Anisotropy of the magnetoelastic properties in the epitaxial $Co_2Fe_xMn_{1-x}Si$ Heusler alloys magnetic layers

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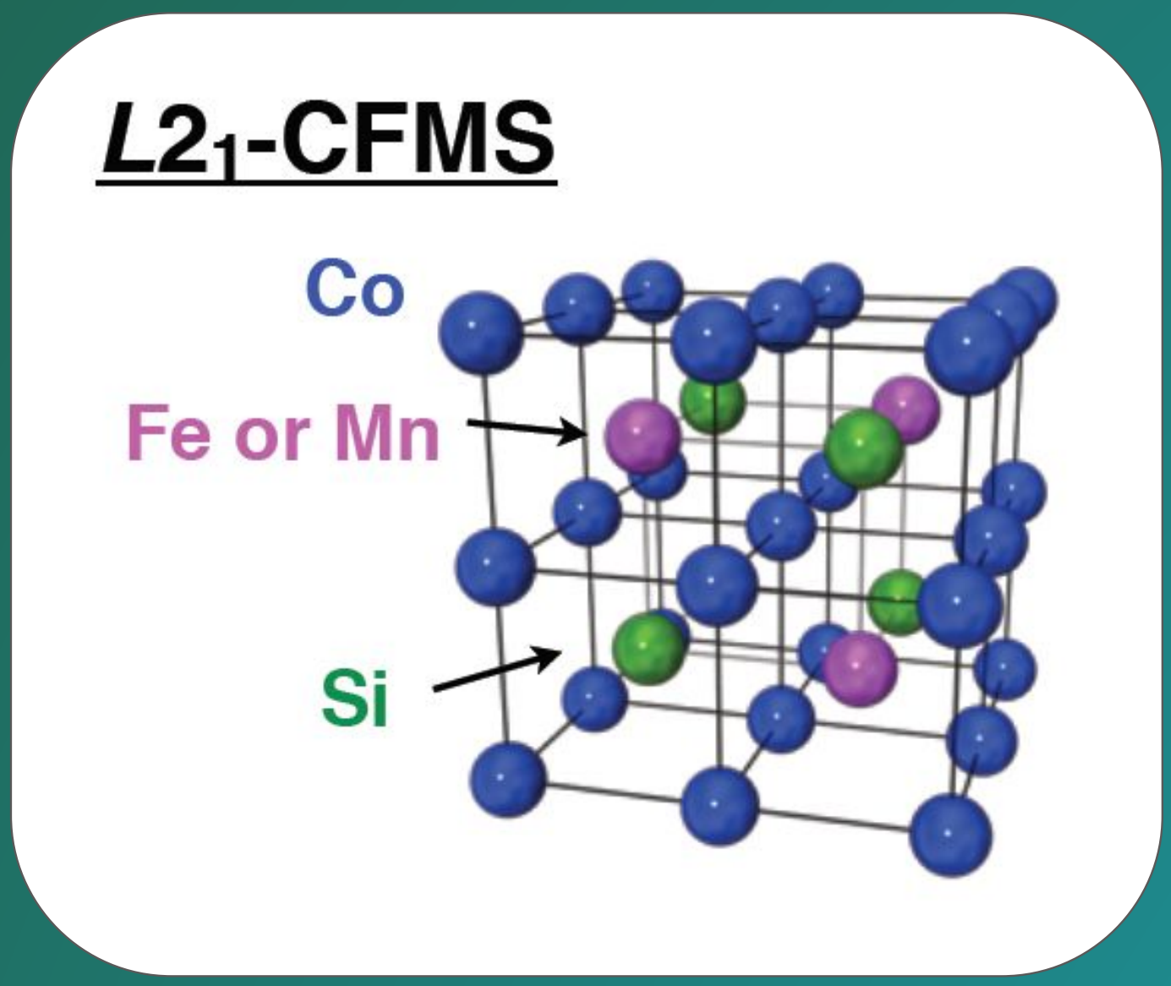
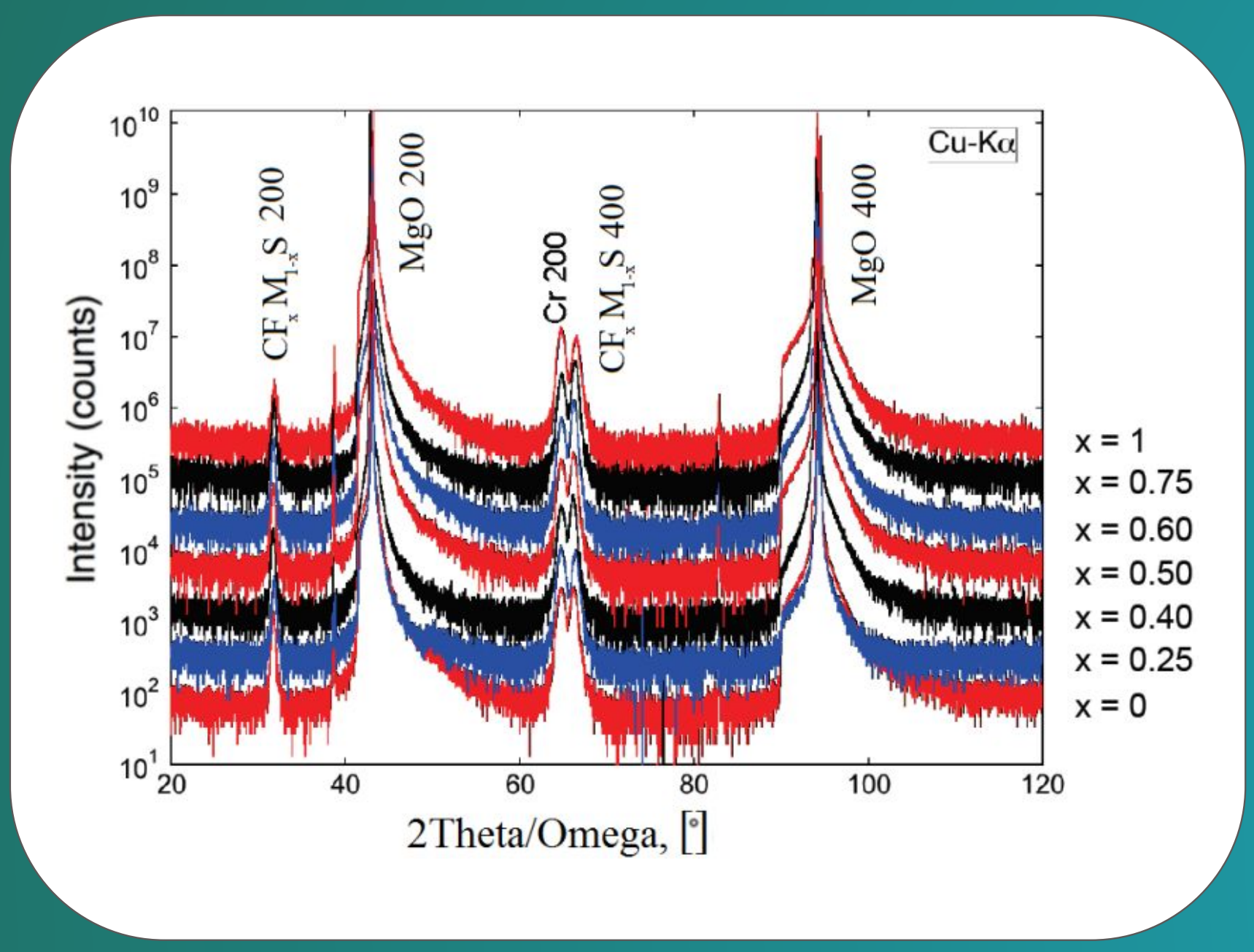
A strain modulated ferromagnetic resonance technique was applied to determine two cubic magnetoelastic constants of the epitaxially grown 30-nm-thick $Co_2Fe_xMn_{1-x}Si$ magnetic layers with different Fe and Mn contents, which were deposited on a MgO substrate with a 20-nm-thick Cr buffer layer—MgO (001) ∥ Cr(001) ∥ $Co_2Fe_xMn_{1-x}Si$ (001). It was found that, for the samples with the Fe content x = 0.4 or higher, the magnitudes of the two cubic magnetoelastic constants are clearly different, showing that the magnetoelastic properties of these samples are different than in the case of isotropic samples for which these two constants are expected to be equal. The magnitude of the cubic magnetocrystalline anisotropy constant reveals an evident maximum at the composition of x = 0.4, which corresponds to the minimum of the minor spin density of states, and thus the correlation between the cubic magnetocrystalline anisotropy and the electronic band structure. For all the investigated samples, a large perpendicular component of the magnetocrystalline anisotropy was observed as well as inhomogeneous broadening of the ferromagnetic resonance linewidth.

