Quantum-Well-Controlled High-Order Anisotropic Magnetoresistance in Epitaxial Fe(001) Thin Films

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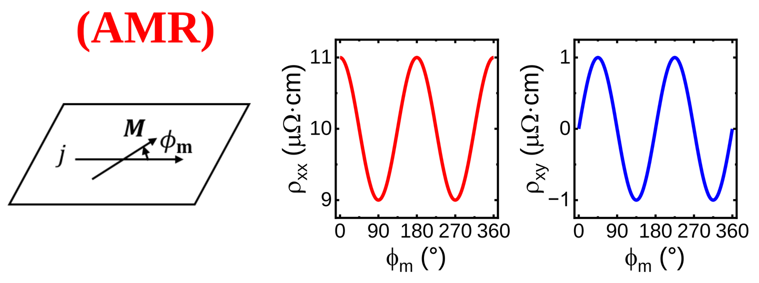
Introduction

➢ Anisotropic magnetoresistance (AMR)

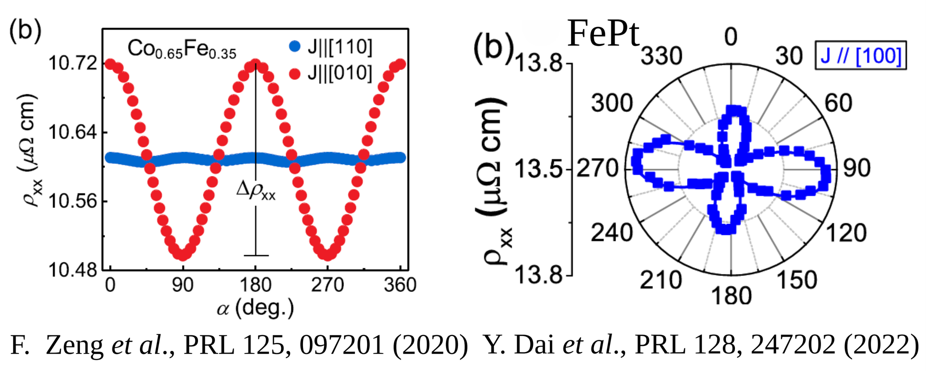


$\rho_{xx}(\phi) = \rho_0 + \Delta\rho_2 \cos 2\phi$

$\rho_{xy}(\phi) = \Delta\rho_2 \sin 2\phi$ ← Planar Hall effect (PHE)

J. M. D. Coey, Magnetism and Magnetic Materials

➢ AMR in single crystal

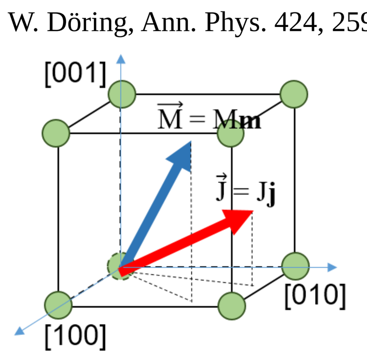


F. Zeng *et al.*, PRL 125, 097201 (2020) Y. Dai *et al.*, PRL 128, 247202 (2022)

$\Delta\rho_2^{J\parallel[100]} \neq \Delta\rho_2^{J\parallel[110]}$ Four-fold angular dependence

➢ Phenomenological model of AMR based on crystal symmetry

W. Döring, Ann. Phys. 424, 259 (1938)



From Ohm's law $E_i = \rho_{ij} J_j$, expansion of ρ_{ij} on **m**:

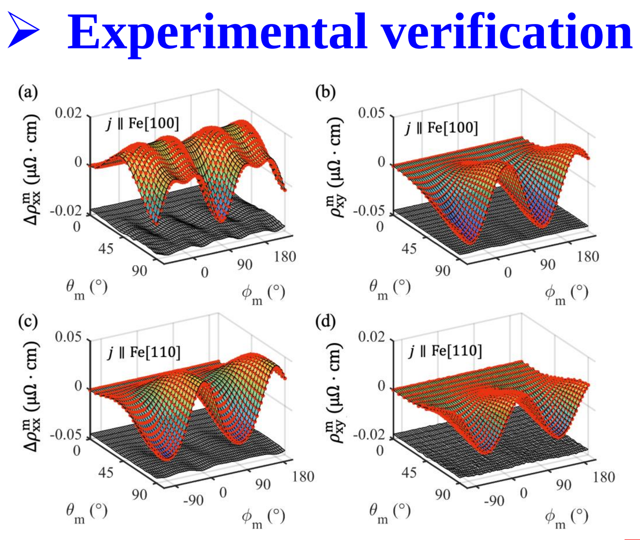
$$\rho_{ij}(\mathbf{m}) = a_{ij} + a_{klij} m_k m_l + a_{klmnij} m_k m_l m_m m_n + \cdots$$

⇩ **Onsager relation:** $\rho_{ij}(\boldsymbol{m}) = \rho_{ji}(-\boldsymbol{m})$ **Cubic crystalline symmetry**

$\rho_{xx}^{J\parallel[100]}(\phi) = \rho_0 + \Delta\rho_2 \cos(2\phi) + \Delta\rho_4 \cos(4\phi)$ $\rho_{xy}^{J\parallel[100]}(\phi) = \Delta\rho_2' \sin(2\phi)$

$\rho_{xx}^{J\parallel[110]}(\phi) = \rho_0 + \Delta\rho_2' \cos(2\phi) - \Delta\rho_4 \cos(4\phi)$ $\rho_{xy}^{J\parallel[110]}(\phi) = \Delta\rho_2 \sin(2\phi)$

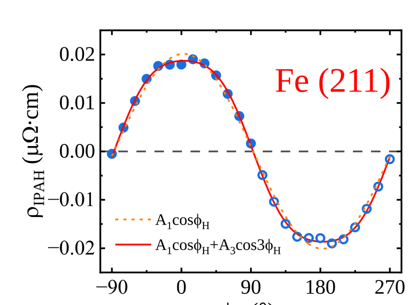
➢ Experimental verification



H. Chen *et al.*, PRB 111, 014437 (2025)

➢ High order galvanomagnetic effects

In-plane anomalous Hall effect



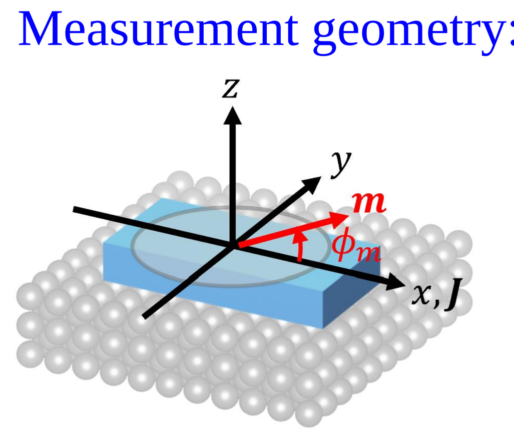
High order Spin-orbit coupling ⇩ High order Spin-dependent transport

H. Chen *et al.*, PRB 111, 174423 (2025) W. Peng *et al.*, arXiv:2402.15741 (2024)

High order angular dependence of AMR?

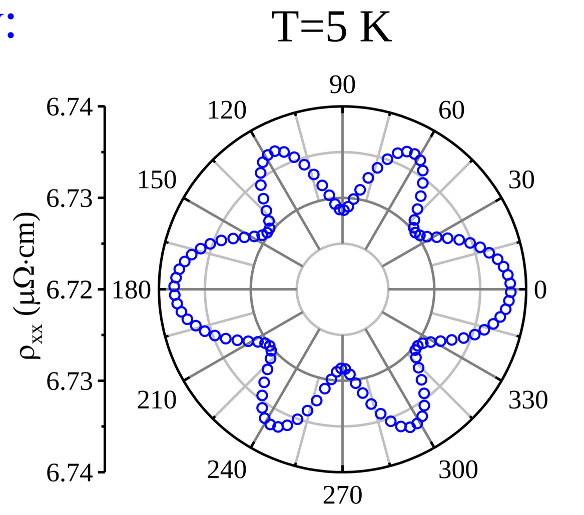
Six-fold angular-dependent AMR

Measurement geometry:

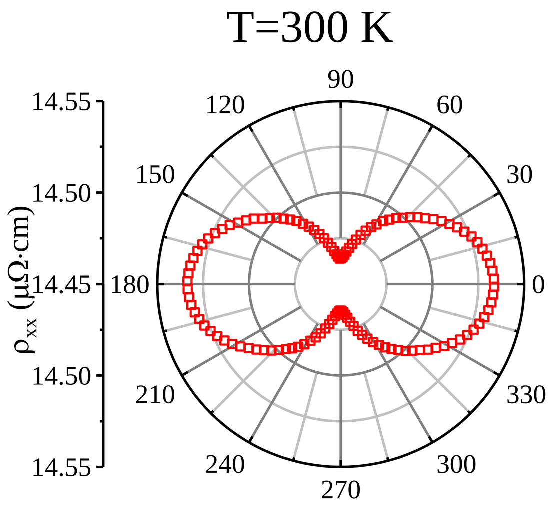


Fe(4.6 nm)/MgAl$_2$O$_4$(001)

T=5 K

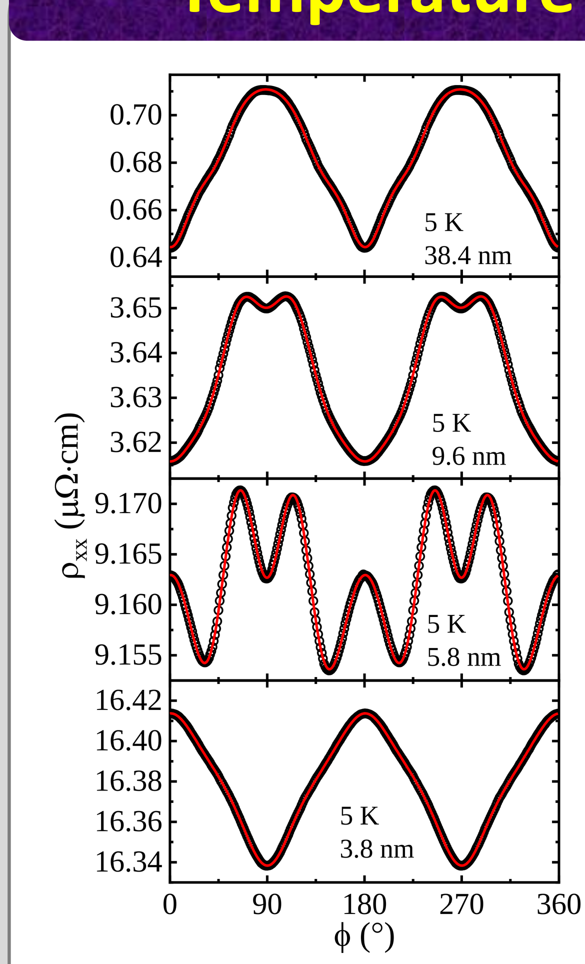


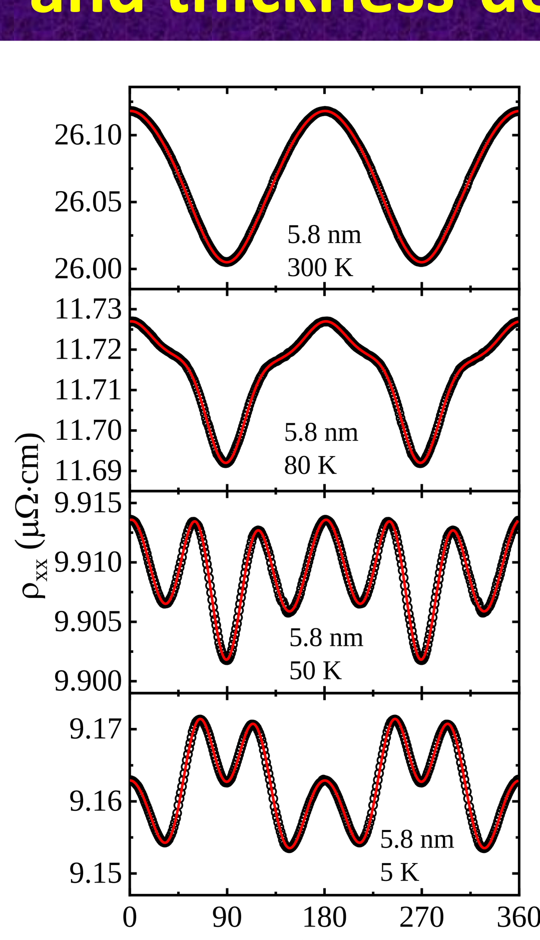
T=300 K

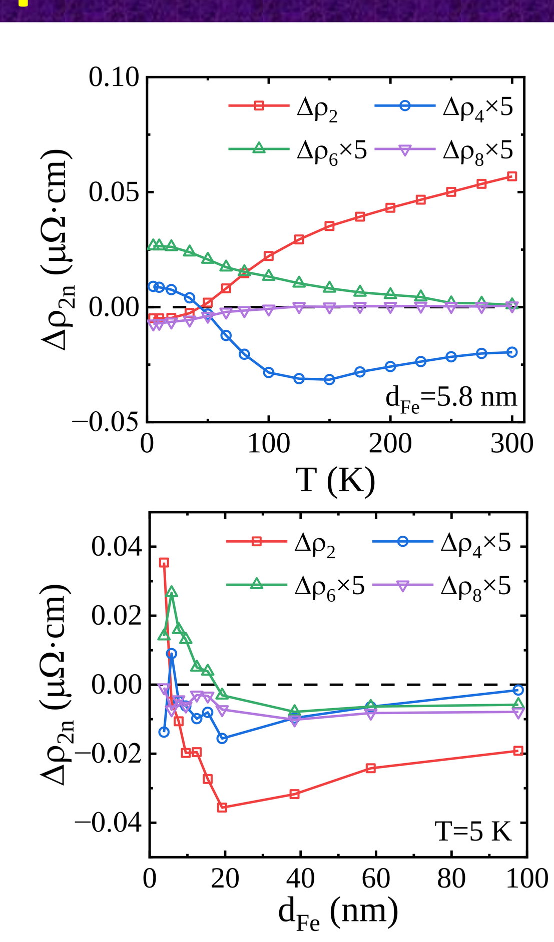


Six-fold angular-dependent AMR is observed at low temperature

