Magnetotransport anisotropies in GaMnAs: how to analyse, how to classify

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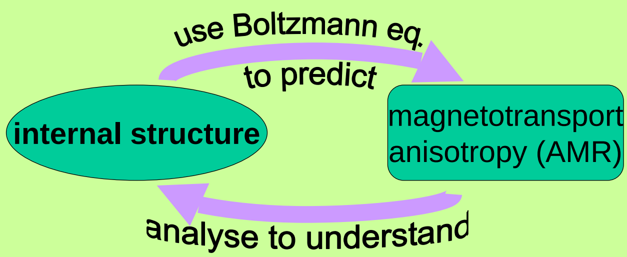
Intro

In an isotropic material, the sheet resistance does not depend on current direction and transversal resistance is zero. In a ferromagnet, (for instance diluted magnetic semiconductors) a special direction is given by the magnetization, the symmetry is lowered and both resistances become a function of the current direction. This effect, called magnetotransport anisotropy is further promoted by the particular symmetry of the crystalline environment: e.g. cubic in GaAs.



Conclusion

- a recipe how to extract anisotropy params.
- classification of anisotropy using these: (normal/cubic/monoclinic symmetry)
- microscopic calculation of the anisotropy parameters
- in agreement with (different) experiments: normal AMR < 0,
- sign switch AMRip vs. AMRop due to growth strain

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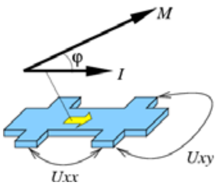
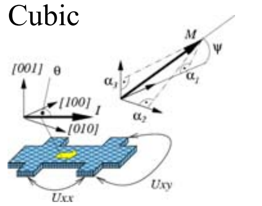
Isotropic

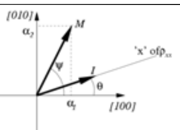


- φ: angle between M and I the only param.
- = polycrystalline (random psi, constant phi)
- $\rho_{xx} = \rho_\perp + (\rho_\parallel - \rho_\perp)\cdot \cos^2\varphi$
- $\rho_{xy} = (\rho_\parallel - \rho_\perp)\cdot \sin\varphi\cos\varphi$

Cubic



- many angles: $\alpha_1,\alpha_2,\alpha_3(M)$, $\beta_1,\beta_2,\beta_3(I)$
- $\rho_{xx} = \rho_0 + \frac{1}{2}u_2\cos 2\vartheta\cos 2\psi + \frac{1}{2}v_1\sin 2\vartheta \sin 2\psi$
- $\rho_{xy} = -\frac{1}{2}u_2\sin 2\vartheta\cos 2\psi + \frac{1}{2}v_1\cos 2\vartheta\sin 2\psi$



Cubic – inplane configuration

- two angles: ψ, ϑ, while $\varphi = \psi - \vartheta$
- ψ: magnetization to [100]
- ϑ: current to [100]

Phenomenology

- $\underline{E} = \underline{\underline{\rho}}\cdot \underline{j}$
- for current I along $(\beta_1,\beta_2,\beta_3)$, voltage U along $(\gamma_1,\gamma_2,\gamma_3)$: $R = \rho_{\beta\gamma} = U/I = \sum_{i,j}\rho_{ij}\beta_i\gamma_j$

Most general AMR (Cubic material):

- $\rho_{xx} = U(\alpha_1^2)\beta_1^2 + U(\alpha_2^2)\beta_2^2 + \alpha_1\alpha_2[V(\alpha_1^2)+V(\alpha_2^2)]\beta_1\beta_2$
- $\rho_{xy} = -U(\alpha_1^2)\beta_1\beta_2 + U(\alpha_2^2)\beta_2\beta_1 + \alpha_1\alpha_2[V(\alpha_1^2)\beta_1^2 - V(\alpha_2^2)\beta_2^2]$

Fourier expansion of U and V

- $U(\alpha_1^2) = u_1 + u_2\alpha_1^2 + u_4\alpha_1^4$
- $V(\alpha_1^2) = v_1$

´Magnetocrystalline anisotropy´

Isotropic vs. cubic

$v_1 = u_2$ vs. $v_1 \neq u_2$

Normal AMR: $(v_1+u_2)/u_1$=NOR
Cubic AMR: $(u_2-v_1)/u_1$=CUB

Uniaxial (in the plane)

- $\rho_{xx} = w_{22}(\alpha_2,\alpha_1)\beta_1^2 + w_{22}(\alpha_1,\alpha_2)\beta_2^2 + [w_{12}(\alpha_1,\alpha_2) + w_{12}(\alpha_2,\alpha_1)]\beta_1\beta_2$
- $w_{22}(\alpha_1,\alpha_2) = u_1 + u_2\alpha_1^2 + u_4\alpha_1\alpha_2$