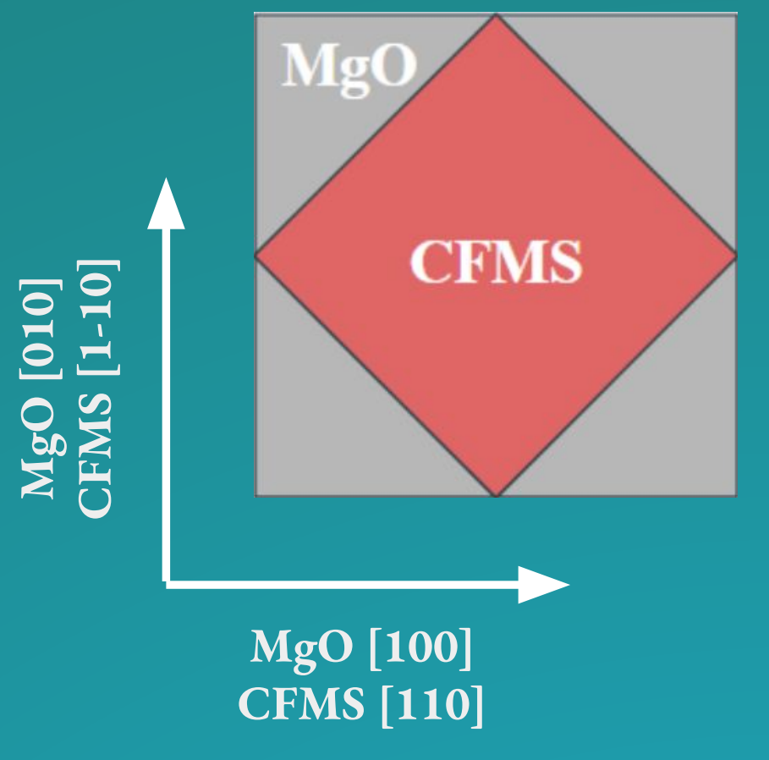
Samples information

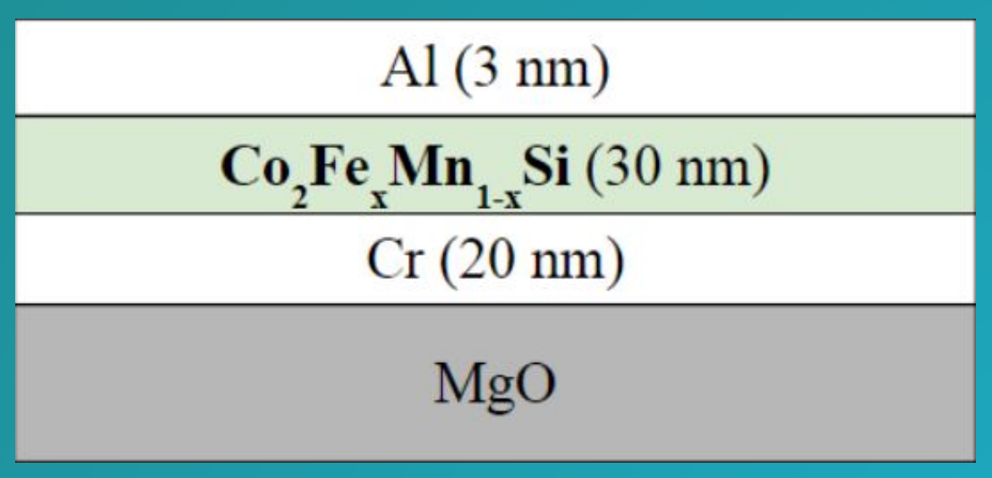




Ultrahigh-vacuum-compatible magnetron sputtering deposition:

Buffer layer deposition T_R
⇓
Annealing 600° C
⇓
Magnetic layer deposition T_R
⇓
Post-annealing 500° C
⇓
Cover layer deposition T_R



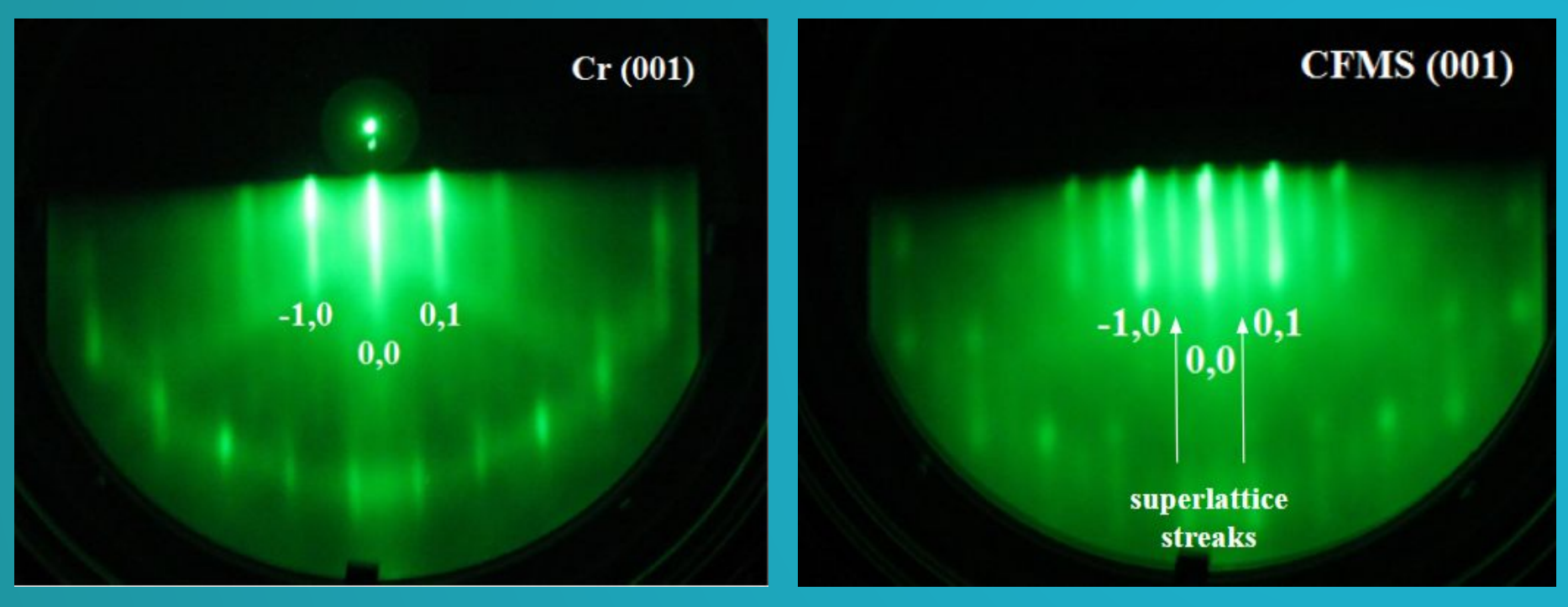


Al capping layer to prevent an oxidation

Cr buffer layer to obtain a low roughness surface

well crystalline with cubic symmetry; at least B2 ordered structure

flat surface with epitaxial relationships:
MgO (001) ∥ Cr (001) ∥ CFMS (001)



