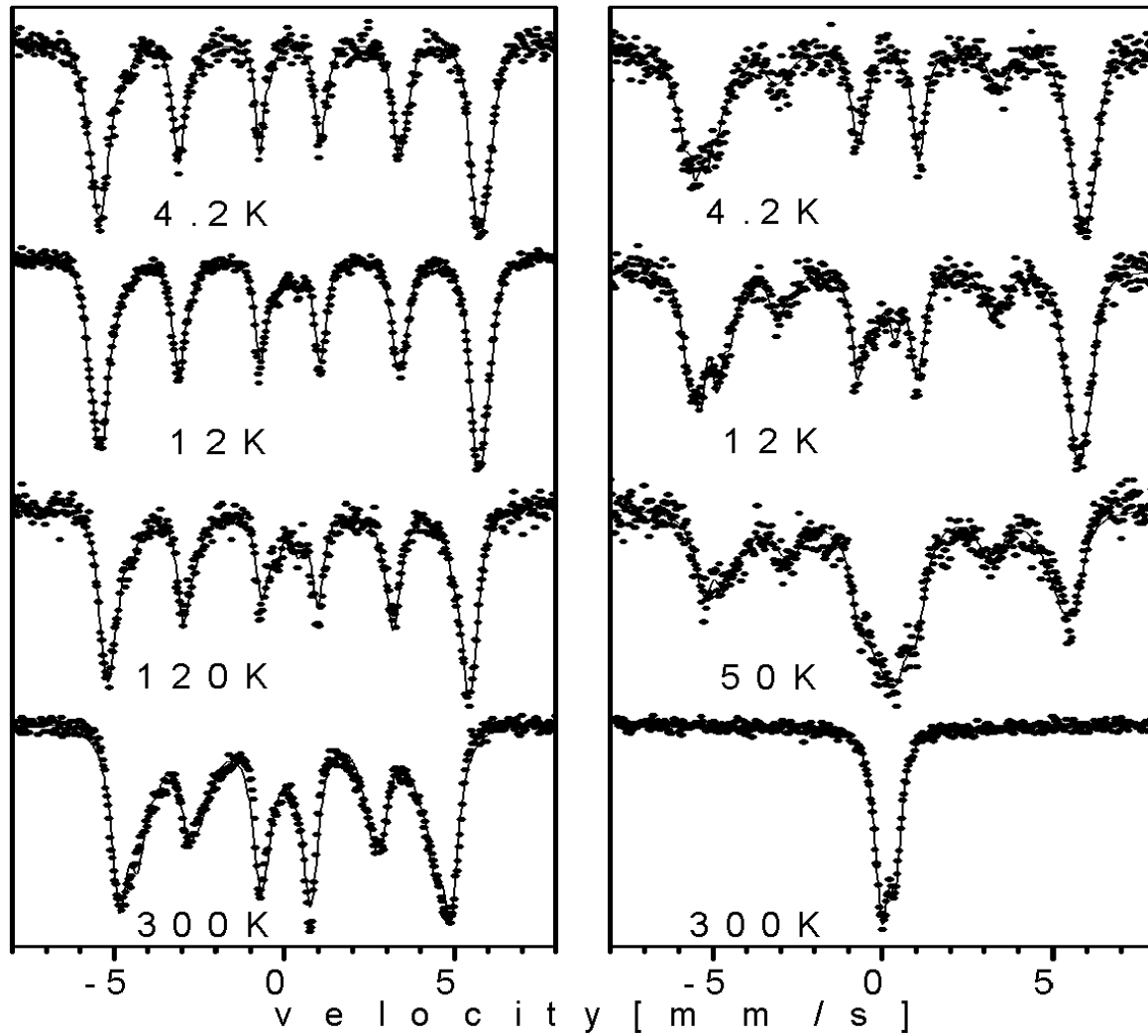
Below 1nm Fe layer thickness

- No reflectivity peak is observed
- Superparamagnetic relaxation



$[0.2 \text{ nm Fe} / 0.6 \text{ nm Ag}]_{324}$

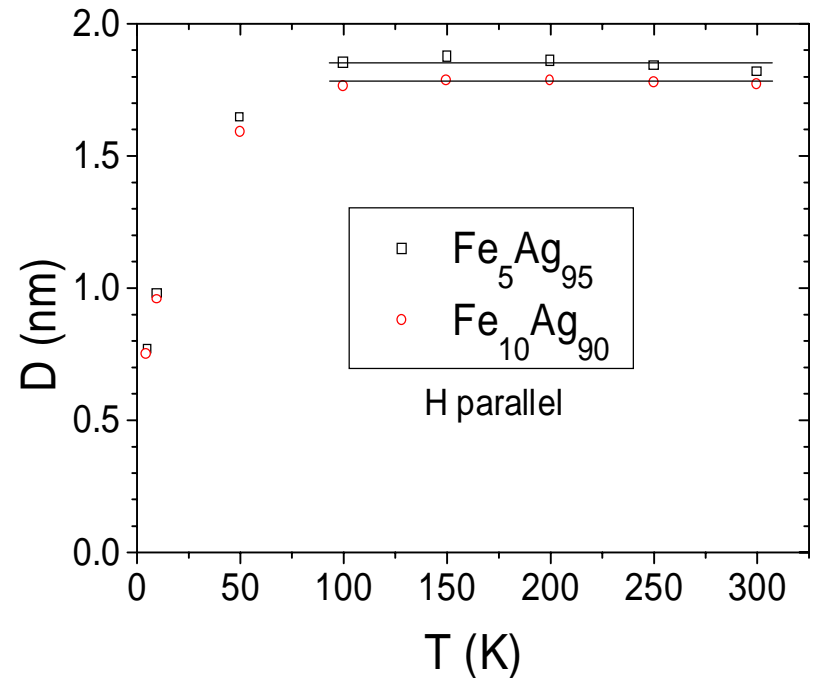
