Ferromagnetic Resonance Studies of (Ga,Mn)N

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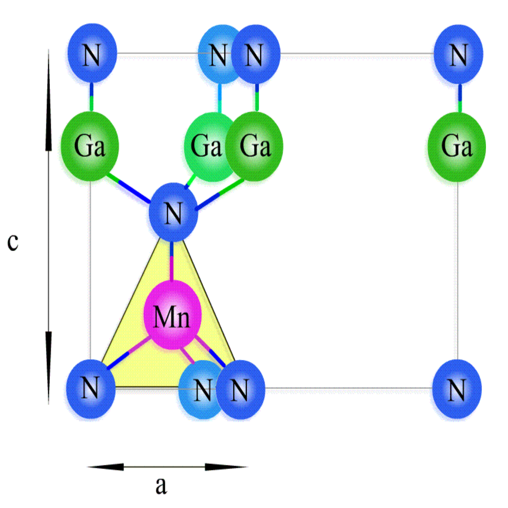
MOTIVATION



Dilute ferromagnetic semiconductors, in particular (Ga,Mn)N predicted to have an exceptionally high Curie temperature (T_C), have attained great research importance due to its unique ability to combine the properties of semiconductors and magnetic materials. Moreover, GaN being a wide band gap semiconductor has been dominating the photonics and high power electronics. So it is important to make an effort to understand the underling magnetic properties of (Ga,Mn)N. We report ferromagnetic resonance (FMR) studies of a (Ga,Mn)N layer grown by molecular beam epitaxy . Investigated sample with a concentration of 9.7% Mn showed ferromagnetic signature, as evidenced by SQUID magnetometry, with T_C = 12.8 K.

SQUID MAGNETIZATION RESULTS

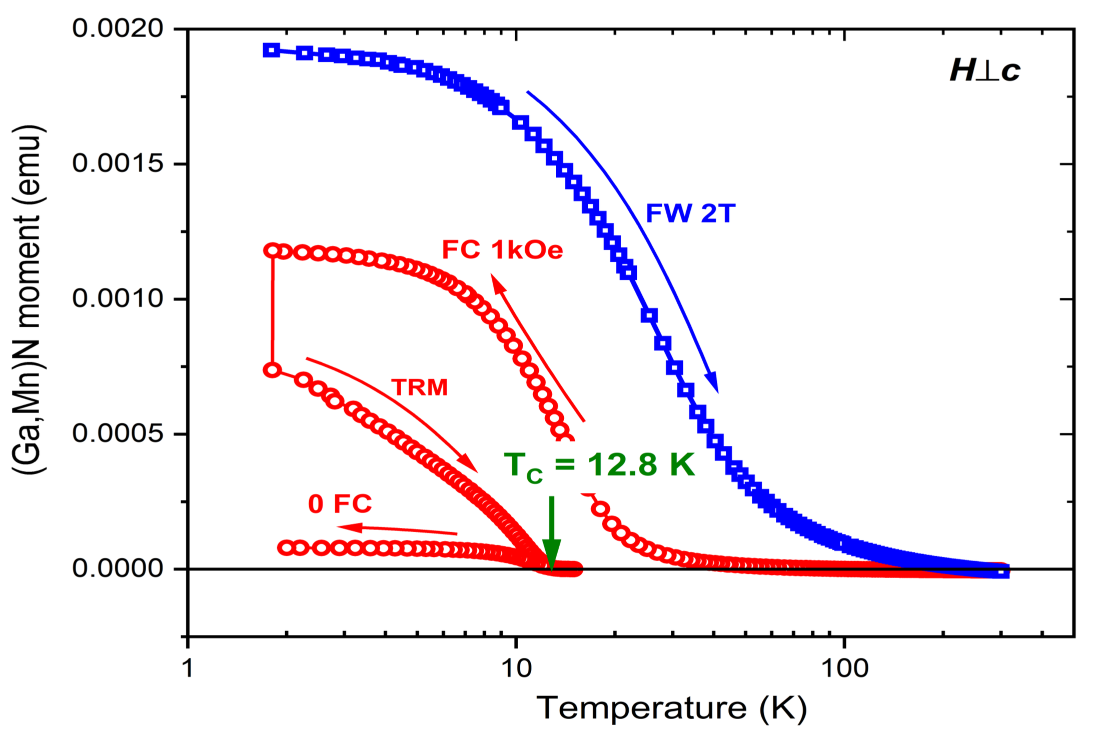


Figure 1: Temperature dependence of the magnetization of (Ga,Mn)N with 9.7% Mn. The sample is initially field-cooled (FC) in a magnetic field of H = 1 kOe and after quenching the field, the thermoremanent magnetization (TRM) is recorded during warming . The temperature at which TRM vanishes indicates the Curie temperature (T_C).

