AMR and Magnetometry studies of GaMnAs films

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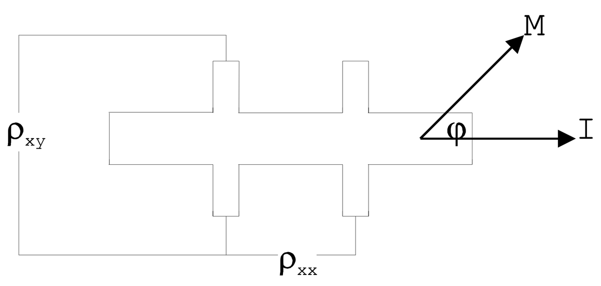
Introduction

In a ferromagnet the spin-orbit interaction can give rise to an Anisotropic Magneto-Resistance (AMR). For an isotropic material (e.g. polycrystal) the resistance has the form

$$\rho_{xx} = \frac{1}{2}(\rho_{\parallel} + \rho_{\perp}) + \frac{1}{2}(\rho_{\parallel} - \rho_{\perp})\cos 2\varphi \qquad (1)$$

$$\rho_{xy} = \frac{1}{2}(\rho_{\parallel} - \rho_{\perp})\sin 2\varphi \qquad (2)$$

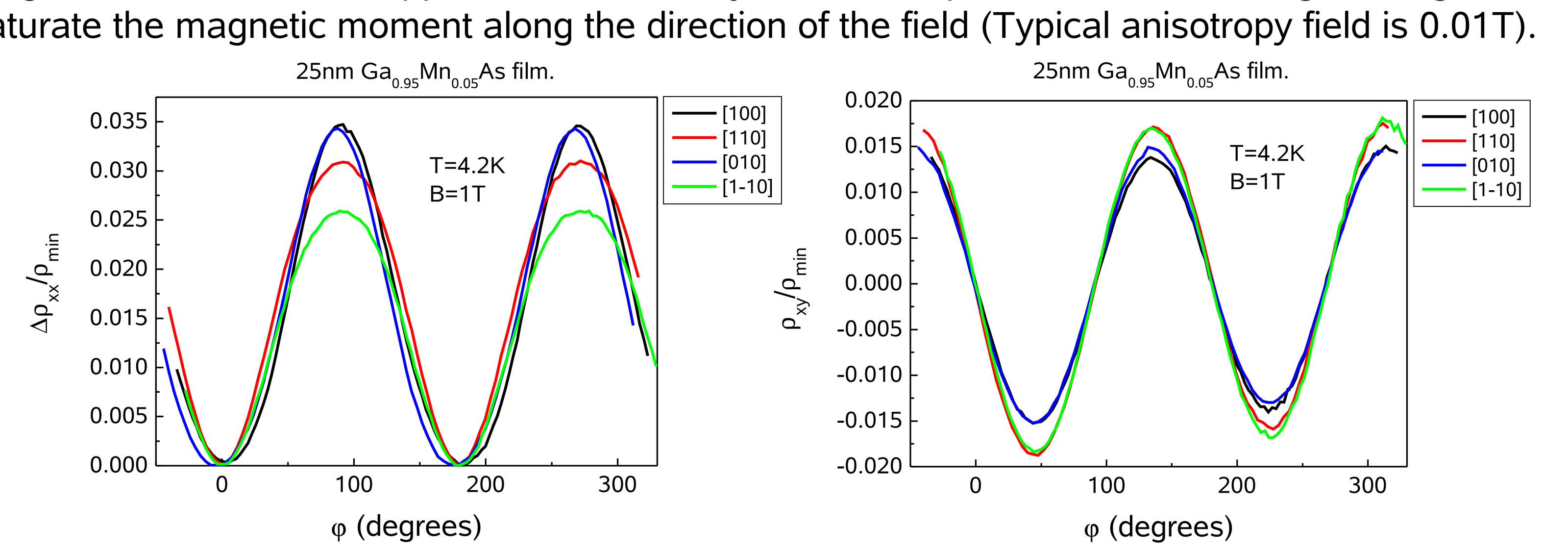


φ is the angle between the magnetisation (M) and the current (I).

