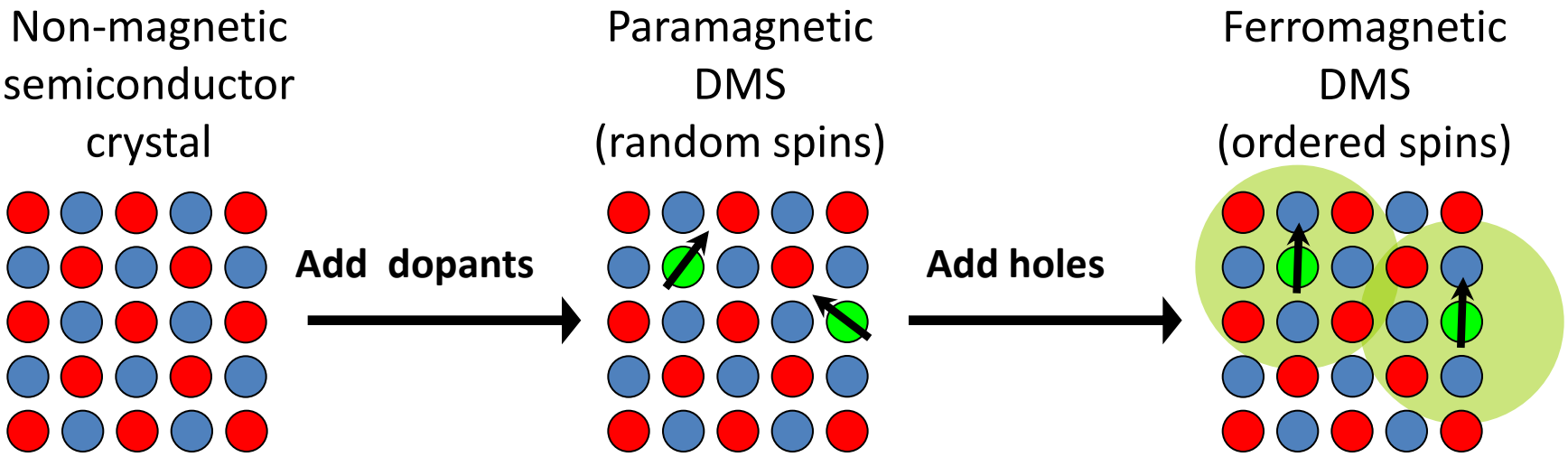
The University of Nottingham

# Highlights and future possibilities in ferromagnetic semiconductor research

Kevin Edmonds

*School of Physics and Astronomy,*
*University of Nottingham, UK*

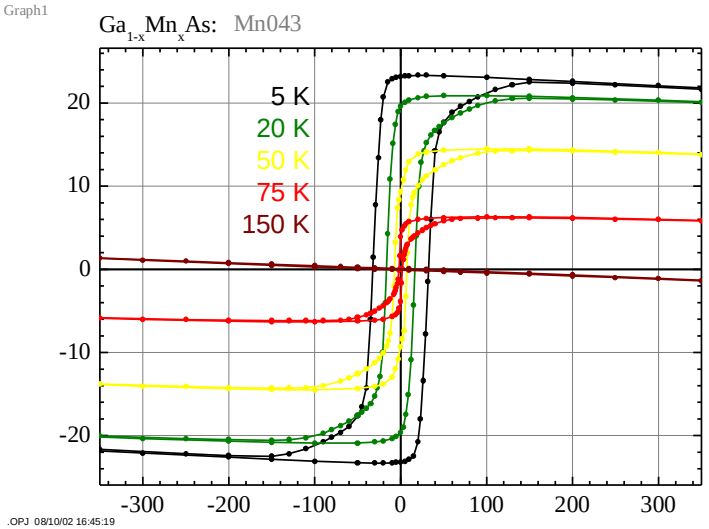
# Diluted magnetic semiconductors



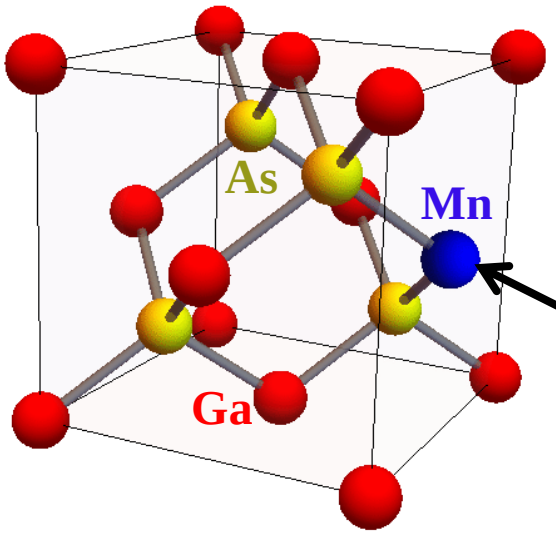

**1978:** Paramagnetic (II,Mn)VI semiconductors

**1992:** Ferromagnetic (In,Mn)As with $T_C$ ~10K (Ohno *et al.*)

**1998:** Ferromagnetic (Ga,Mn)As with $T_C$ ~100K (Ohno *et al.)*



# $Ga_{1-x}Mn_xAs$



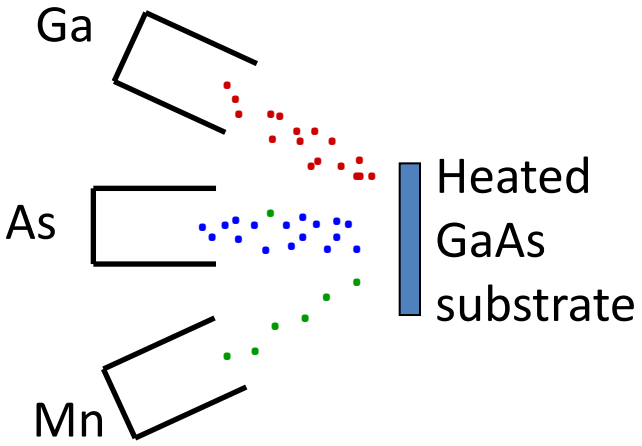