FERROMAGNETIC RESONANCE SPECTROSCOPY

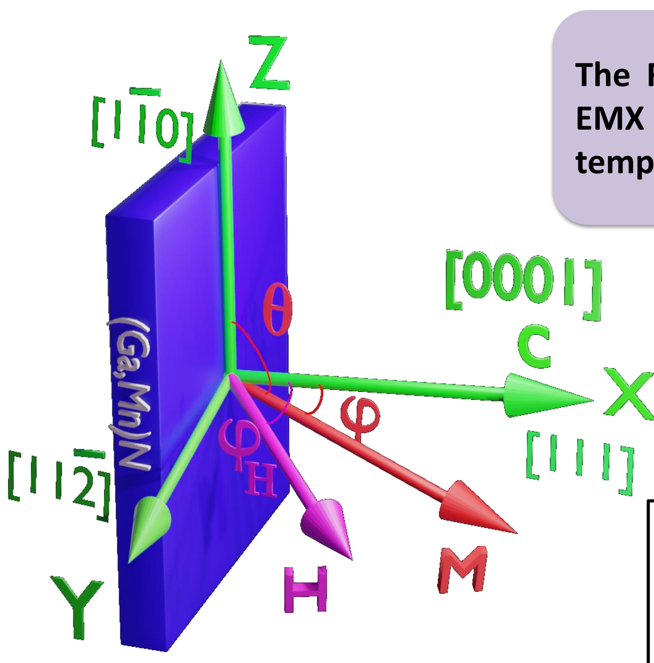


Figure 2: Sample structure and the coordinate system used in our measurements.

The FMR measurements were performed using a Bruker EMX spectrometer operating at 9.5 GHz. The sample temperature was controlled in a liquid-He flow cryostat.

- **The resonance condition is defined by the Smit Beljers equation:**

$$\frac{h\nu}{g\mu_B} = \frac{1}{M\sin\theta}\left(\frac{\partial^2F}{\partial\theta^2}\cdot\frac{\partial^2F}{\partial\varphi^2}-\left(\frac{\partial^2F}{\partial\theta\partial\varphi}\right)^2\right)^{1/2}\Bigg|_{\theta_{eq},\varphi_{eq}}$$

- **The equilibrium angles of the magnetization vector (θ_{eq}, φ_{eq}) fulfill the following conditions:**

$$\partial F/\partial\theta = \partial F/\partial\varphi = 0$$

- **The magnetic energy density , F consists of Zeeman energy, demagnetization energy, and magnetocrystalline anisotropy energy which can be expressed as:**

$$F = -HM\sin^2\theta\{\cos(\varphi-\varphi_H)\} + (2\pi M^2 - K_2)\sin^2\theta\cos^2\varphi \quad ....(1)$$
$$\text{With } 2\pi M^2 - K_2 = H_2 M$$

- **Solutions are given by :**

$$H_{res}^2 = H_2^2\sin^2(2\varphi) + \left(H_2(3\cos^2\varphi - 1) + \sqrt{(H_2\sin^2\varphi)^2 + H_0^2}\right)^2 \quad ...(2)$$
$$\varphi_H = \varphi + a\sin\frac{H_2\sin(2\varphi)}{H} \quad ....(3)$$

- **$H_0 = \left(\frac{h\nu}{g\mu_B}\right)^2$ and H_2 denotes resonant magnetic field and uniaxial anisotropy field respectively**

Literature and acknowledgments

[1] T. Dietl, H. Ohno, Rev. Mod. Phys. **86**, 1 (2000).
[2] S. Nakamura, T, Mukai, M. Senoh, App. Phy. Lett., **64**, 13 (1994).
[3] G. Kunert et al., Appl. Phys. Lett. **100**, 155321 (2012).
[4] K. Gas *et al.* J. Alloys Compd. **747**, 946 (2018).