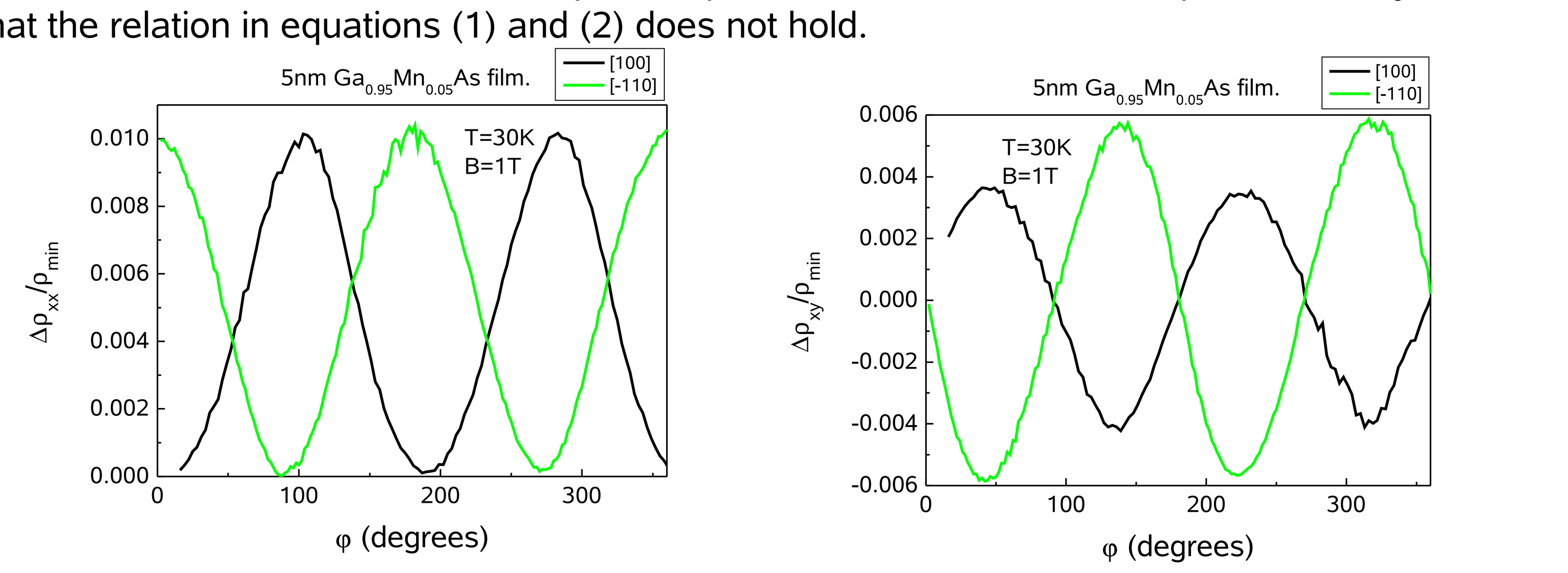
This has been observed experimentally for the diluted magnetic semiconductor $Ga_{1-x}Mn_xAs$[1] for which $\rho_{\parallel} < \rho_{\perp}$ is generally observed.

In crystalline material the AMR can also depend upon the angle of both M and I with respect to the crystal axes. Here we show that this is indeed the case for a 25nm $Ga_{0.95}Mn_{0.05}As$ film in which the crystalline contribution accounts for 10% of the AMR and contains both cubic and uniaxial components. This is confirmed with measurements of a device with a Corbino geometry in which the current is averaged over all in plane directions and only the magnetocrystalline contribution to the AMR is observed. For a 5nm $Ga_{0.95}Mn_{0.05}As$ film the crystalline contribution is the dominant effect resulting in $\rho_{\parallel} > \rho_{\perp}$ for certain current directions. Furthermore, AMR and SQUID magnetometry results indicate that in these 5nm films the easy axis of the magnetisation can have an out of plane component.

A series of four Hall bars were measured with the current along different crystal directions. A magnetic field of 1T was applied and rotated by 360° in the plane. This field is large enough to saturate the magnetic moment along the direction of the field (Typical anisotropy field is 0.01T).



These results show that the AMR depends upon the direction of I with respect to the crystal and that the relation in equations (1) and (2) does not hold.



For the 5nm $Ga_{0.95}Mn_{0.05}As$ films the AMR can have opposite sign depending upon the direction of the current indicating that the crystalline contribution to the AMR is dominant.