Model

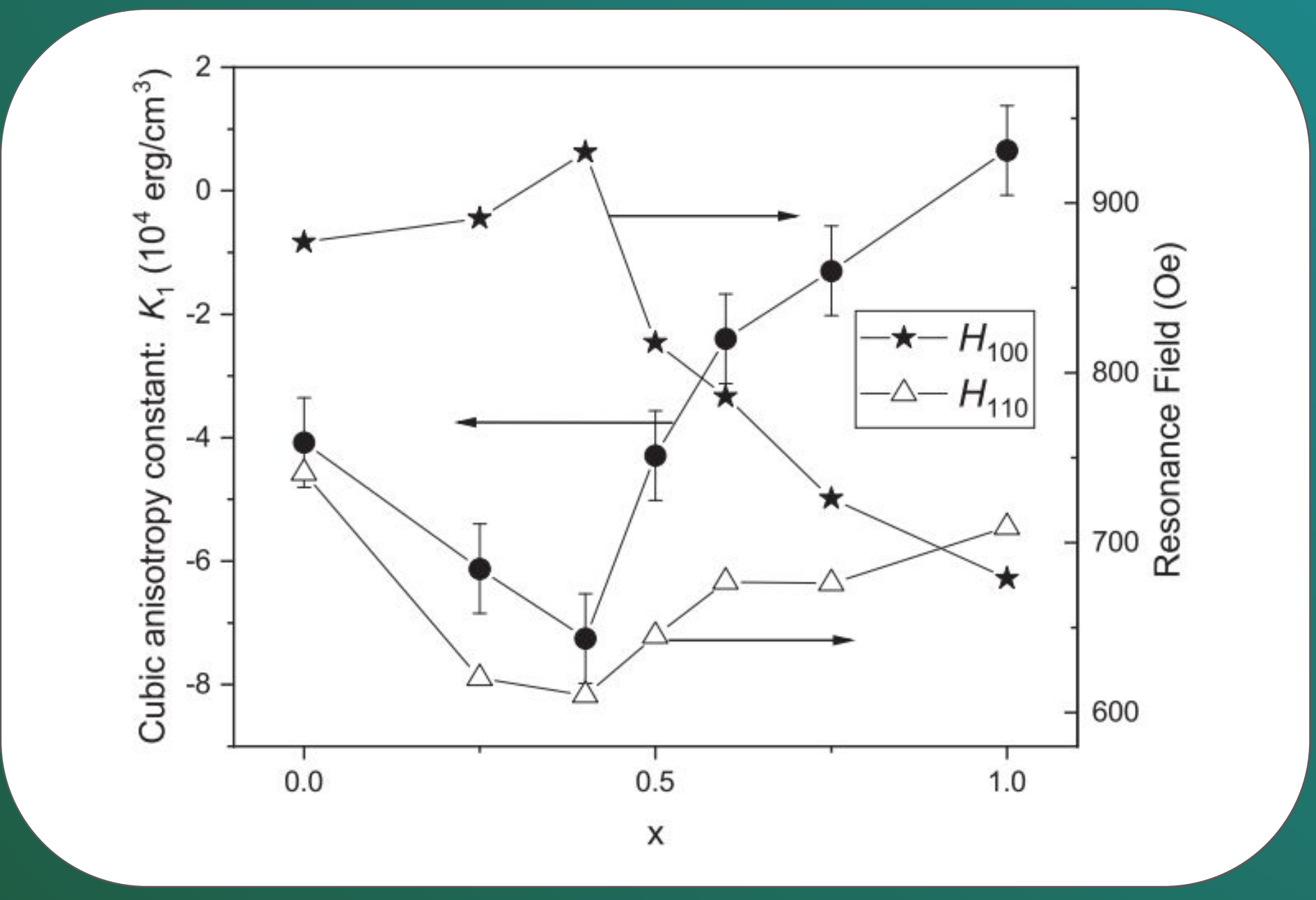
The following terms determine the Zeeman, magnetostatic, magnetocrystalline anisotropy, elastic and magnetoelastic energy, respectively. M_s is the saturation magnetization and H is the external magnetic field.

$$F = -\sum_{i=1}^{3} M_i H_i + 2\pi M_s^2 \alpha_3^2 + E_{mc} + E_{el} + E_{me}$$

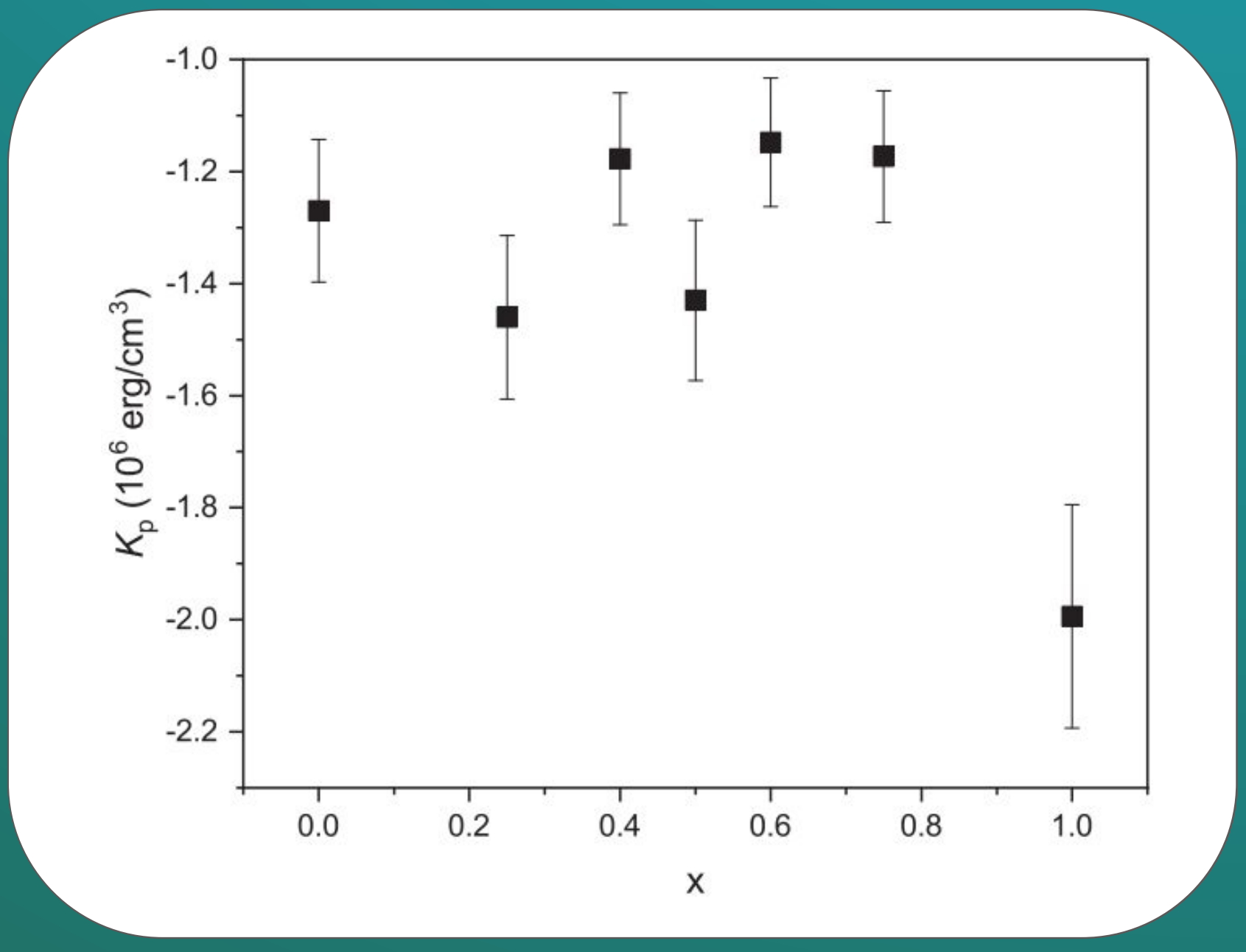
Magnetocrystalline anisotropy

$$E_{mc} = K_p(1-\alpha_3^2) + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2)$$