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FERROMAGNETIC RESONANCE RESULTS

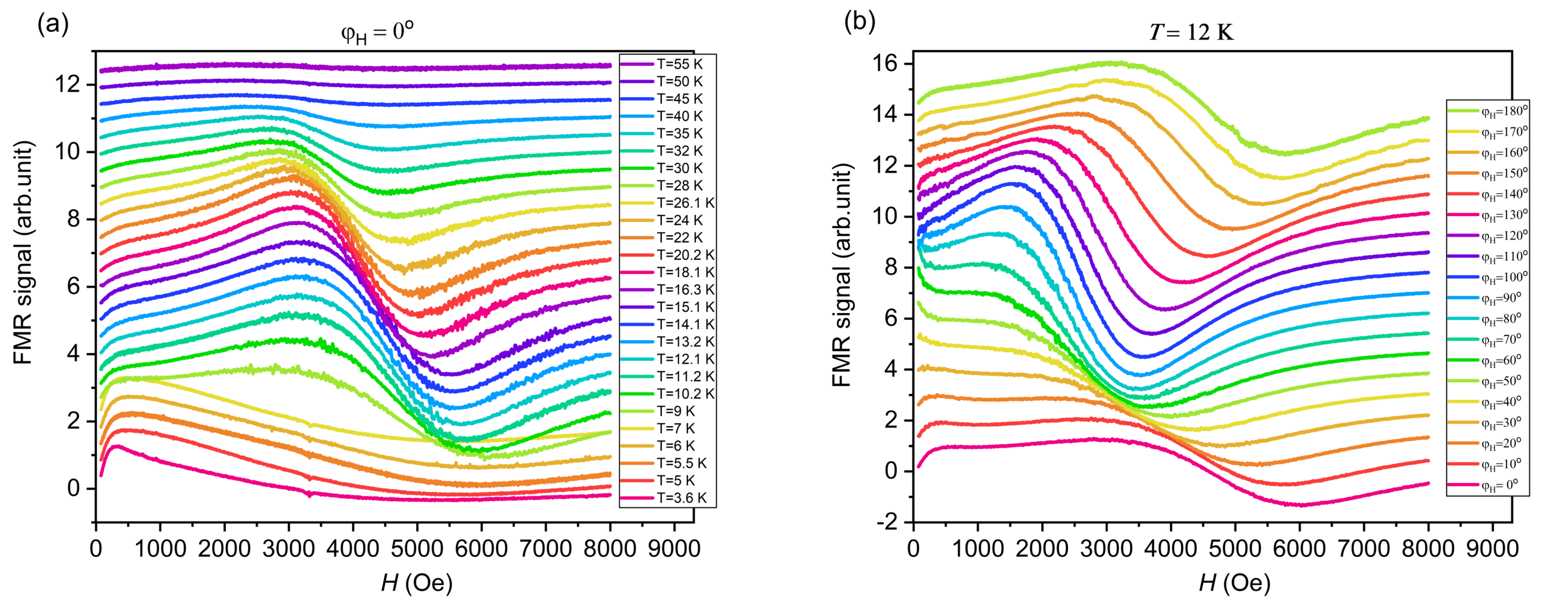

Figure 3: (a) Temperature dependence of the FMR signal for the magnetic field along the out of plane [111] direction. (b) Angular dependence of the FMR signal at T=12 K.

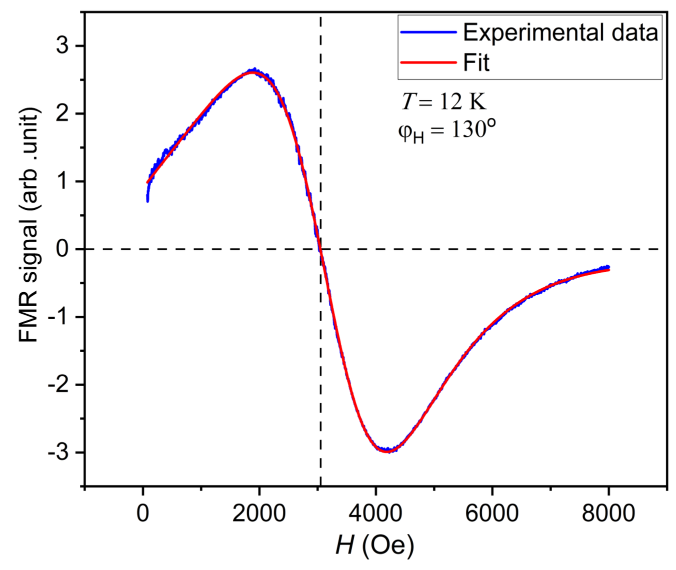

Figure 4: Fitting the experimental data with the Lorentzian derivative. Blue and red lines show experimental data and the fit, respectively.