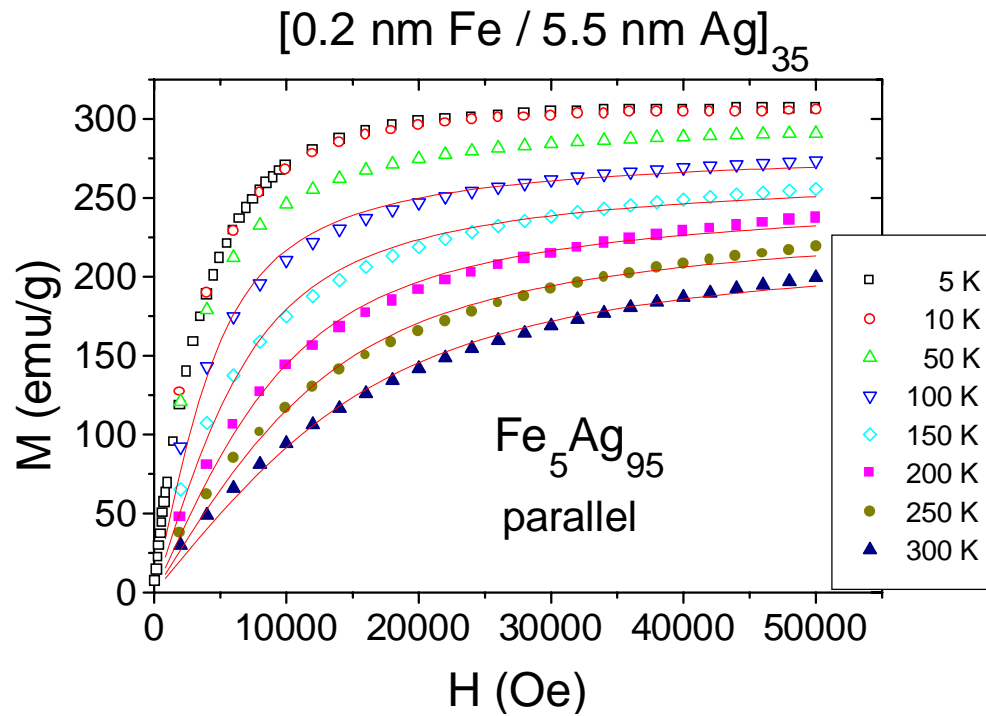
$[0.2 \text{ nm Fe} / 2.6 \text{ nm Ag}]_{162}$



No substrate component!

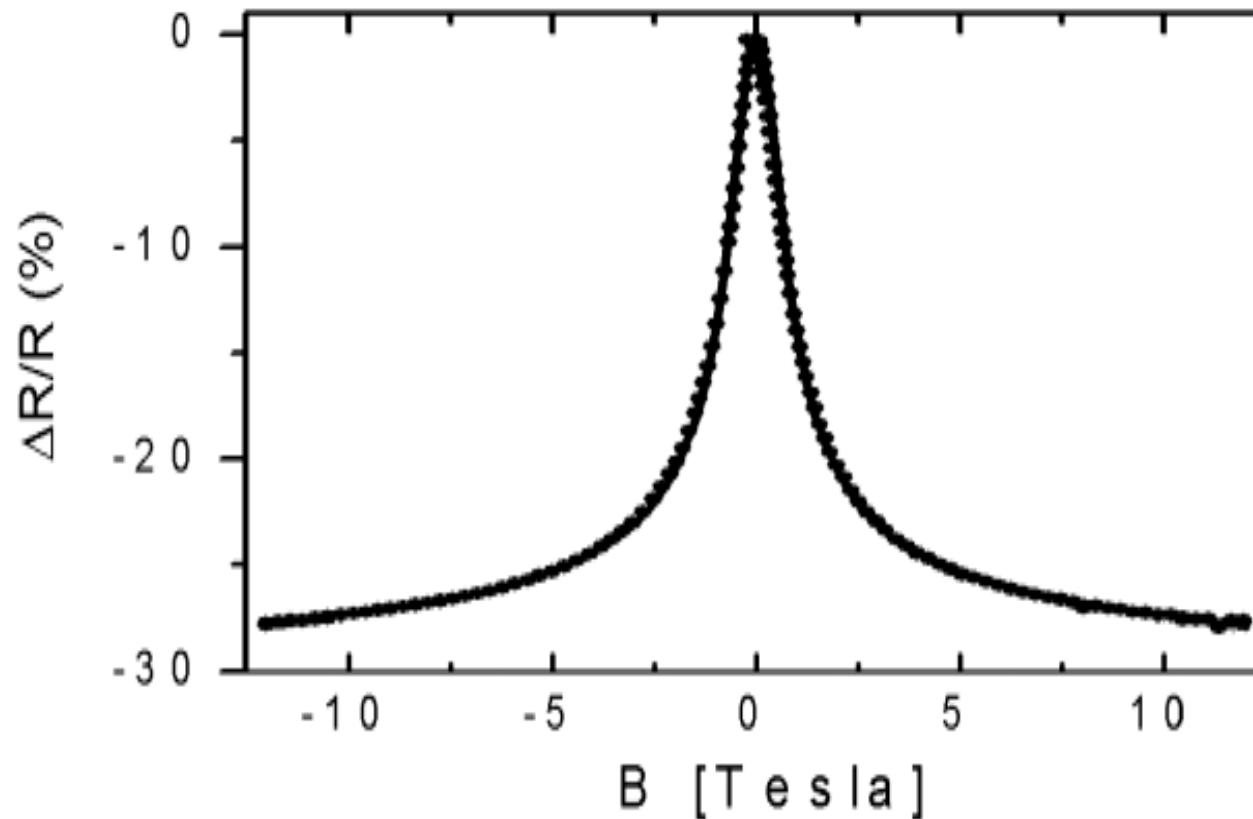
The samples can be removed from the Si substrate.