The energy of magnetocrystalline anisotropy depends on one perpendicular magnetocrystalline anisotropy constant K_p and the first cubic magnetocrystalline anisotropy constant K_1



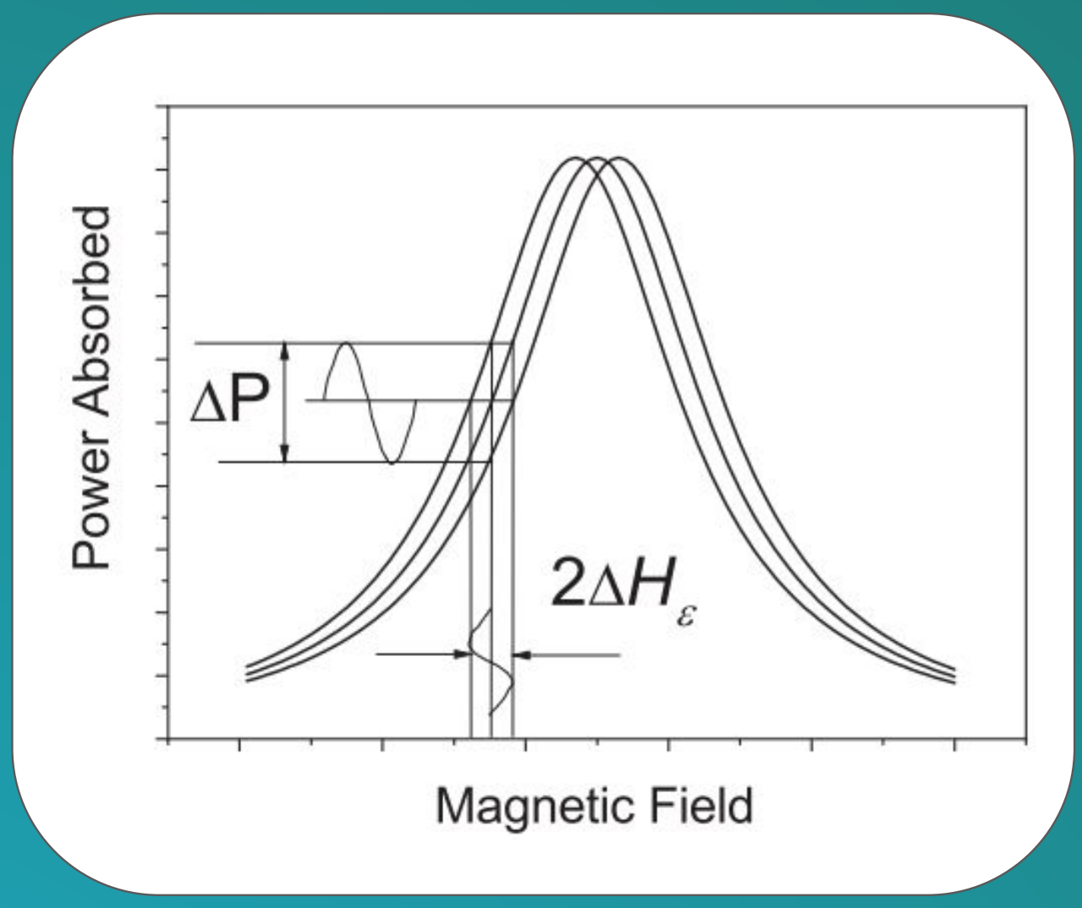
The first cubic magnetocrystalline anisotropy constant K_1 as a function of Fe content (black circles) for the $Co_2Fe_xMn_{1-x}Si$ magnetic layers studied in the experiments.



The changes of the perpendicular magnetocrystalline anisotropy constant K_p as a function of the Fe content, x, in the $Co_2Fe_xMn_{1-x}Si$ magnetic layers.

Magnetoelastic properties

Strain modulated ferromagnetic resonance (SMFRM) technique enables determination of magnetoelastic properties of magnetic thin films by studying the shift of the FMR line caused by a periodic strain.



$$m_\sigma = m_0 \frac{G_0}{G_\sigma} \frac{I_{strain}}{I_{magnet}}$$

$$\Downarrow$$

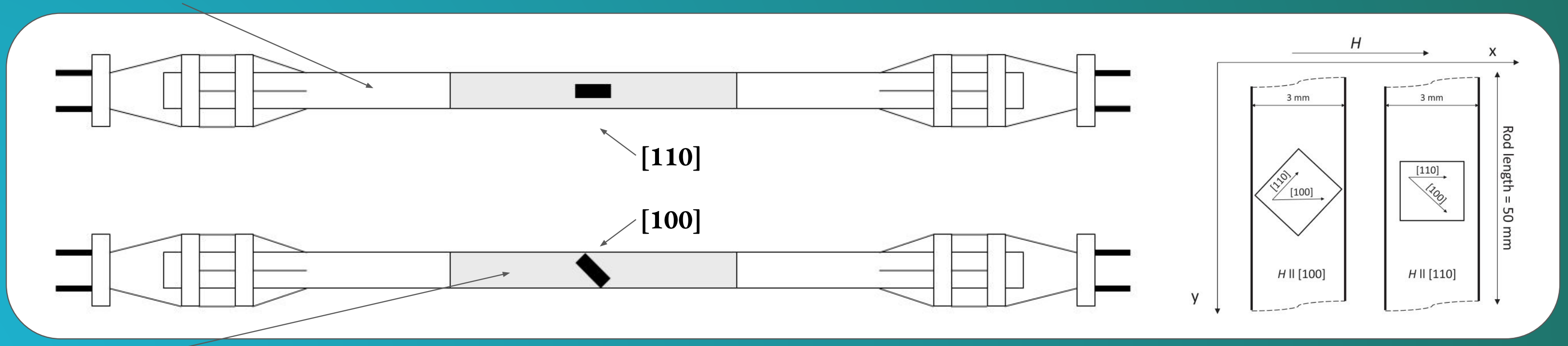
$$m_\sigma = \Delta H_\sigma = H_{strain} - H_{magnet}$$