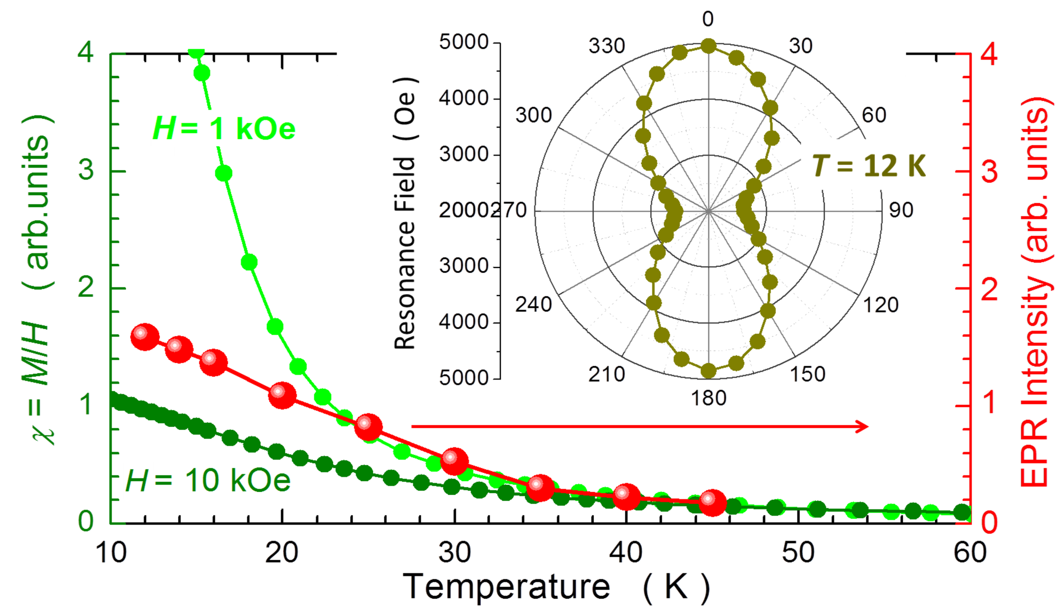

Figure 5: Comparison of magnetic susceptibilities determined by SQUID at fields of 1 and 10 kOe with that determined from FMR signal intensity at fields about 2 kOe. The inset shows the angular dependence of the resonance fields at 12 K.

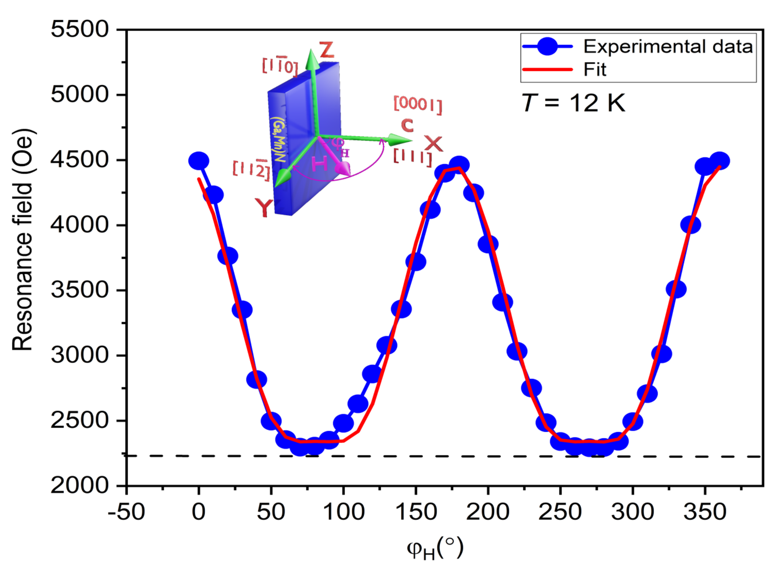

Figure 6: Angular dependence of the ferromagnetic resonance fields for the magnetic field rotating within the [1$\bar{1}$0] plane.