Mn-substituted zinc-blende GaAs

fraction $x$ ~0.01-0.08 randomly occupied by Mn

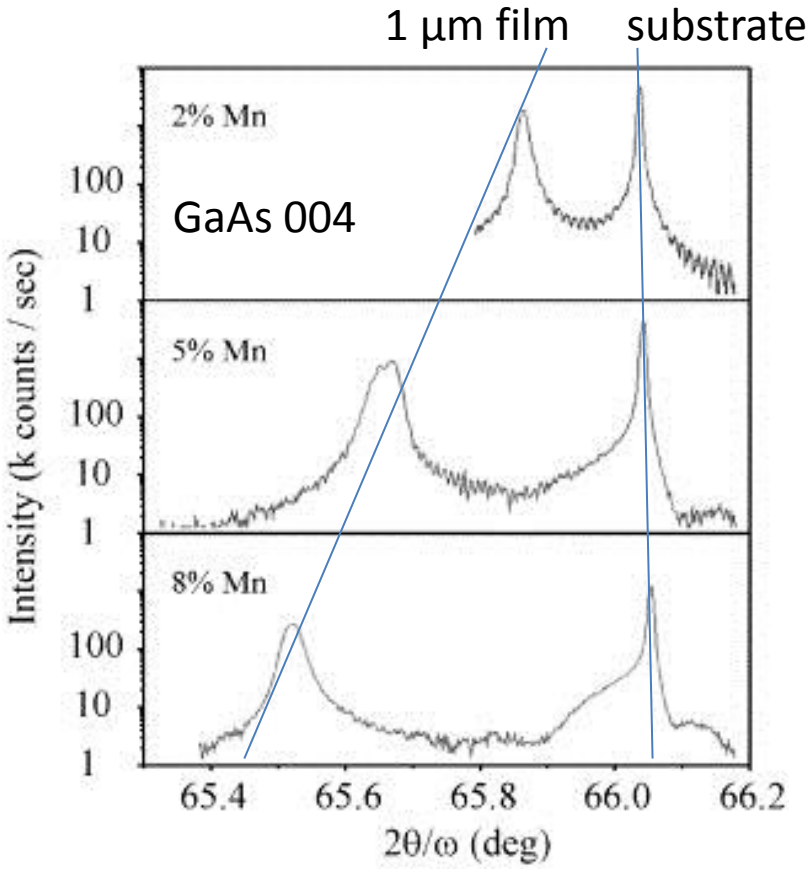
- Mn is a *p*-type dopant in GaAs
→ conductivity

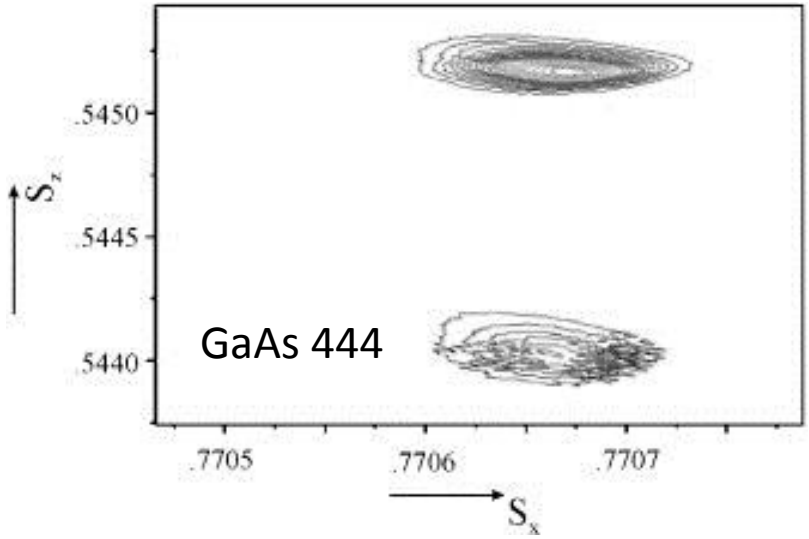
- half-filled 3*d* electronic shell
→ $S$ = 5/2 magnetic moment

Molecular beam epitaxy



# Structure

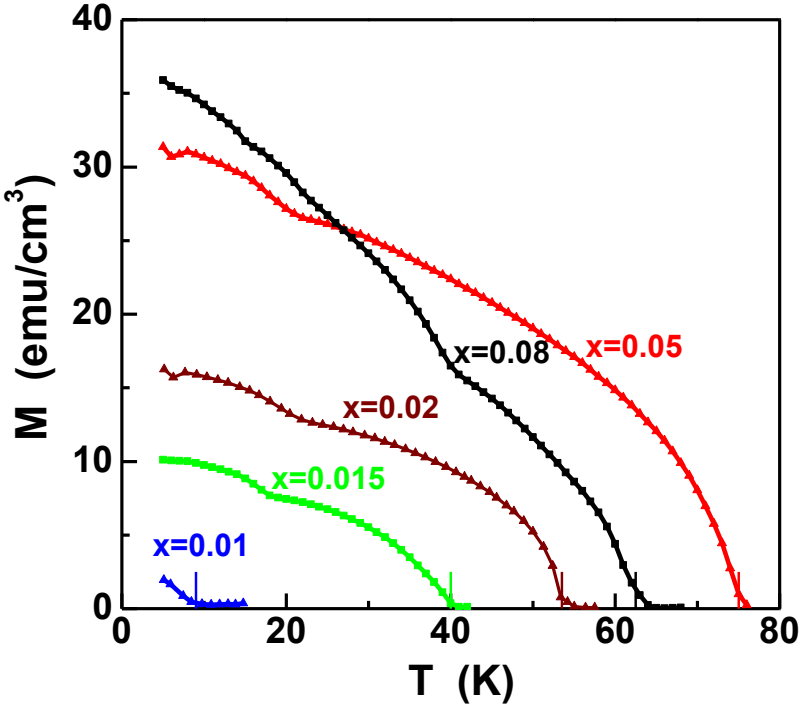


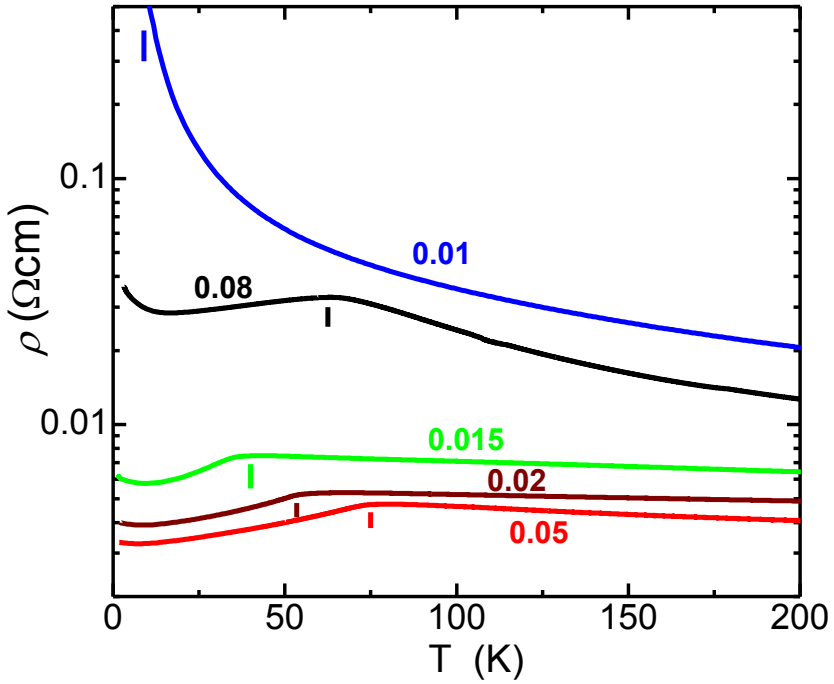




- Compressive strained (Ga,Mn)As on a GaAs(001) substrate
- Strain increases with increasing %Mn