$$\Downarrow$$

magnetoelastic constants b_i

The periodic shift of the resonance curve results in the modulation of an absorbed power ΔP, giving an effect equivalent to the modulation of the external magnetic field with the amplitude ΔH. The shift of the FMR resonance line is related to the ME effect. Thus using an appropriate model enables calculation of the ME constants.

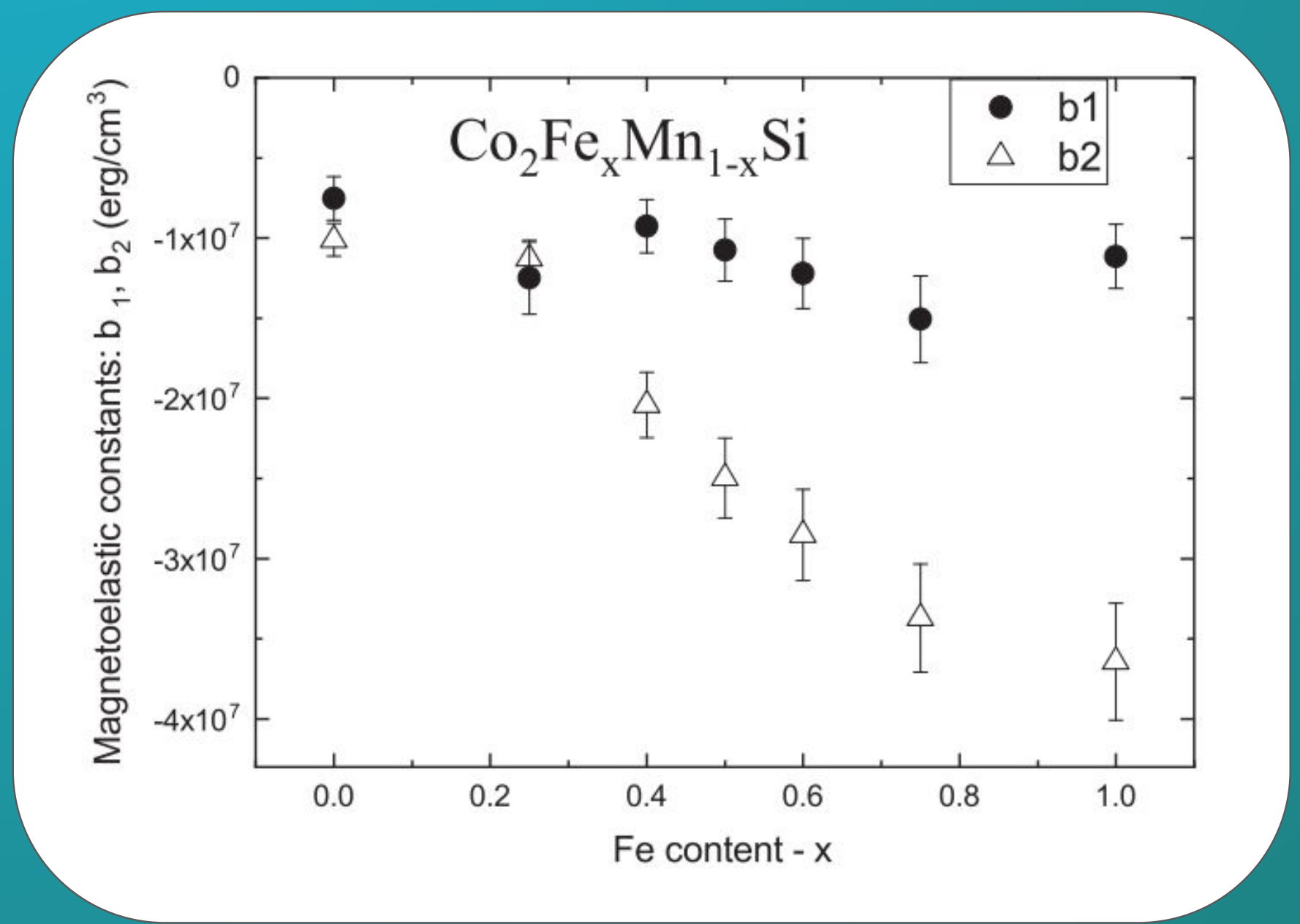
Polycrystalline quartz



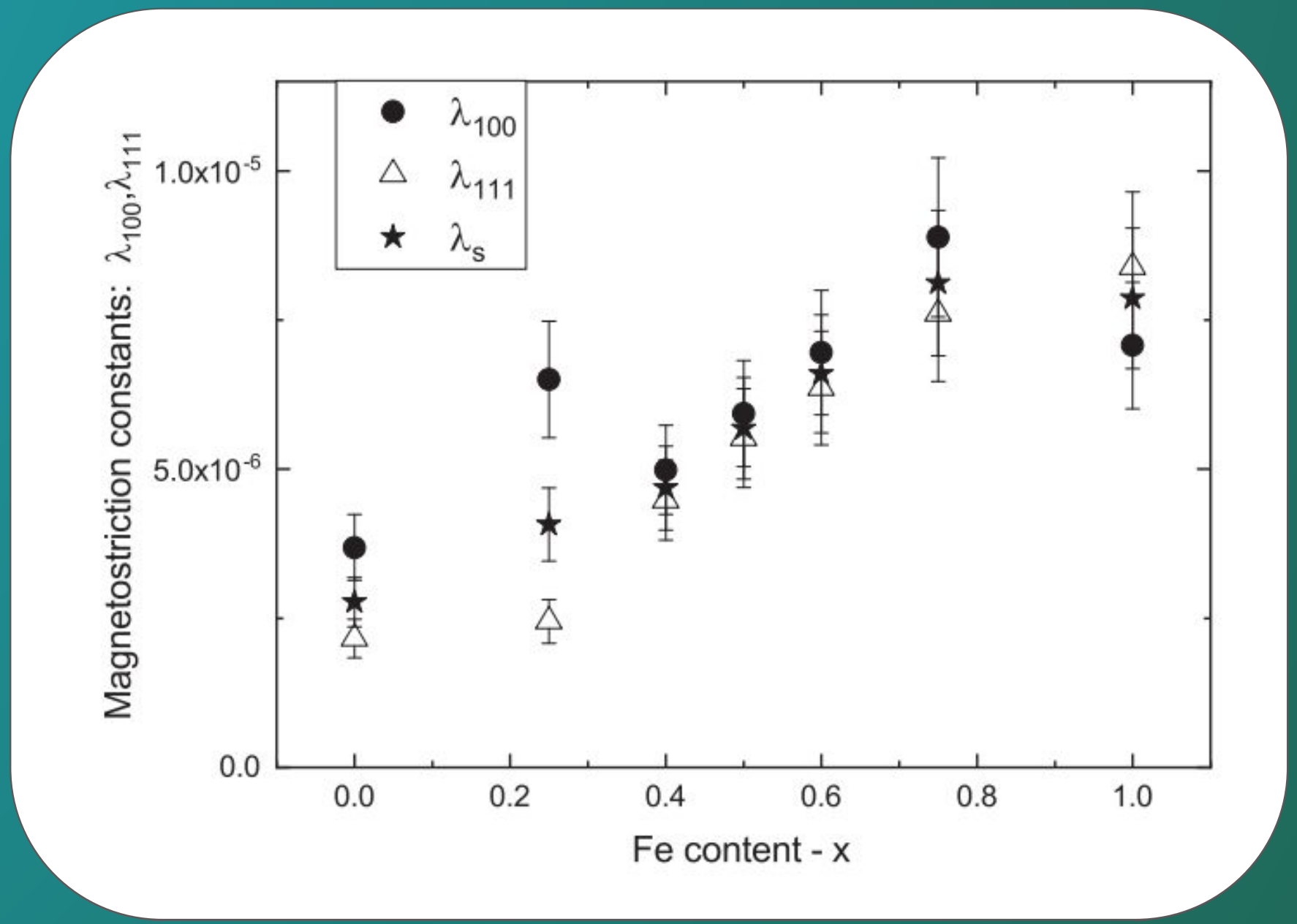
Monocrystalline quartz