- **Angular dependence of the ferromagnetic resonance fields for the magnetic field rotated in the [1$\bar{1}$0] plane was measured to elucidate magnetic anisotropy.**
- **Experimental data were fitted using eqs. (2) and (3). The obtained parameters are: 2πM-K_2/M = -960 Oe and H_0 = 2620 Oe. This gives g = 2.59 at 12 K.**

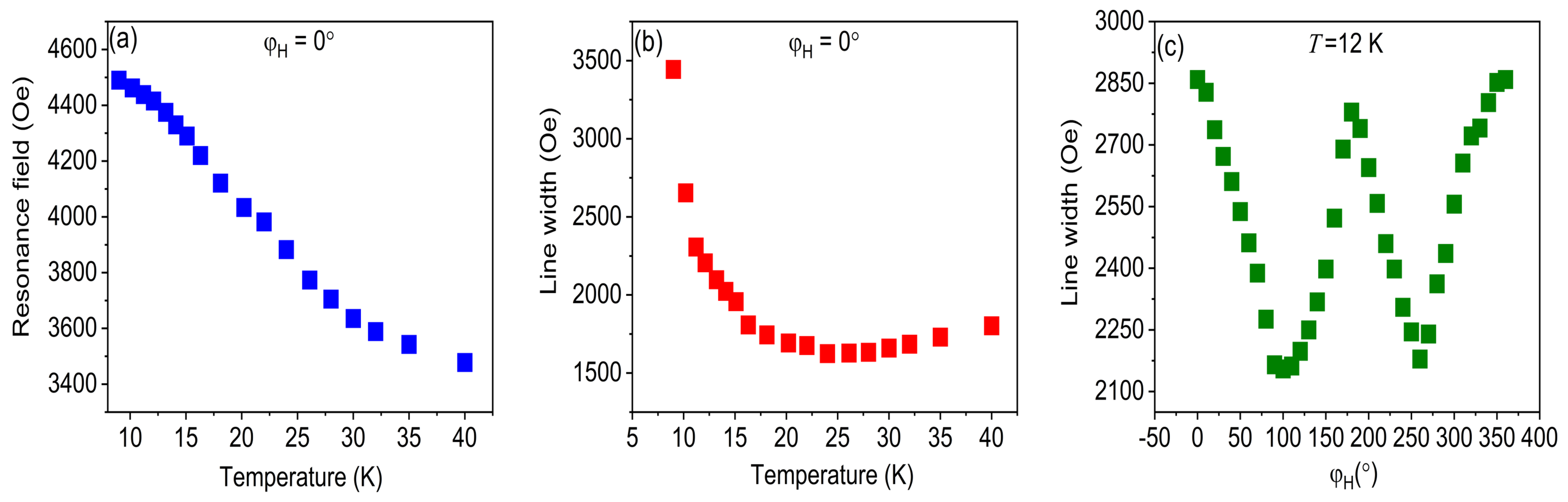

Figure 7: (a) Temperature dependence of the resonance field for the magnetic field along the out of plane [111] direction. (b) Temperature dependence of the line width for the magnetic field along the out of plane [111] direction. (c) Angular dependence of the line width at T=12 K.

- **Resonance field decreases with temperature and a g factor equal to 2 is observed at T = 40 K.**
- **The linewidth of the signal decreases with temperature reaching a minimum value at about 25 K. The angular dependence of the line width indicates that it is governed by fluctuations of the magnetic moment throughout the sample. The broadening above 25 K is attributed to increased damping.**

CONCLUSIONS

- **No ferromagnetic resonance is observed below 7 K apart from a very weak paramagnetic signal of Mn^{2+}.**
- **The lack of low temperature FMR signal is attributed to the inhomogeneous broadening caused by non-uniform distribution of magnetic ions and thus inhomogeneities in coupling strengths influencing the local magnetic anisotropies of Mn^{3+} ions.**
- **Uniaxial magnetic anisotropy dominates in the sample, with the magnetic easy axis perpendicular to the *c* axis.**