Phenomenological model

The effect of crystal symmetry on AMR was first worked out by Doring[2]. Briefly, the analysis involves expressing the resistivity as a series expansion

$$\rho = \sum_{i,k=1}^{3} \omega_{ik}\beta_i\beta_k \qquad \omega_{ik} = a_{ij} + a_{kij}\alpha_k + a_{klij}\alpha_k\alpha_l + \dots$$

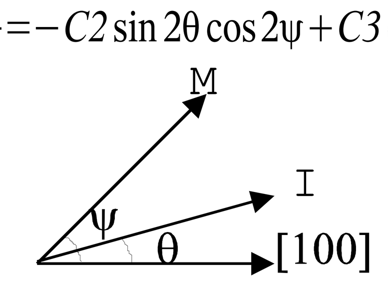
where α and β are the direction cosines of M and I with respect to the crystal axes. The relationship between the coefficients a_{ij} etc can be obtained by applying the transformation matrices appropriate to the symmetry present in the crystal.

Under cubic and uniaxial symmetry the AMR will have the form (to 4th order)

$$\frac{\Delta\rho_{xx}}{\rho} = C1 + C2\cos 2\theta\cos 2\psi + C3\sin 2\theta\sin 2\psi + C4\sin 2\psi + C5\cos 4\psi$$

$$\frac{\Delta\rho_{xy}}{\rho} = -C2\sin 2\theta\cos 2\psi + C3\cos 2\theta\sin 2\psi$$

ψ is the angle between M and the [100] direction.



θ is the angle between I and the [100] direction

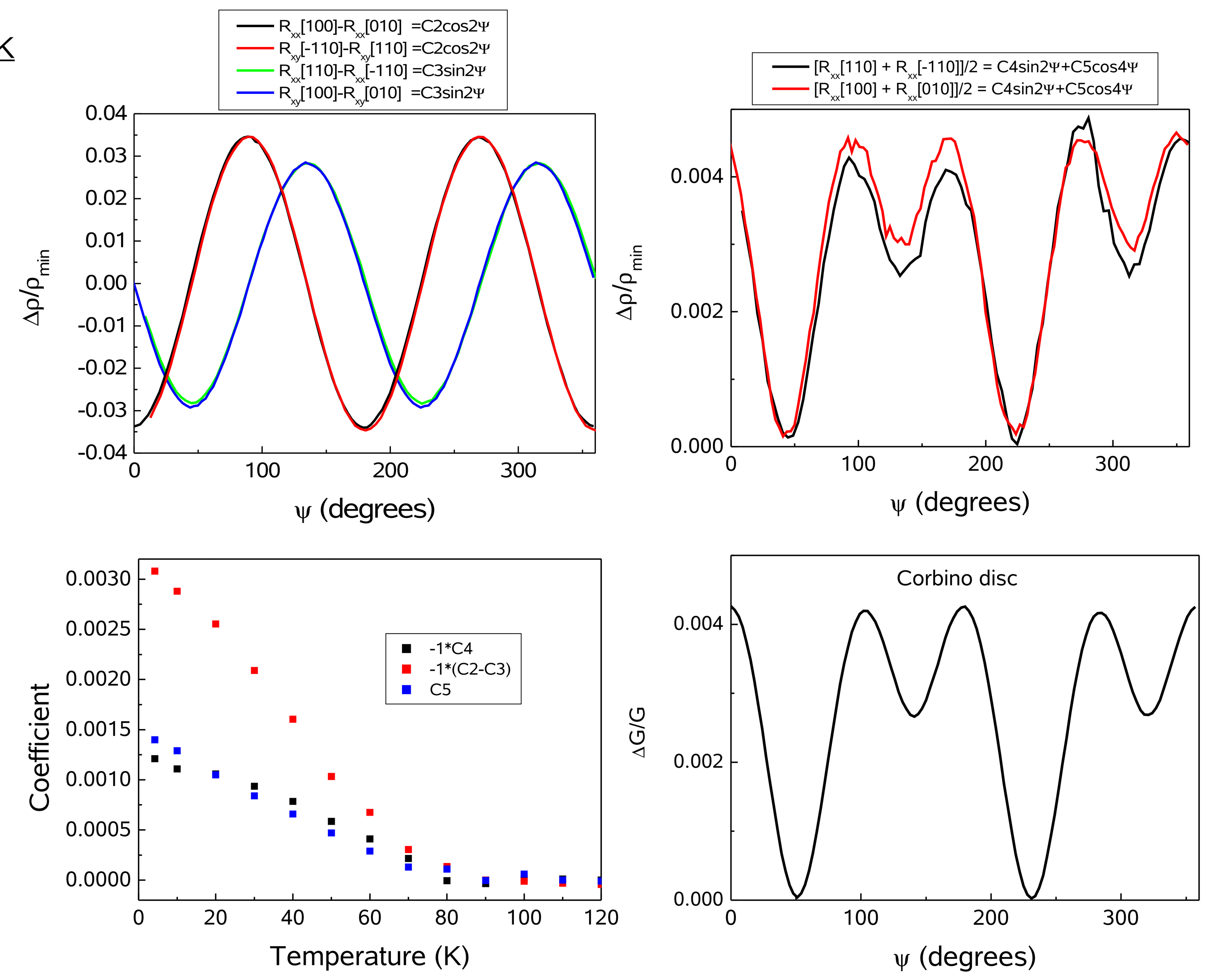
For an isotropic material C2=C3 and C4=C5=0.