Appropriate arrangement of the SMFMR experiment (the measurements were performed with the external magnetic field parallel to the [100] or [110] axis of the epitaxially grown magnetic layer) enables determination of two cubic magnetoelastic constants b_1 and b_2 defined by the formula for magnetoelastic energy:

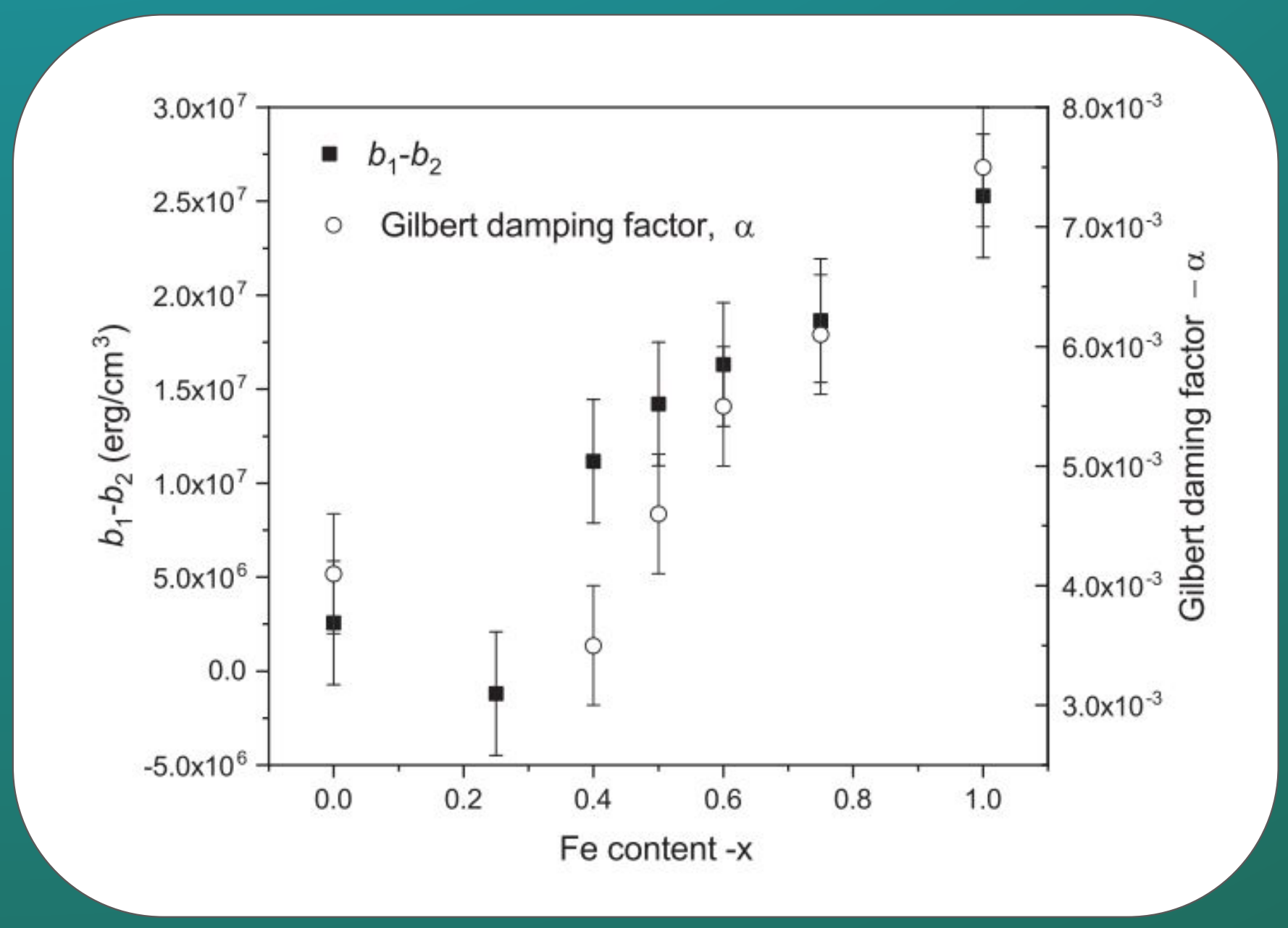
$$E_{me} = b_1(\alpha_1^2\varepsilon_{11} + \alpha_2^2\varepsilon_{22} + \alpha_3^2\varepsilon_{33}) + \\ + 2b_2(\alpha_1\alpha_2\varepsilon_{12} + \alpha_2\alpha_3\varepsilon_{23} + \alpha_1\alpha_3\varepsilon_{13})$$