Grain size from magnetisation measurements



The magnetoresistance is similar to that of granular composites prepared by co-deposition of the elements

[2.6 nm Ag / 0.2 nm Fe]₇₅



$$\frac{\Delta R}{R} = -A_1 [L(mH / kT)]^2 - A_2 H^2$$

$$m = 19 \mu_B, \quad A_1 = 5.3 \cdot 10^{-1}, \quad A_2 = 5 \cdot 10^{-5}$$

Why to deal with bad multilayers?

- poor man cooks with water

- **granular interface structure**

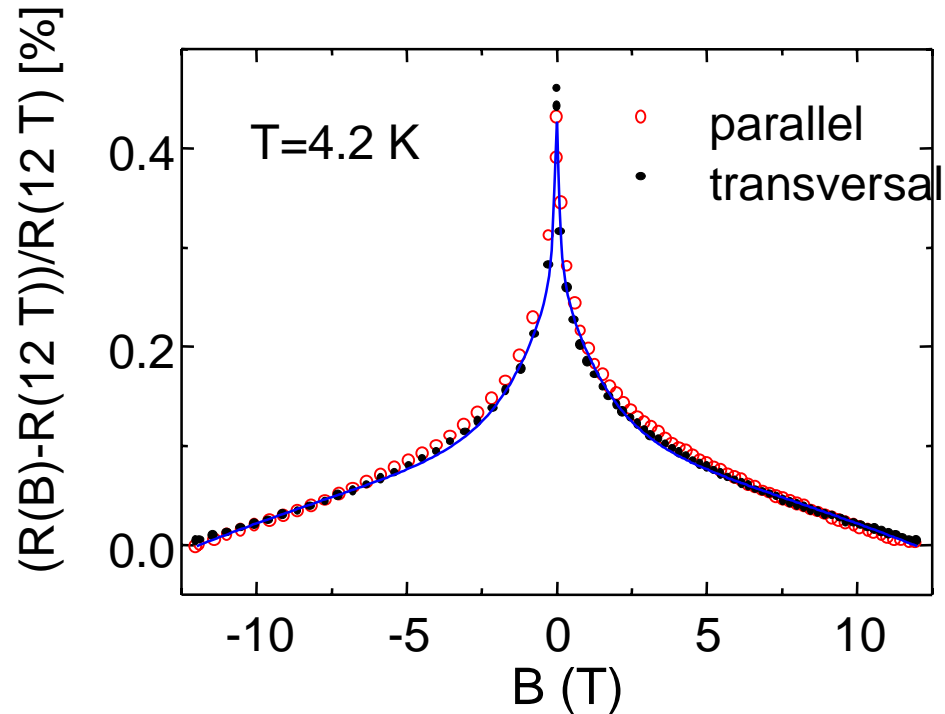
- **distinct features as compared to co-deposition**