# $Ga_{1-x}Mn_xAs$ – magnetism and transport

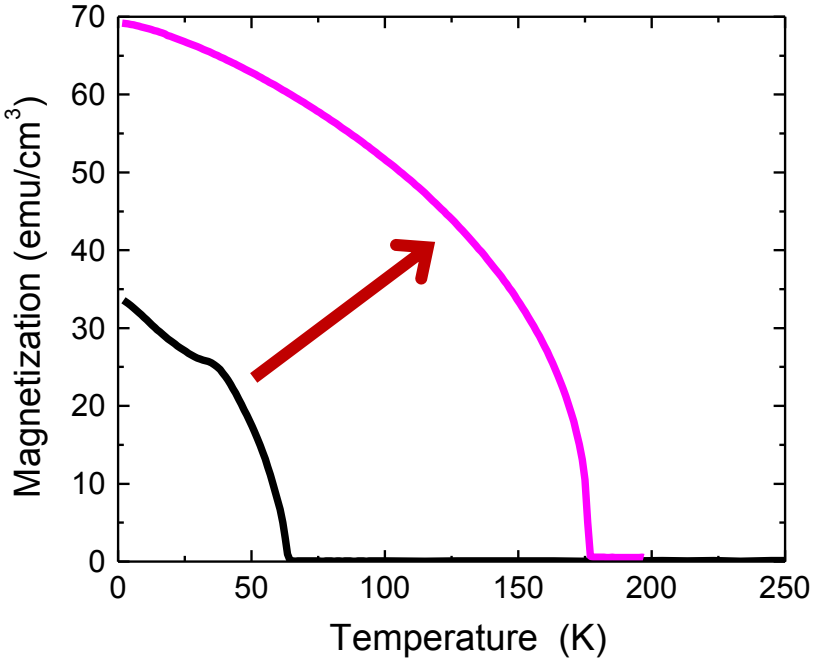
for varying *nominal* Mn concentration *x*

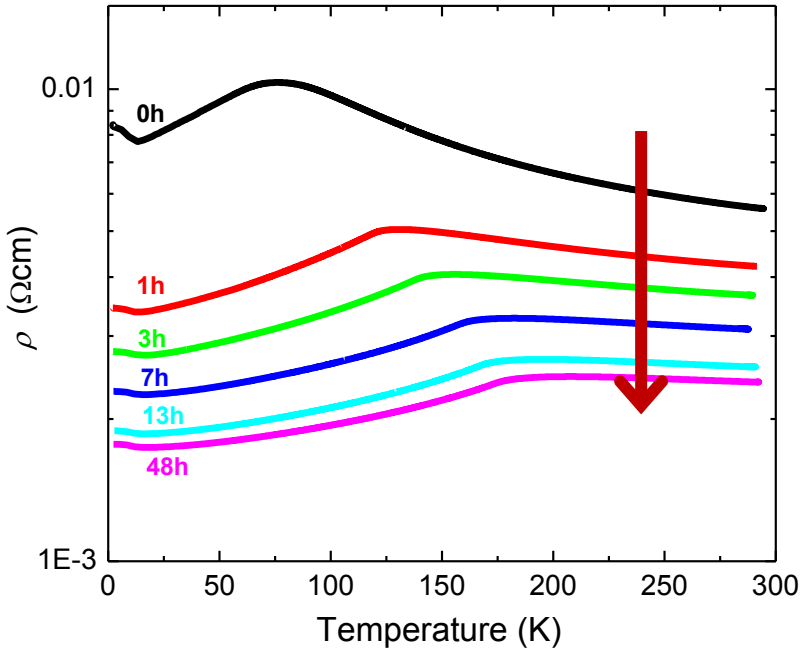


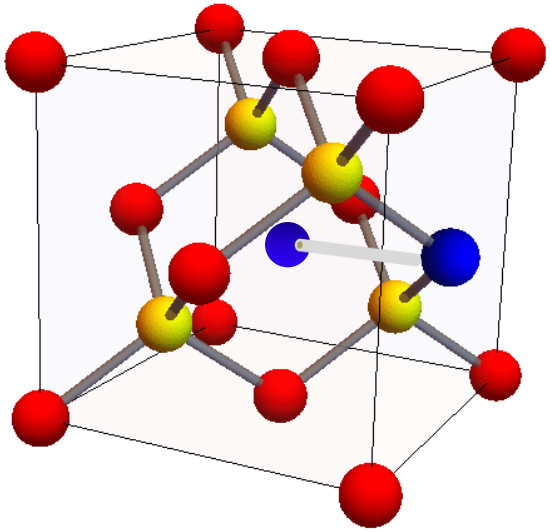
# Effect of annealing in air at 180°C

(lower than the growth temperature!)



# *Interstitial* Mn

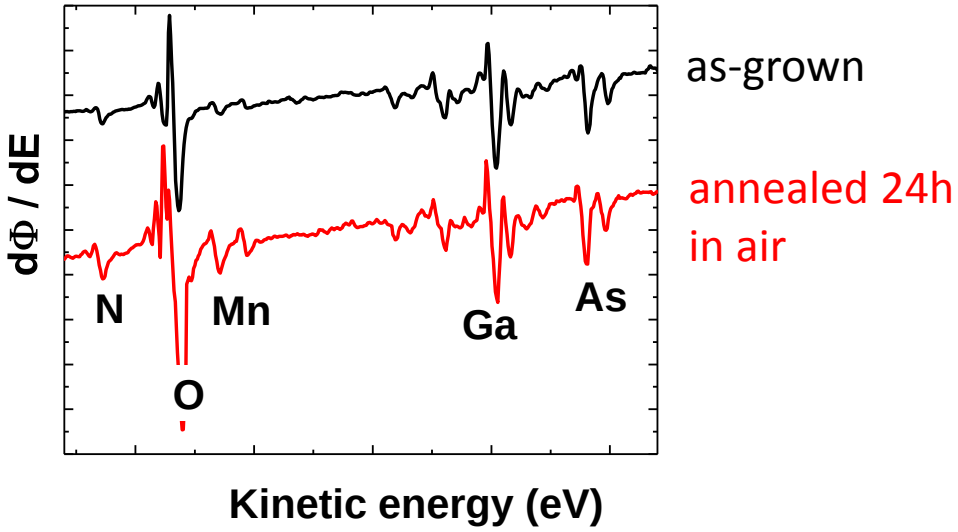


K.M. Yu *et al.*, PRB (2002); Edmonds *et al.* PRL (2004)