C2,C3 and C5 arise from cubic and uniaxial symmetry, so C2-C3 and C5 are good measures of the crystalline contribution to the AMR. C4 arises from uniaxial symmetry alone.

Extracting the crystalline components

By combining the data from the four devices with current along different crystal directions it is possible to extract values for these coefficients

T=4K

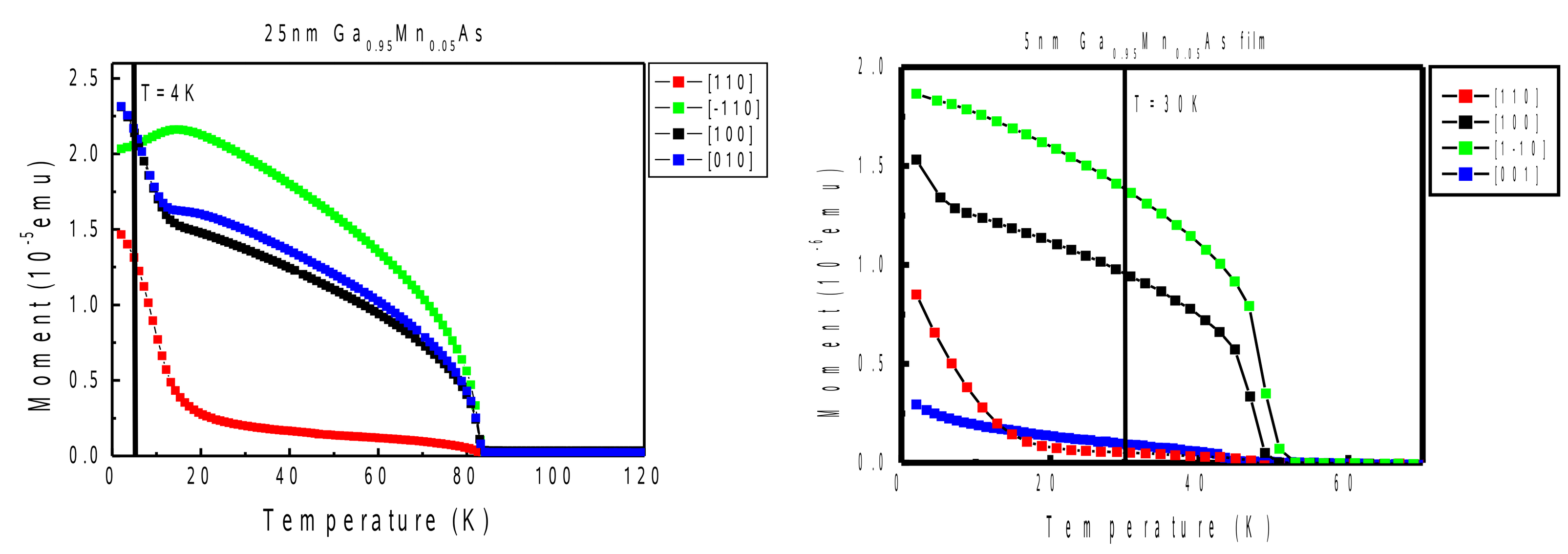


The conductance of the Corbino disc contains cos4θ and sin2θ terms of the same order of magnitude as the magnetocrystalline contribution extracted from the Hall Bars.