Temperature- and thickness-dependent AMR

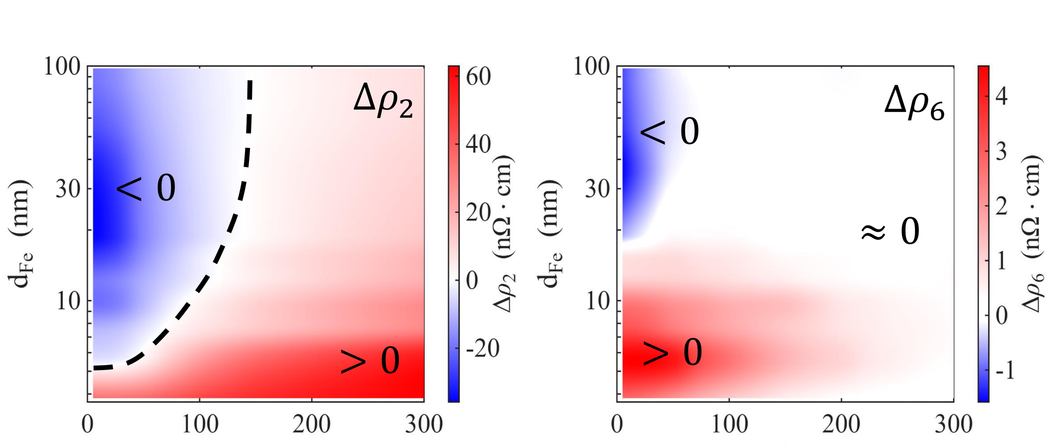






Fitting function: $\rho_{xx}(\phi) = \rho_0 + \Delta\rho_2 \cos 2\phi + \Delta\rho_4 \cos 4\phi + \Delta\rho_6 \cos 6\phi + \cdots$