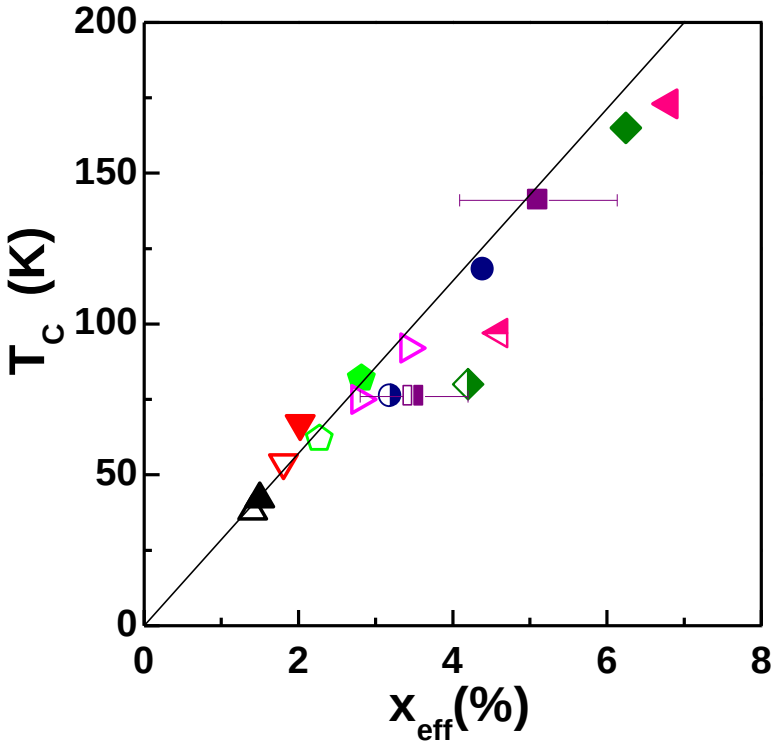
- Compensating donor defect
- Antiferromagnetic coupling to substitutional neighbours
- Weakly bound → diffuses readily