appearance of perpendicular anisotropy

the grain size can be varied on the nanometer scale

Granular interface

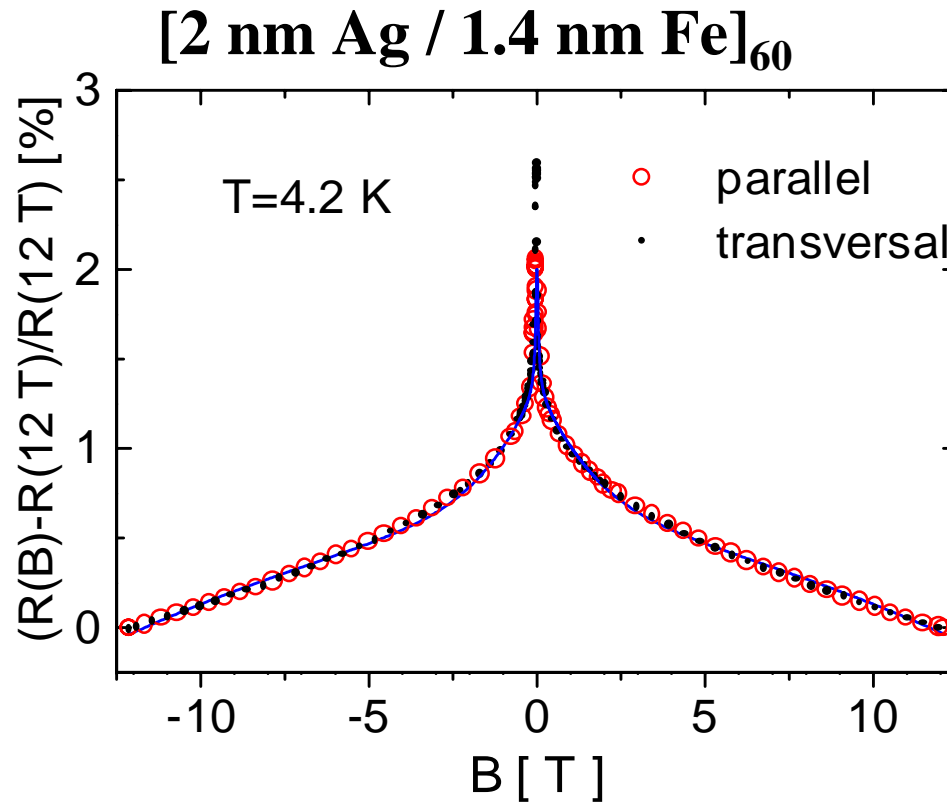
8 nm Ag / 25 nm Fe / 8 nm Ag
trilayer



$$\Delta R/R = -(A_1 L (m_1 H/kT) + A_2 L (m_2 H/kT))^2 - A_3 H^2 + A_4$$

$$m_1 = 6.4 \mu_B, m_2 = 382 \mu_B,$$
$$A_1 = 0.042, A_2 = 0.086, A_3 = 3 \cdot 10^{-5} \text{ T}^{-2} \text{ and } A_4 = 2 \cdot 10^{-2}.$$

Multilayer magnetoresistance is dominated by the granular interface



$$m_1=6.6 \mu_B, m_2=188 \mu_B,$$

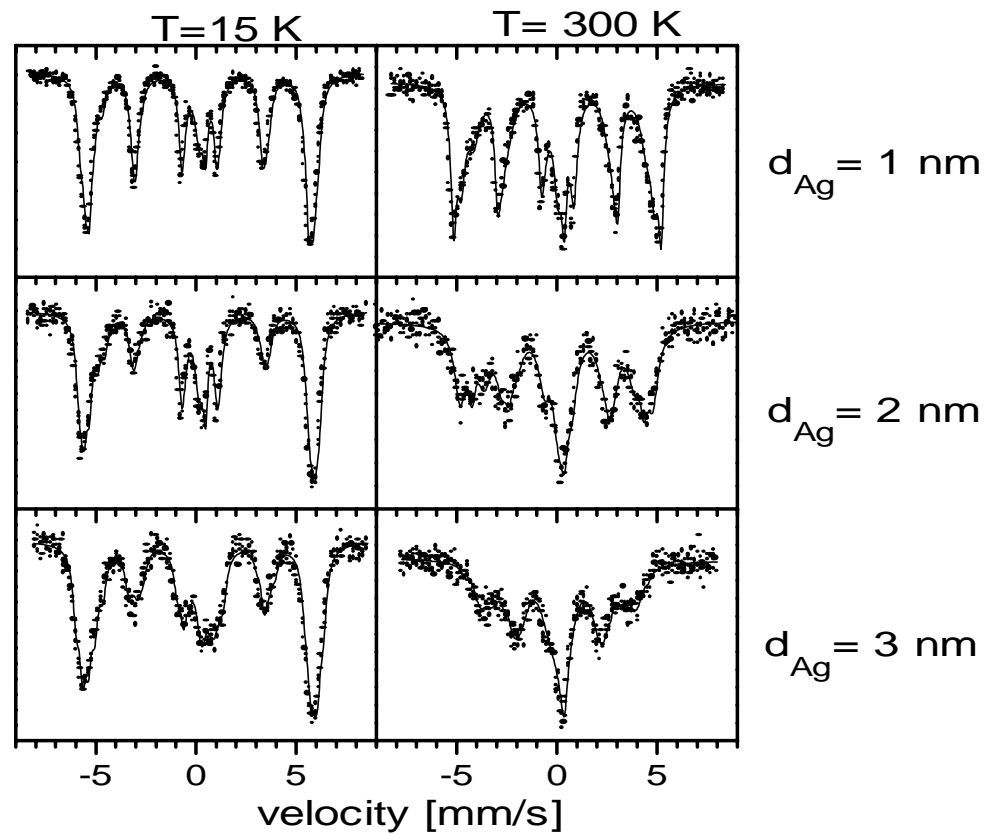
$$A_1=0.019, A_2=0.043, A_3=4.3 \cdot 10^{-6} \text{ T}^{-2} \text{ and } A_4=4 \cdot 10^{-3}$$