➢ Sign reversal of $\Delta\rho_2$ and $\Delta\rho_6$



➢ Possible explanation

$$\sigma_{xx} \sim \sum_{nk} v_{x,nk}^2 \tau_{nk} = \bar{\tau}_0 \sum_{nk} v_{x,nk}^2$$

$$\rho_{xx} \sim \frac{1}{\bar{\tau}_0} \cdot \frac{1}{\sum_{nk} v_{x,nk}^2} = f^{\tau}(\phi) \cdot g^{v}(\phi)$$

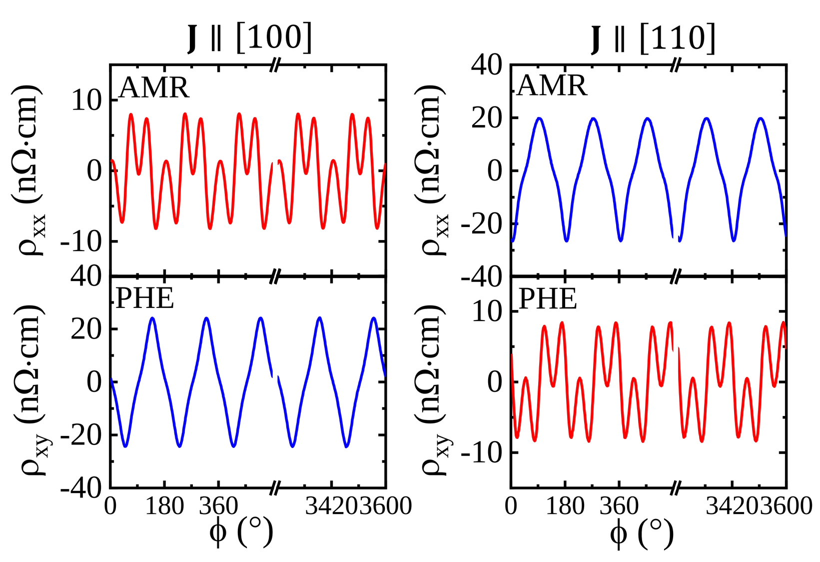
Relaxation time contribution: $f^{\tau}(\phi) = c_0^{\tau} + c_2^{\tau}\cos 2\phi + c_4^{\tau}\cos 4\phi$

Fermi velocity contribution: $g^{v}(\phi) = c_0^{v} + c_2^{v}\cos 2\phi + c_4^{v}\cos 4\phi$

$\Delta\rho_6 = 1/2 \cdot (c_4^{v} c_2^{\tau} + c_4^{\tau} c_2^{v}) \cos 6\phi$

High order angular-dependent AMR

➢ Reciprocal relation



High-order expansion of AMR and PHE: (Considering C_4 symmetry, truncated at 6[th] order)

$\rho_{xx}^{J\parallel[100]}(\phi) = \Delta\rho_2 \cos(2\phi) + \Delta\rho_4 \cos(4\phi) + \Delta\rho_6 \cos(6\phi)$

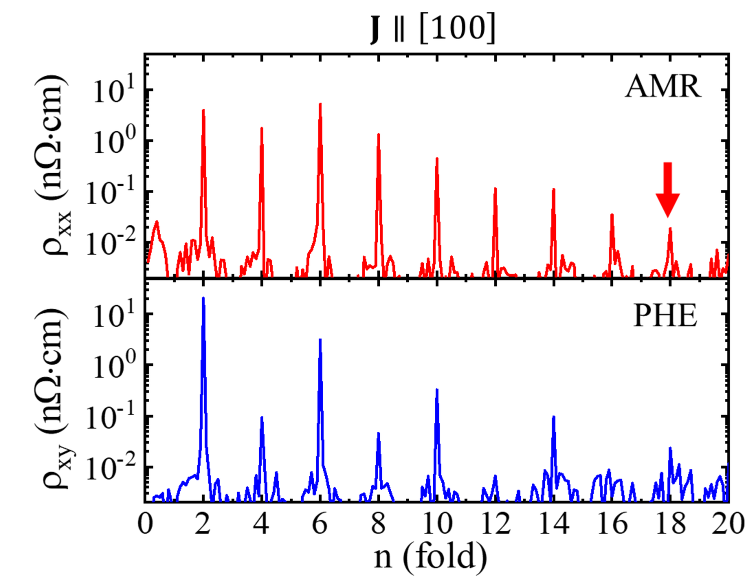
$\rho_{xy}^{J\parallel[100]}(\phi) = \Delta\rho_2' \sin(2\phi) - \Delta\rho_6' \sin(6\phi)$