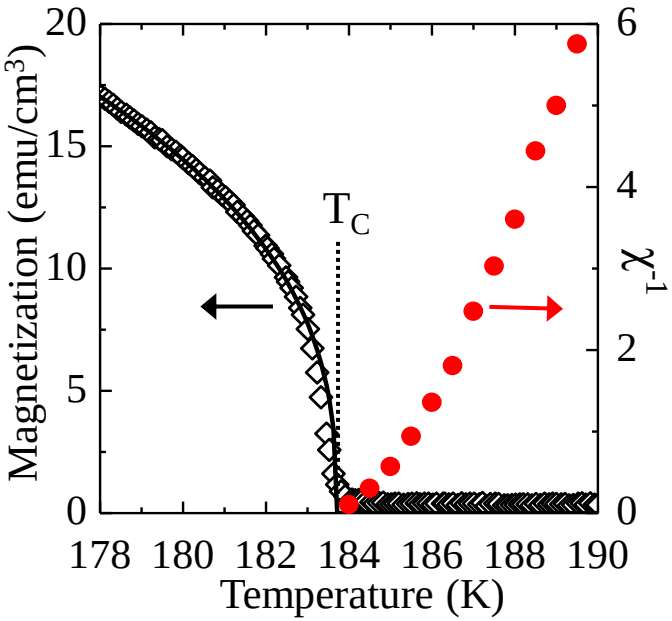
See talk by T. Lima

**Auger spectra:**
Enhanced surface Mn after annealing



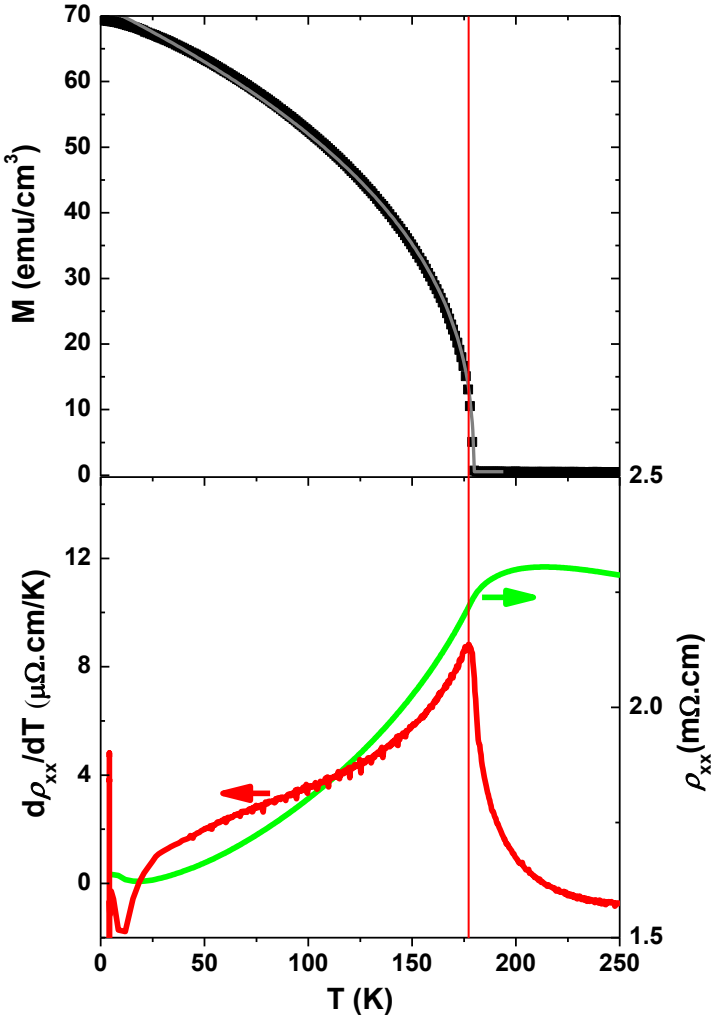
# Post-annealed samples

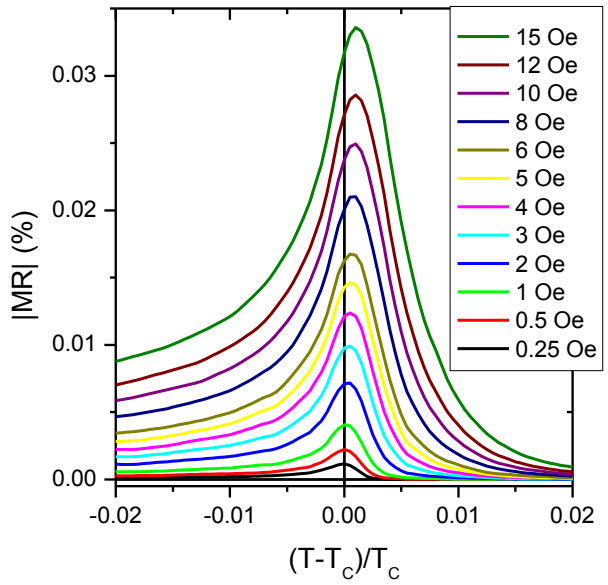


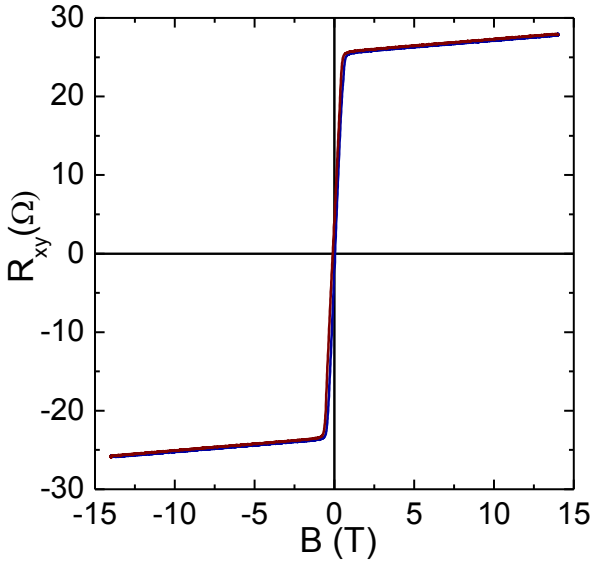




$x_{eff}$ = *effective* concentration of uncompensated substitutional Mn

# Hole-mediated ferromagnetism



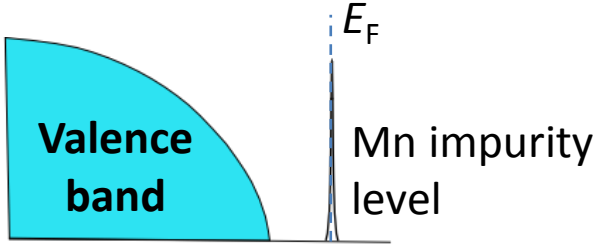




M. Wang *et al.*, Appl. Phys. Lett. 104, 132406 (2013)

# Hole-mediated ferromagnetism

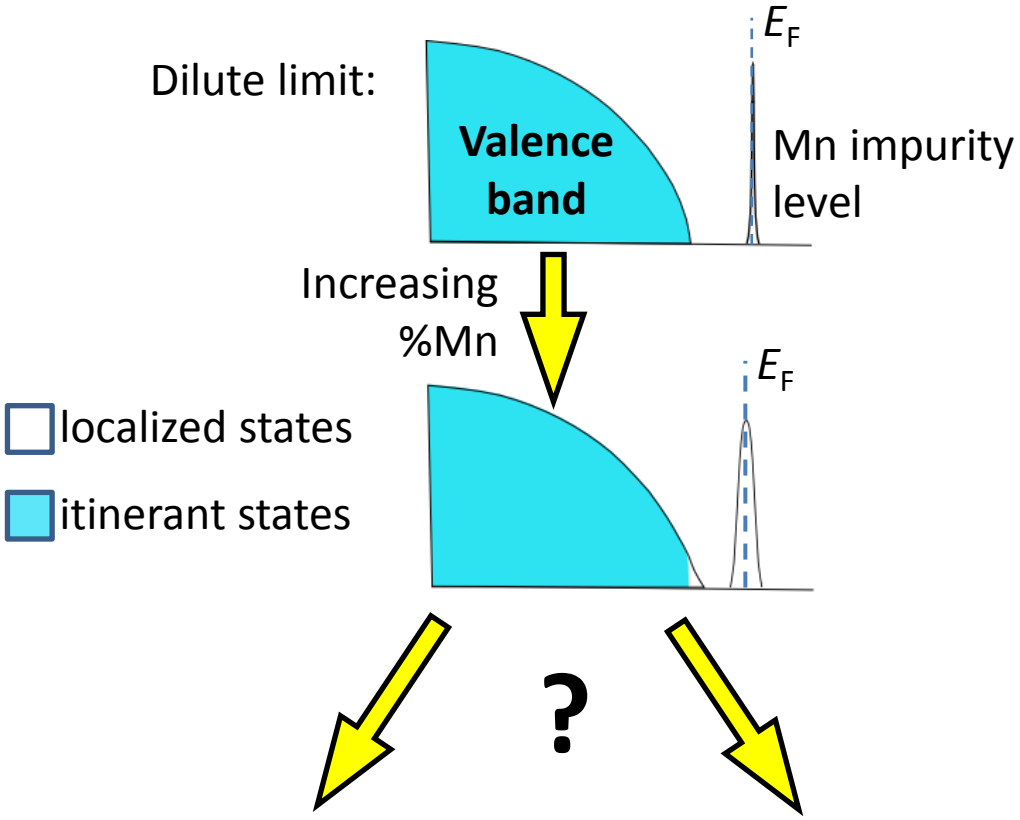
Dilute limit:



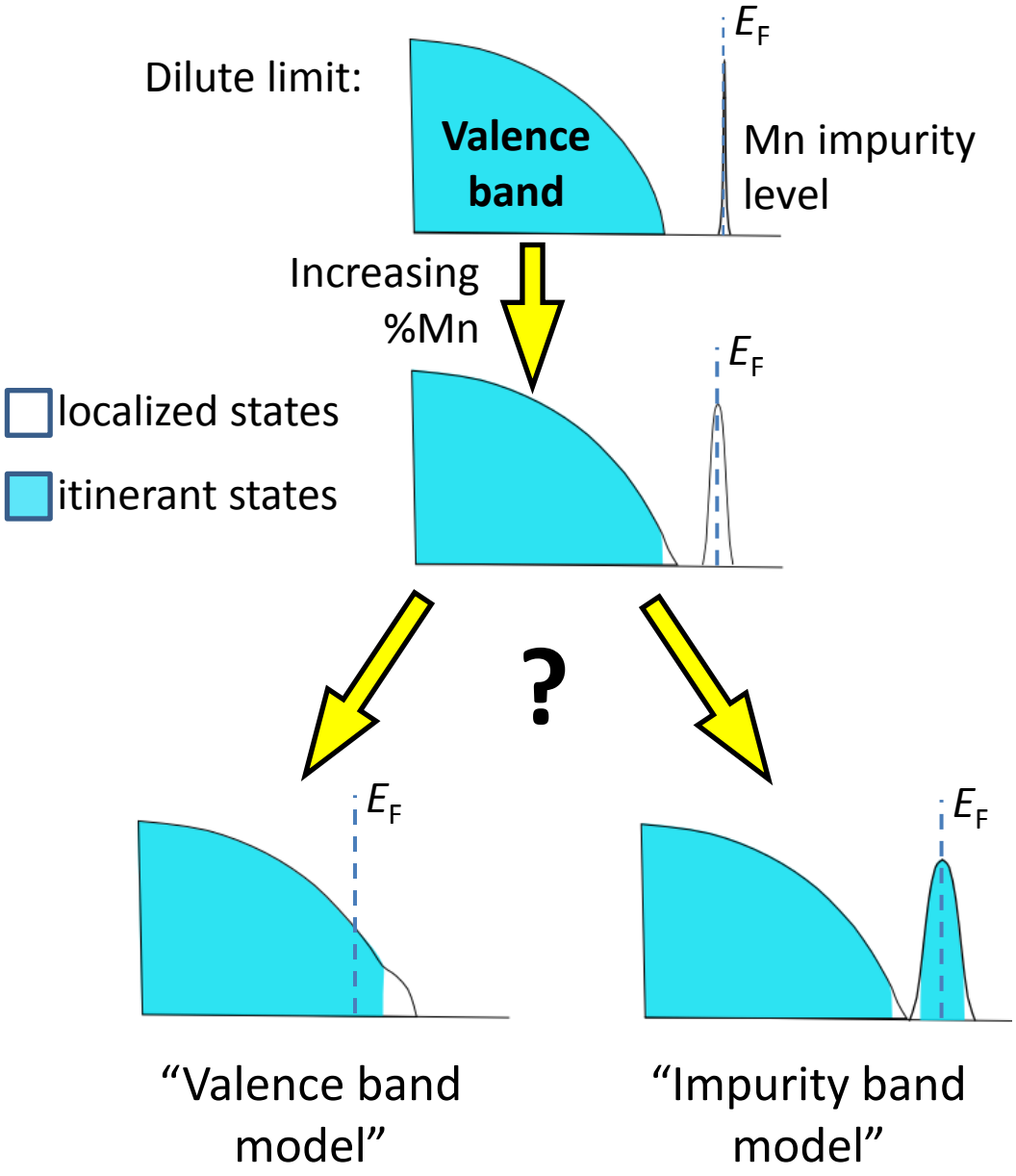

localized states

itinerant states

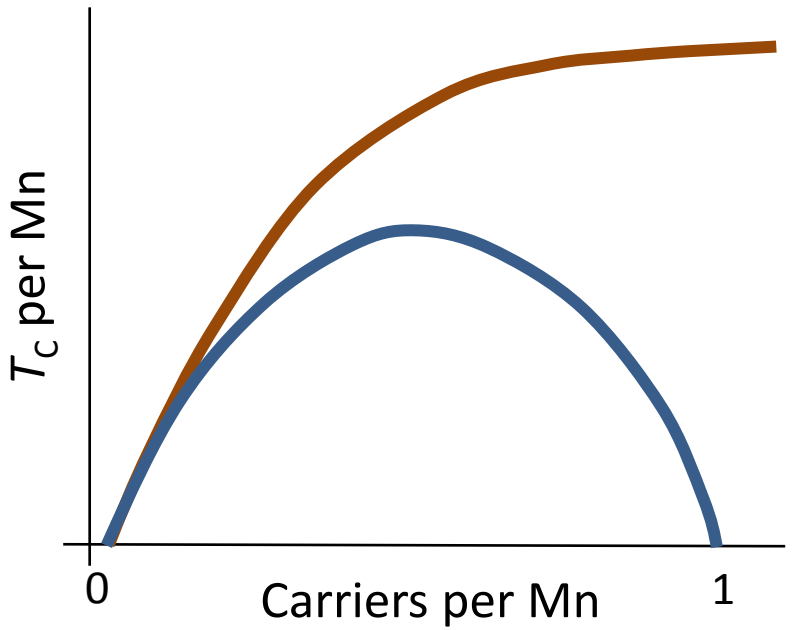
# Hole-mediated ferromagnetism



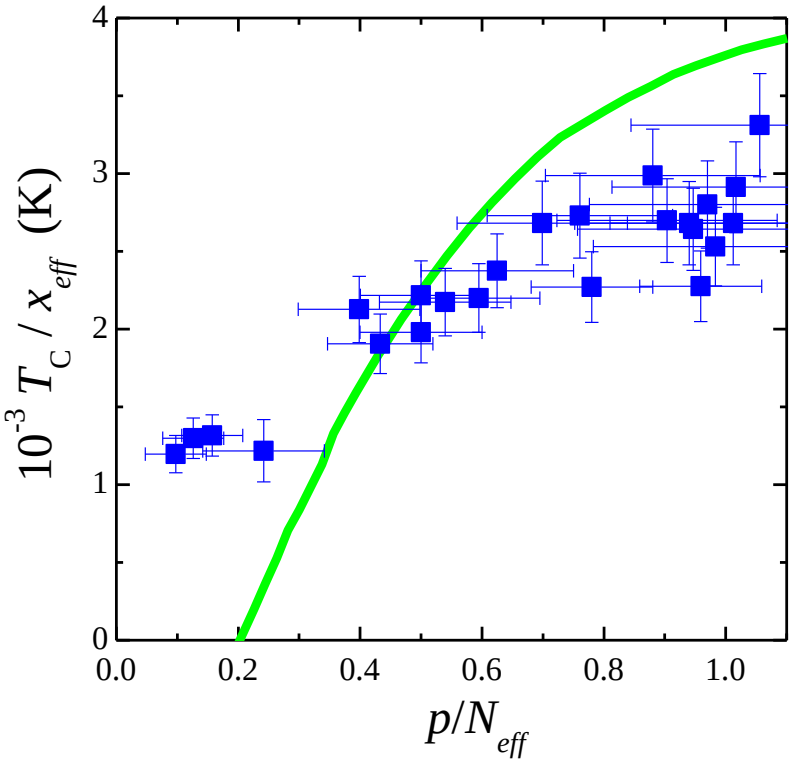
# Hole-mediated ferromagnetism




Predicted dependence of $T_C$ on carrier density $p$:



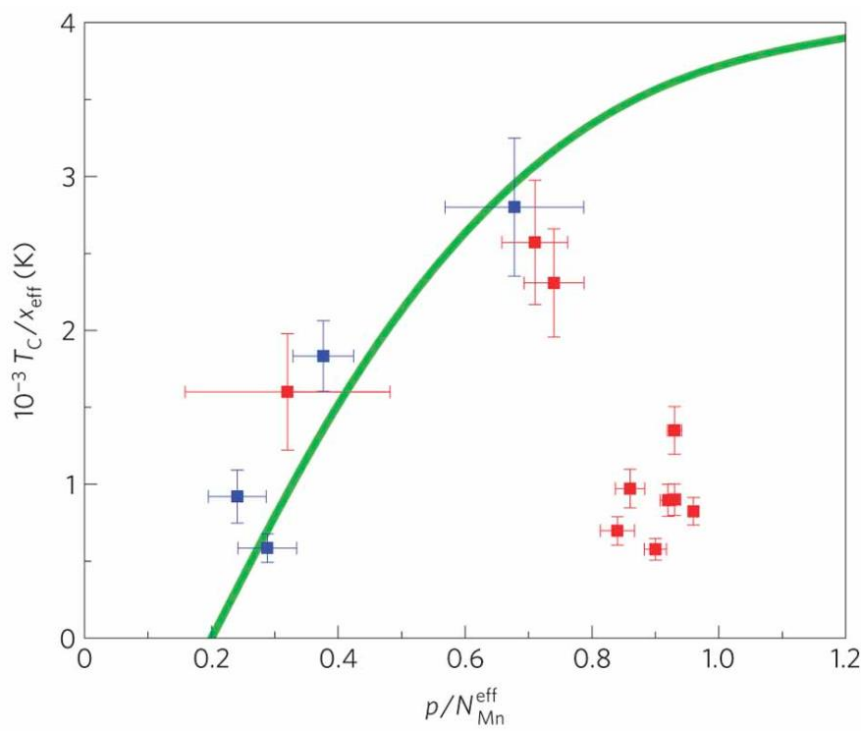
# Magnetic transition temperature $T_C$ versus carrier density $p$