perpendicular anisotropy when $d_{\text{Fe}} < 1\text{ nm}$

relative line intensities of the Mössbauer spectra

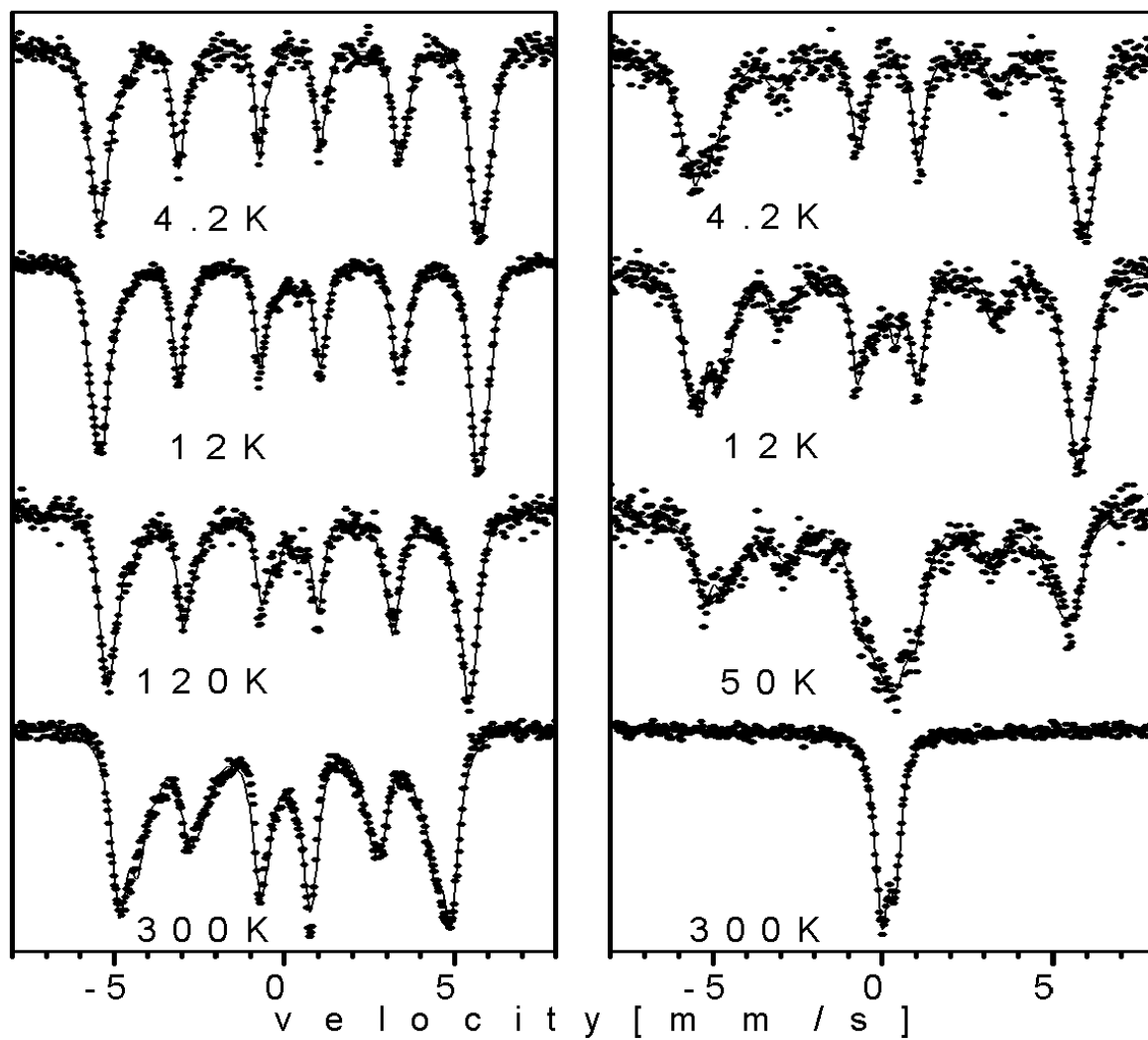
$$I_{2-5} = 4 \sin^2 \Theta / (1 + \cos^2 \Theta)$$