Magnetometry

SQUID magnetometry shows that the magnetic anisotropy contains both cubic and uniaxial components, consistent with the AMR.

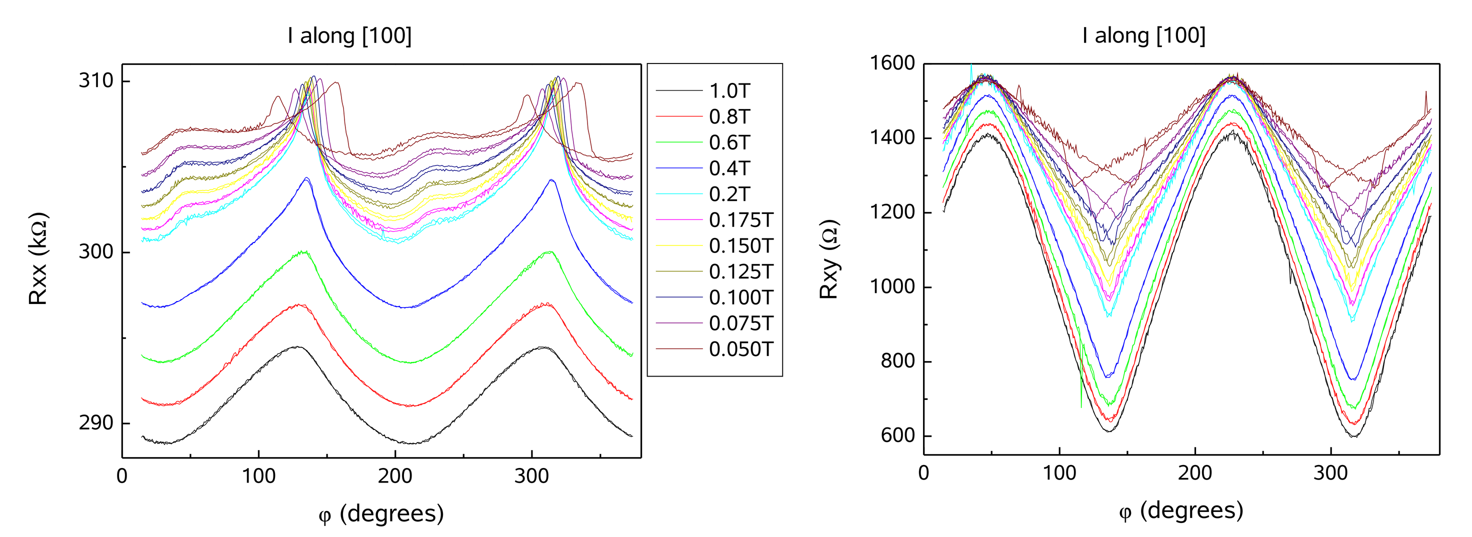
Remnance (B=0T)



For the 5nm $Ga_{0.95}Mn_{0.05}As$ film the remnance has a small out of plane component.

5nm $Ga_{0.95}Mn_{0.05}As$ films

T=4K



At 4K the AMR is distorted when the moment points out of plane on crossing the in plane hard axes.

Conclusion

The AMR in GaMnAs films contains a contribution due to the crystal symmetry.

This has cubic and uniaxial components, consistent with the magnetic anisotropy.

It accounts for 10% of the AMR observed in 25nm $Ga_{0.95}Mn_{0.05}As$ films.

In 5nm $Ga_{0.95}Mn_{0.05}As$ films the crystalline contribution to AMR is dominant.

AMR and magnetometry indicate that the magnetic easy axis can have an out of plane component for the 5nm $Ga_{0.95}Mn_{0.05}As$ films.

References

[1] Goennenwein et al. PRB 71, 193306 (2005), Tang et al. PRL 90, 107201 (2003).

[2] Döring, ann Phys (Leipzig) 32, 259 (1938)