$\rho_{xx}^{J\parallel[110]}(\phi) = \Delta\rho_2' \cos(2\phi) - \Delta\rho_4 \cos(4\phi) + \Delta\rho_6' \cos(6\phi)$

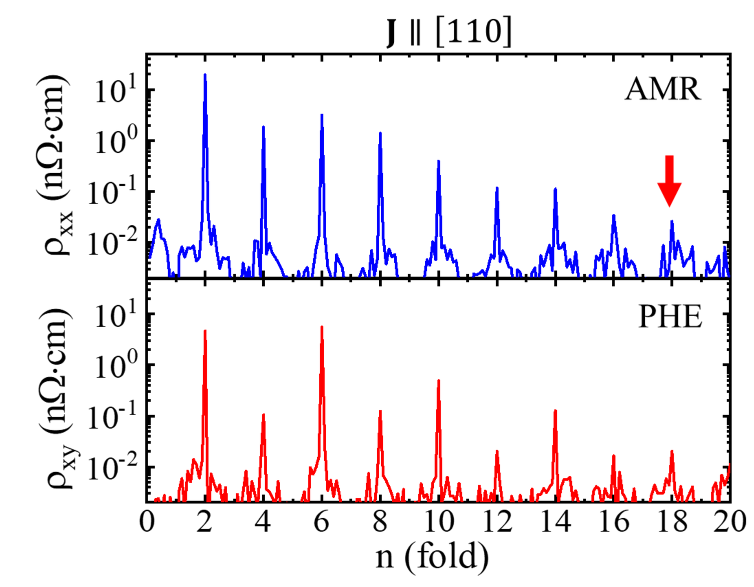
$\rho_{xy}^{J\parallel[110]}(\phi) = \Delta\rho_2 \sin(2\phi) - \Delta\rho_6 \sin(6\phi)$