$$d_{\text{Fe}} = 0.7 \text{ nm}$$



[0.2 nm Fe / 0.6 nm Ag]₃₂₄

[0.2 nm Fe / 2.6 nm Ag]₁₆₂



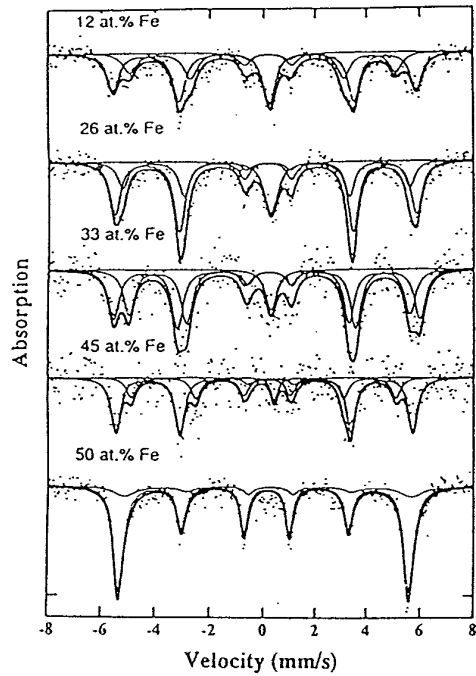


Fig. 7. Mössbauer spectra at 4.2 K for the CB-deposited Fe-Ag

K. Sumiyama et al.
J. Mat.Sci. Eng., 1995

C. Larica et al.
J.M.M.M., 1992

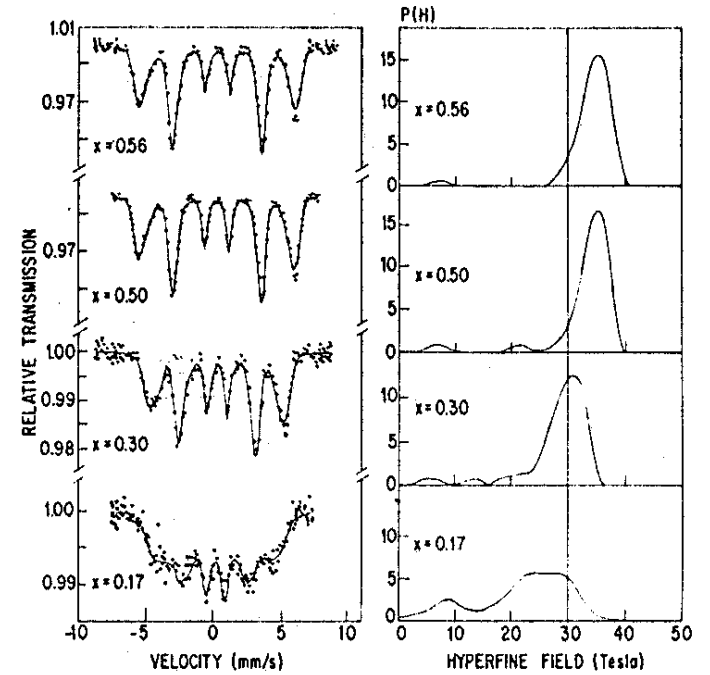


Fig. 2. Mössbauer Spectra and corresponding average hyperfine field distributions for various Ag-Fe films at 5.5 K.

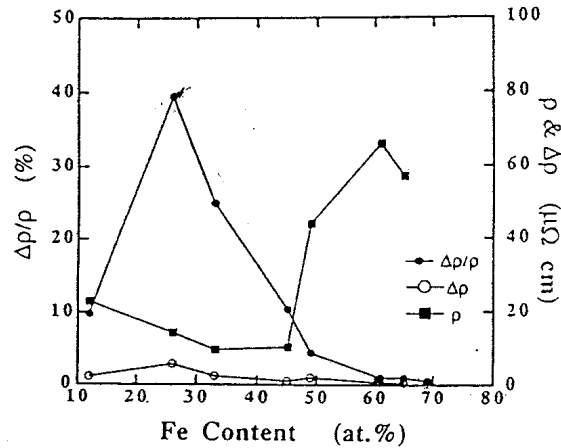
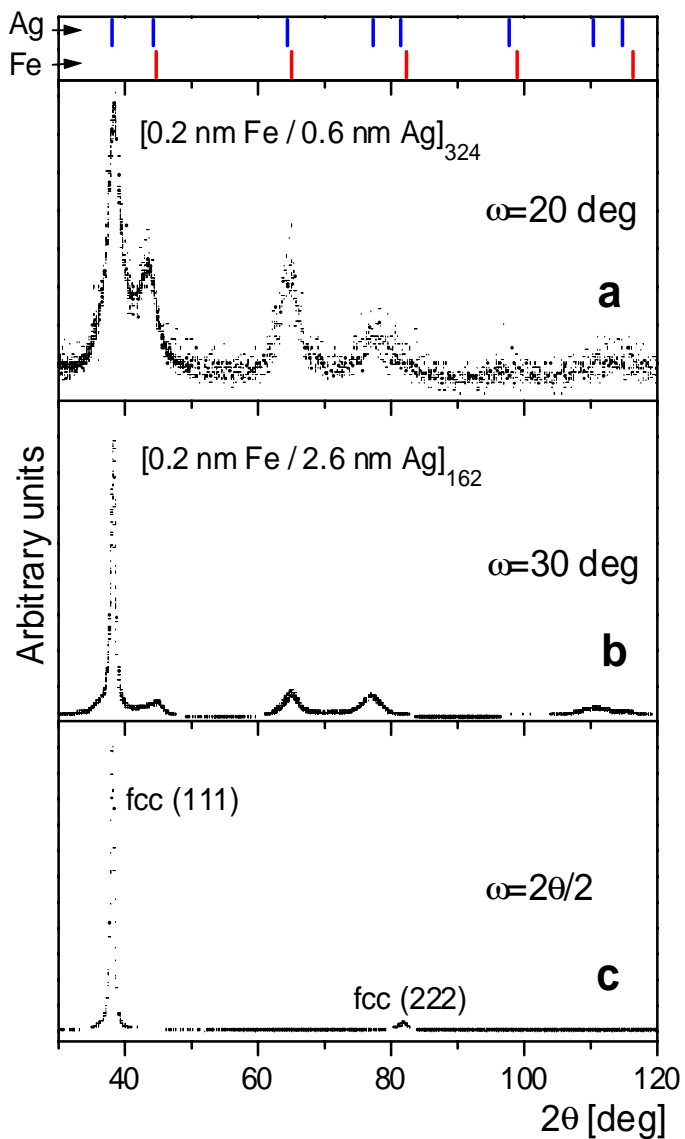