Two magnetoelastic constants b_1 and b_2 for the series of the $Co_2Fe_xMn_{1-x}Si$ epitaxial magnetic layers with different Fe content x.



The calculated λ_{100}, λ_{111}, and averaged polycrystalline λs magnetostriction constants of the $Co_2Fe_xMn_{1-x}Si$ magnetic layers as a function of the Fe content x.



For the [100] or [111] direction, the saturation longitudinal magnetostriction is given by the formulas

$$\lambda_{100} = -\frac{2b_1}{3(c_{11}-c_{12})},$$

$$\lambda_{111} = -\frac{2b_2}{c_{44}}.$$

The minimum of the Gilbert damping dependence on x seems to be slightly shifted towards higher- Fe concentrations, both dependencies are quite similar. This fact suggests that, similarly to the Gilbert damping and the first cubic magnetocrystalline anisotropy constant, the anisotropy of the magnetoelastic properties is also correlated with the band structure of the investigated material.

Conclusions

- The magnitude of the cubic MC anisotropy of the 30 nm $Co_2Fe_xMn_{1-x}Si$ films reveals a pronounced maximum at x = 0.4 correlated with the changes in the density of states at the Fermi level for the minority-spin channel.
- For x = 0.4 or higher the two cubic ME constants (b_1 and b_2) are clearly different, and the difference between them increases with increasing iron content. Hence, with increasing the Fe content the magnetoelastic properties of the $Co_2Fe_xMn_{1-x}Si$ films becomes more and more anisotropic.
- The anisotropy of the magnetostriction constants (λ_{100} and λ_{111}) is rather moderate. Also the magnitudes of the estimated magnetostriction constants are relatively low. They increase with increasing the Fe content, and with increasing saturation magnetization, from about 2×10^{-6} to about 9×10^{-6}.
- All the investigated samples are characterized by large (of an order of 10^6 erg/cm3) negative perpendicular MC anisotropy constant. For this reason, the in-plane orientation of magnetization becomes even more preferred.
- Despite low values of the Gilbert damping factor, the widths of the FMR lines of all samples investigated reveal large inhomogeneous broadening related among others to the two-magnon scattering mechanism.

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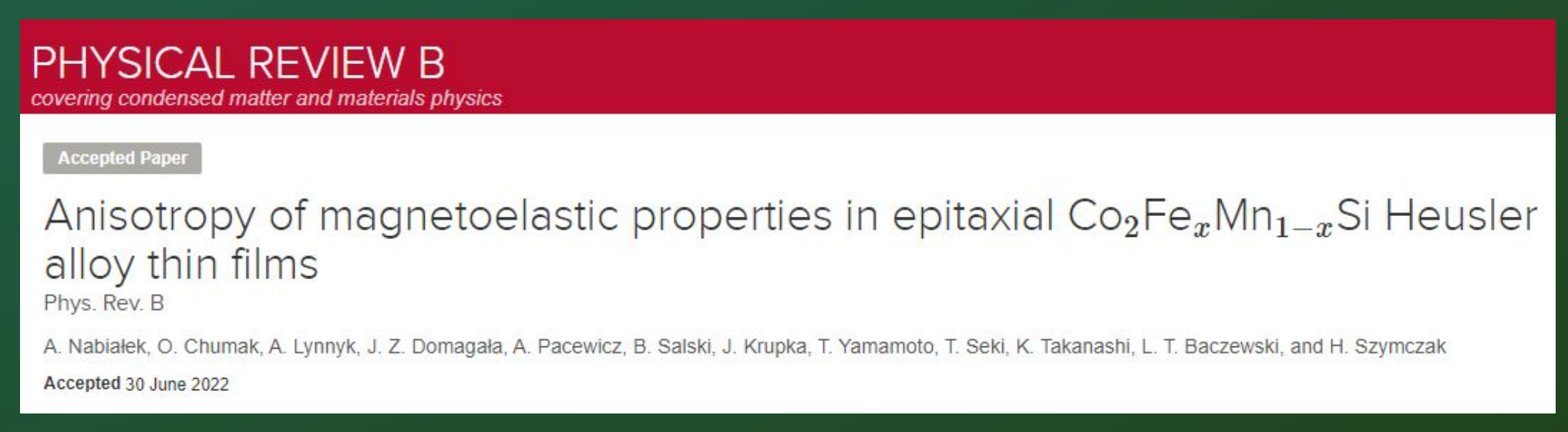

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