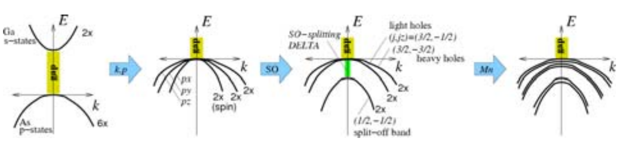
(this is ρ_{xx} if I ||[100])

Uniaxial AMR: u_4/u_1 = UNI

Keeping only the lowest terms:

$$\rho_{xx}/u_1 = 1 + \tfrac{1}{4}\cos 2\varphi\left\{\frac{u_2+v_1}{u_1} + \frac{u_2-v_1}{u_1}\cos 4\vartheta\right\} - \tfrac{1}{4}\frac{u_2-v_1}{u_1}\sin 2\varphi \sin 4\vartheta$$

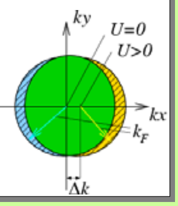
Six-band model



- GaAs within $k.p$ approximation + SO interaction
- Mn moments: mean field, $H_{MF} = J_{pd}\sum_{i,I} S_I\cdot s_i\,\delta(r_i - R_I)$
- Kohn-Luttinger Hamiltonian

Linear transport: Boltzmann equation

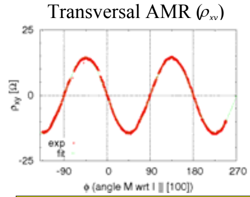
- equilibrium distribution shifted by $\Delta k = \tau\cdot(-e\underline{E}\cdot \underline{v}(\underline{k}))$
- $j_i = 2e\int\frac{d^3k}{(2\pi)^3}\tau(\underline{k})\cdot(-e\underline{E}\cdot\underline{v}(\underline{k}))\frac{\partial f}{\partial E_k}v_i(\underline{k})$
- $v_i(\underline{k}) = (1/\hbar)(\partial E/\partial k_i)$
- relaxation time: $\tau(\underline{k})$, Fermi golden rule



Experimental

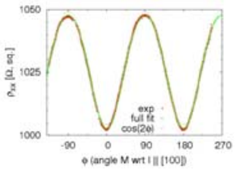
- 3.5% Mn, 50 nm film, measured at 4 K and inplane B = 1.3 T

Transversal AMR (ρ_{xy})



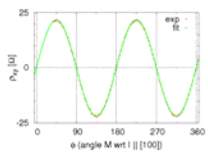
Inferred AMR:
- NOR = -3.6%
- CUB = 0.79%
- UNI = 0.25%

Longitudinal AMR (ρ_{xx})

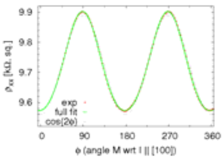


- negative normal AMR (contrary to metals)
- uniaxial anisotr. present

- 5% Mn, 25 nm film, measured at 4 K and inplane B = 1.0 T



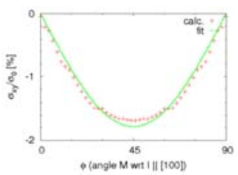
NOR = -3.0%
CUB = 0.36%
UNI = 0.54%



Model calculations

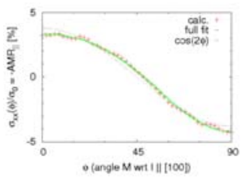
- 3.5% Mn, bulk, no strain, saturated Mn moments, in-plane geometry

Transversal AMR (ρ_{xy})



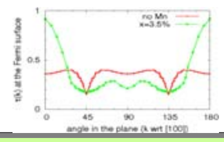
- NOR = -6.0%
- CUB = 1.5%
- UNI not calc.

Longitudinal AMR (ρ_{xx})



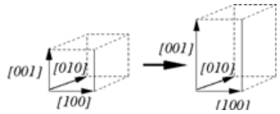
Microscopic mechanism:
- mostly due to the minority hh band
- Fermi surf./vel. change only little
- relaxation times strongly anisotropic

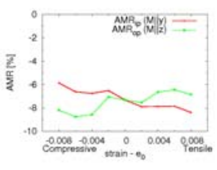
Relaxation times:

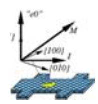


Modelling the effect of strain

- 2.0% Mn, saturated Mn moments
- biaxial strain (substrate – GaMnAs lattice mismatch)







- current along [100]
- w/o strain [010] = [001]
- strain lifts the degeneracy
- tensile/compressive – different sign of AMRip-AMRop
- in agreement with exp. (Matsukura *et al.*, Phys. E ’04)