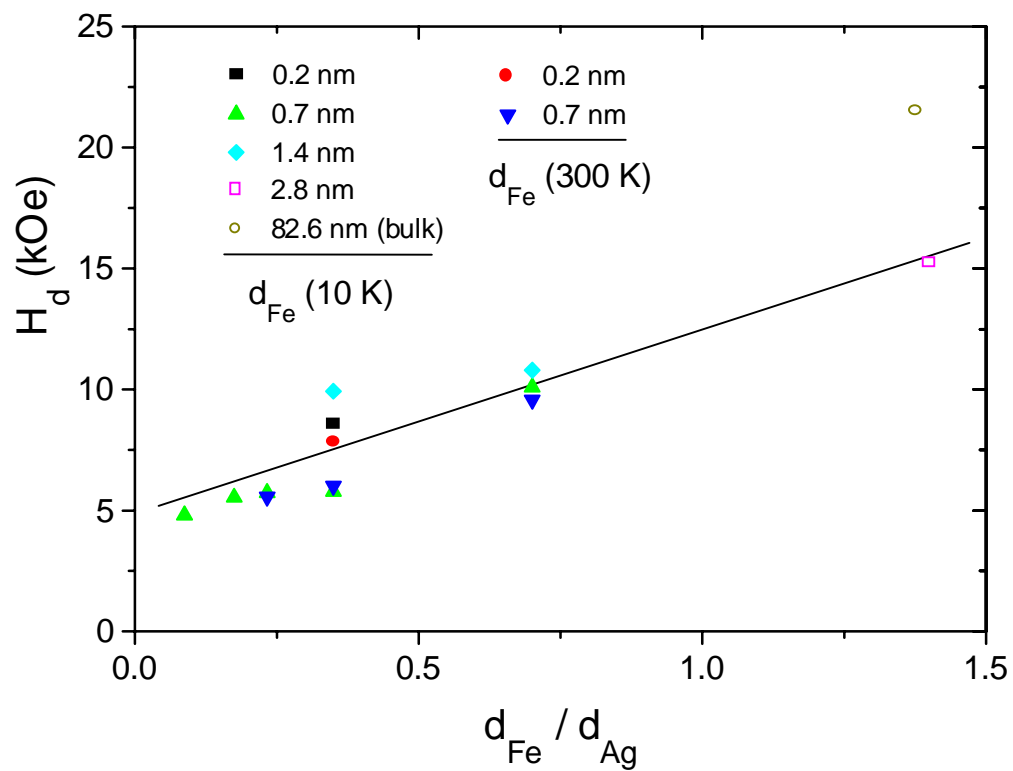
Fig. 8. Concentration dependence of electrical resistivity, $\rho(0)$, $\Delta\rho = \rho(H) - \rho(0)$, and magnetoresistance, $\Delta\rho/\rho$, at 4.2 K of the CB-deposited Fe-Ag films.

K. Sumiyama et al.
J. Mat.Sci. Eng., 1995

stress induced anisotropy?

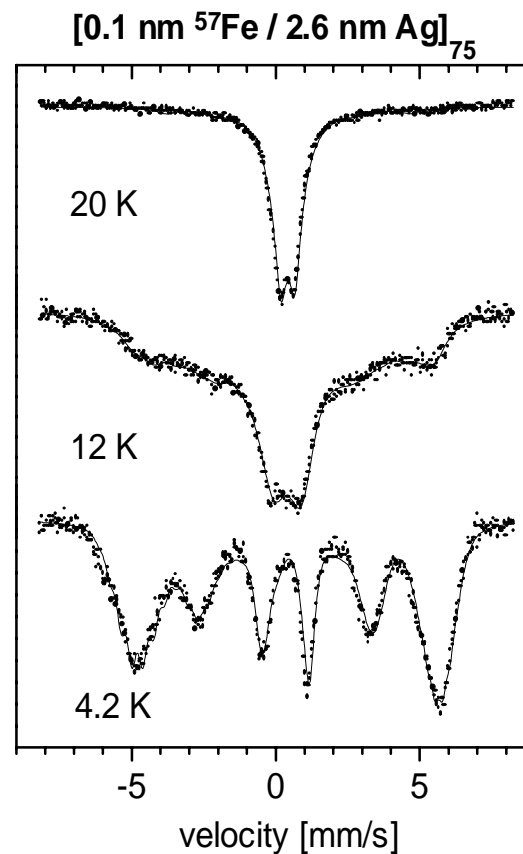


non-spherical particles?



The grain size can be varied on the nanometer scale

$T_B \approx V$ for non-interacting particles (J. L. Dormann et al.)



$D \approx 1$ nm

K. Temst et al., Leuven

Concentration dependence of the magnetoresistance

universal behaviour

maximum GMR around 25% magnetic atom concentration

3D percolation limit

*Conditions for optimum GMR in granular metals ,
D. Kechrakos and K. N. Trohidou, J. Appl. Phys., 89 , 7293 (2001)*