Consistent with experimental results

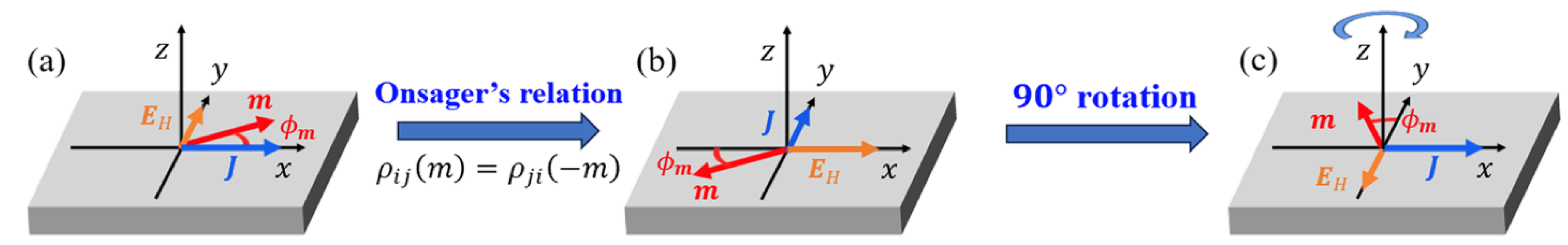
➢ Fast Fourier transformation



Up to 18-fold AMR



➢ Onsager relation prohibits 4-fold PHE with perfect C_4 symmetry

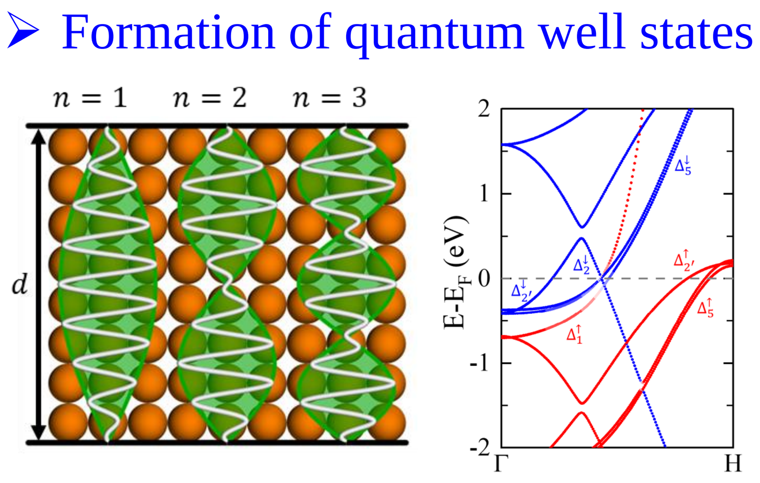


Constraint on PHE:

$\rho_{xy}(\phi) = -\rho_{xy}(\phi + \pi/2)$ ⇨ $\cos 2(\phi + \pi/2) = -\cos 2\phi$ ✓ $\cos 4(\phi + \pi/2) = \cos 4\phi$ ✗

Quantum-well-induced oscillatory AMR in thin films

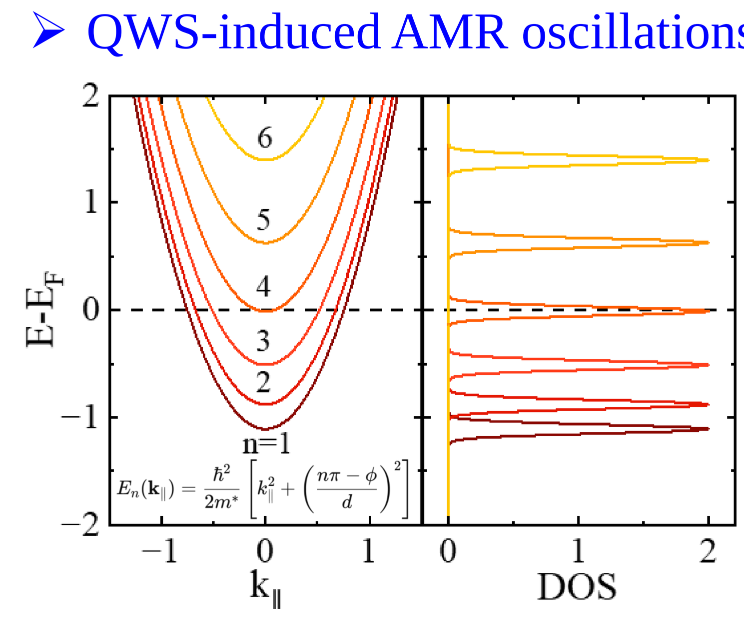
➢ Formation of quantum well states



Confinement along d → Discrete states

QWS condition: $2k_F d + \varphi = 2n\pi$

➢ QWS-induced AMR oscillations



Increase d → QWS subbands cross E_F

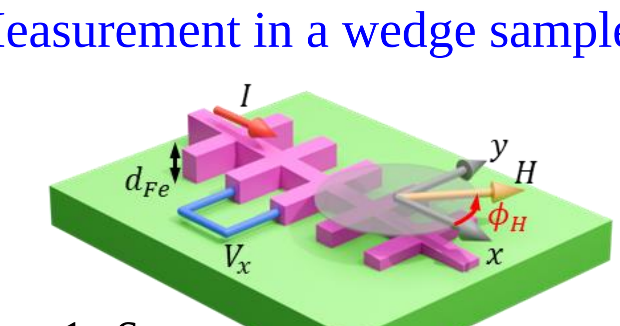
DOS at E_F oscillates with d

AMR exhibits corresponding oscillation

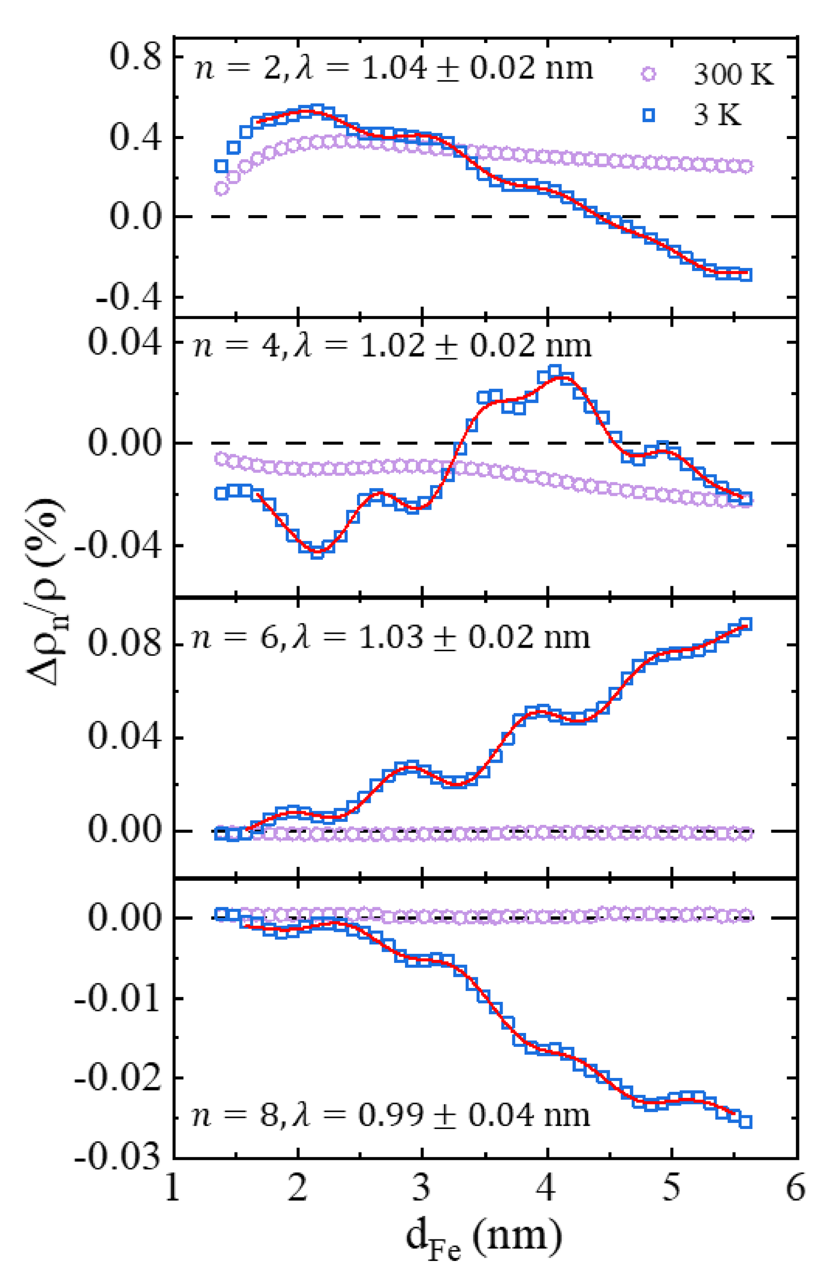
Period: $\lambda = \frac{\pi}{k_F}$ or $\frac{\pi}{k_{BZ} - k_F}$

For $\Delta_{2'}^{\uparrow}$ band: $\lambda \sim 1.0$ nm

➢ Measurement in a wedge sample



d$_{Fe}$: 1~6 nm



Summary

- ➢ 6-fold angular AMR in nominally 4-fold Fe(001) films
- ➢ Sign reversal of 2-fold and 6-fold AMR with thickness
- ➢ Reciprocal relation between AMR and PHE
- ➢ AMR modulation by $\Delta_{2'}^{\uparrow}$-band quantum well states

H. Chen *et al.*, Phys. Rev. Lett. **136**, 086704 (2026)