J. Appl. Phys., Vol. 89, No. 11, 1 June 2001

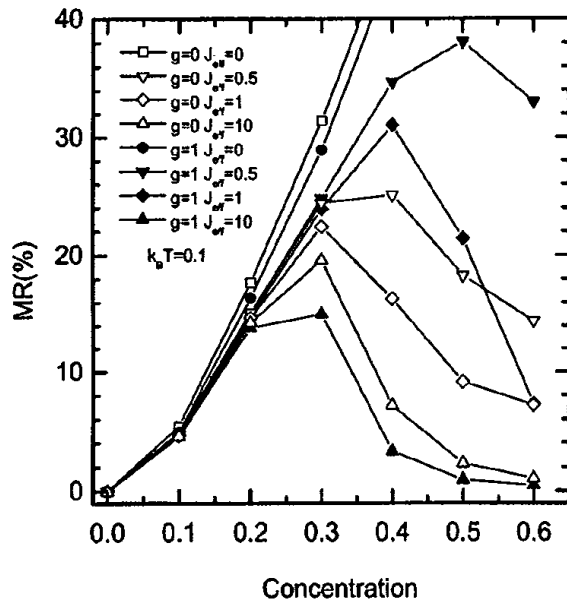
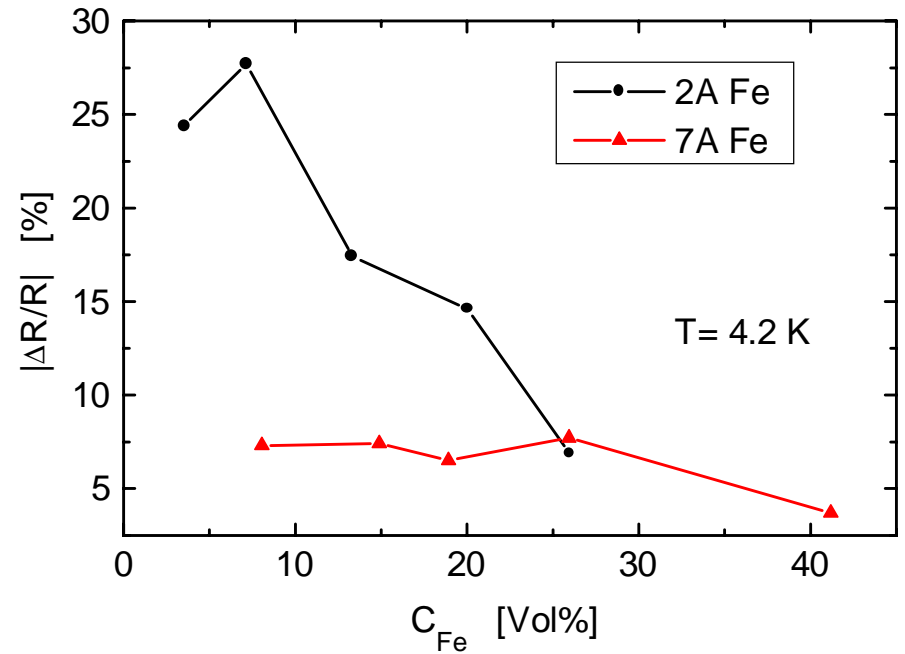
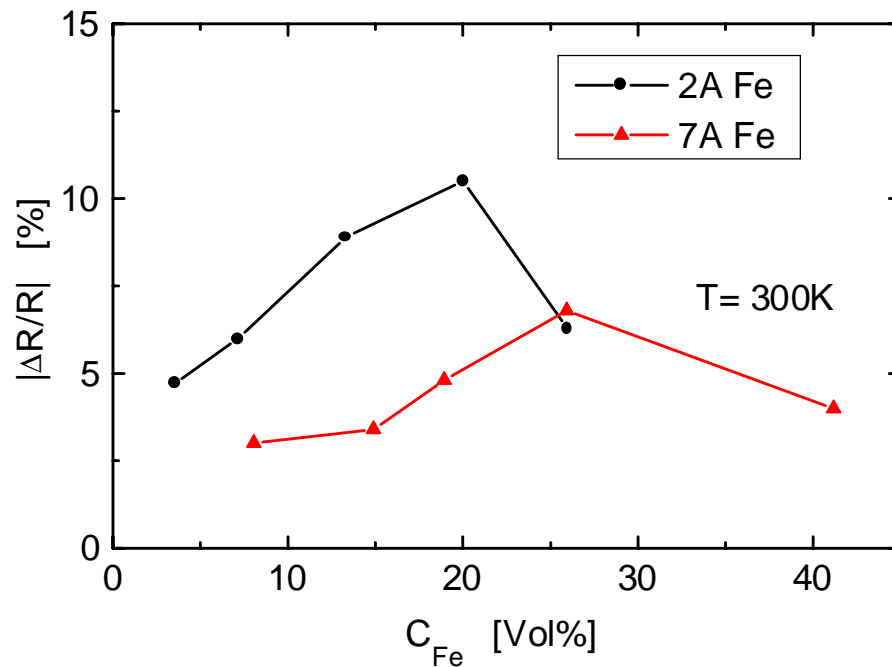


FIG. 2. Magnetoresistance as a function of magnetic particle concentration.

Interplay between dipolar interactions
and interparticle exchange

- the grain size is determined by grain growth process during deposition
- percolation among different size grains and not individual atoms

The larger the space filling factor the lower the percolation threshold



The position of the maximum depends on the size of the magnetic grains and the temperature.

Conclusions

- **Atomic mixing at the interface of Fe/Ag multilayers produces a granular interface structure.**
GMR behaviour of a 8 nm Ag / 25 nm Fe/ 8 nm Ag trilayer
- **Granular composites prepared by sequential deposition show distinct features**
Out of plane magnetic moments
non-universal composition dependence of the magnetoresistance