*p* measured using Hall effect

*Jungwirth et al. PRB 72, 165204 (2005)*

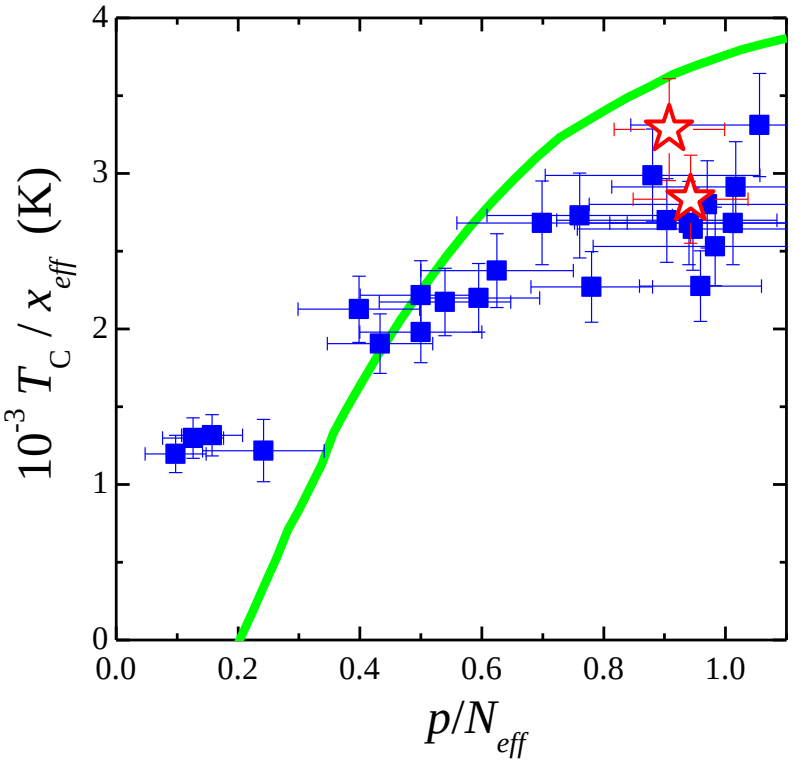
*Wang et al. PRB 87, 121301 (2013)*




*p* estimated from ion channeling measurements of defect concentrations

*Dobrowolska et al. Nature Materials 11, 444 (2012)*

# Magnetic transition temperature $T_C$ versus carrier density $p$



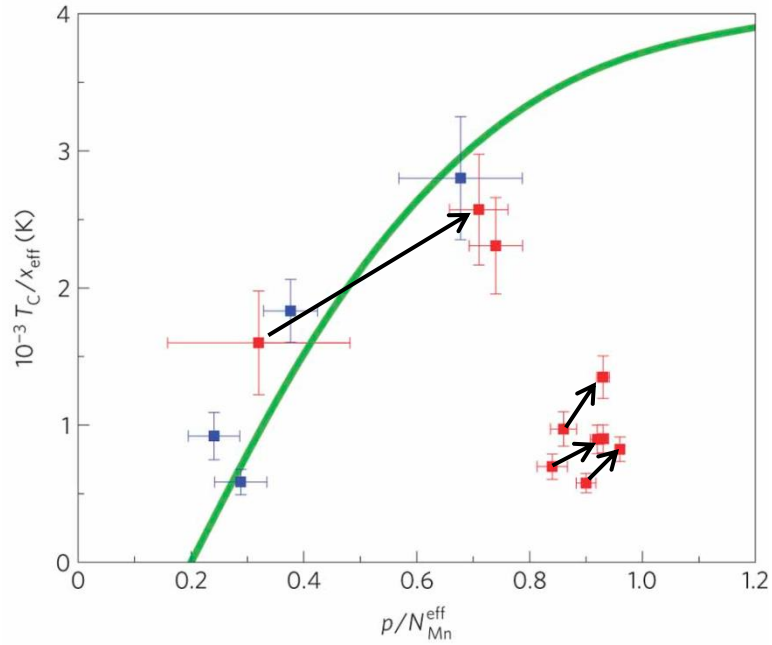

Hall effect measurements

Ion channeling measurements

*Wang et al. Phys. Rev. B 87, 121301 (2013)*

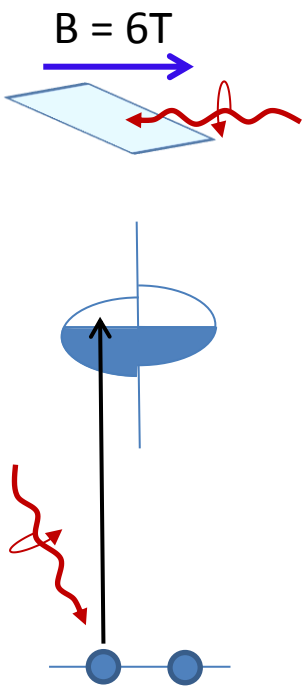
# Hole-mediated ferromagnetism

*Dobrowolska et al. Nature Materials 11, 444 (2012)*

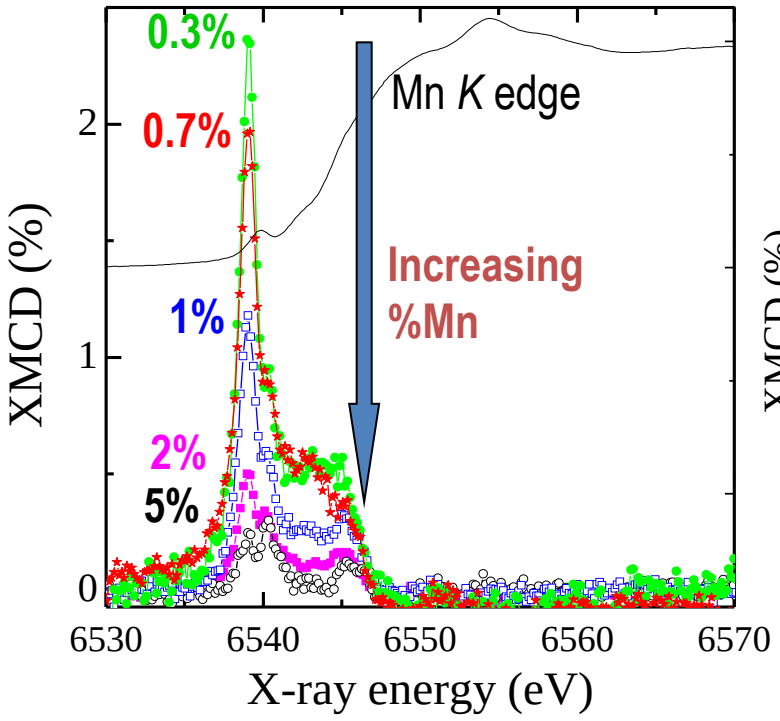



- "*p*" in the above is estimated from measurements of interstitial and substitutional Mn concentrations
- $T_C$ *always* increases when carrier concentration is increased by annealing
- Other defects are probably responsible for the reduced $T_C$

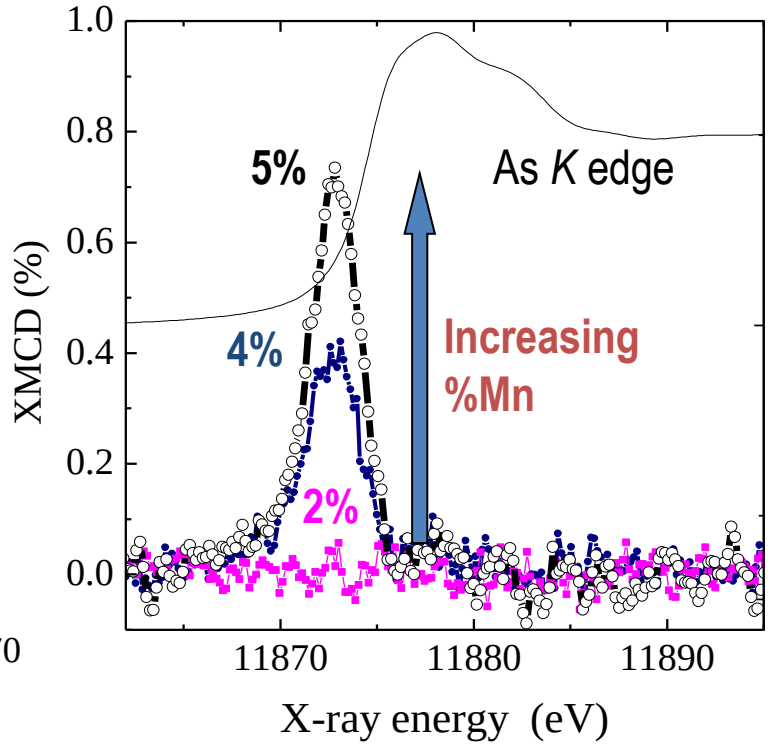
# Insulator-metal transition in (Ga,Mn)As: *K*-edge polarized x-ray spectroscopy




## Manganese




## Arsenic



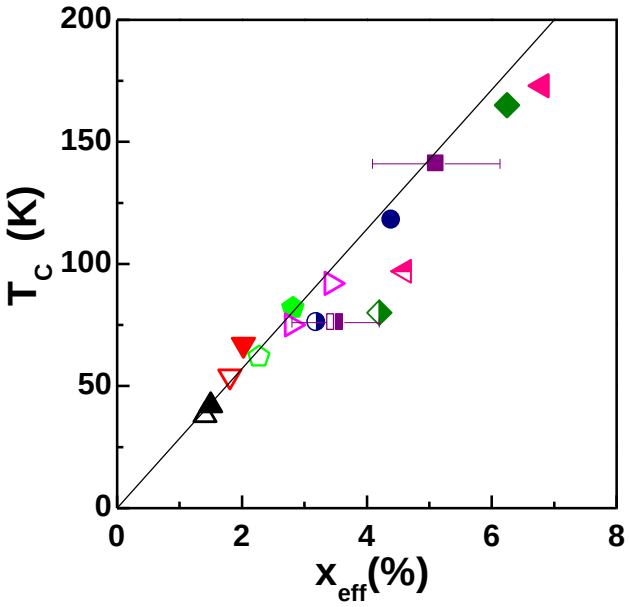

**Transition from localized Mn to delocalized As electronic states**

*Wadley et al. Phys. Rev. B 81, 235208 (2010)*

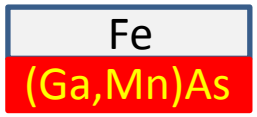
# Future directions

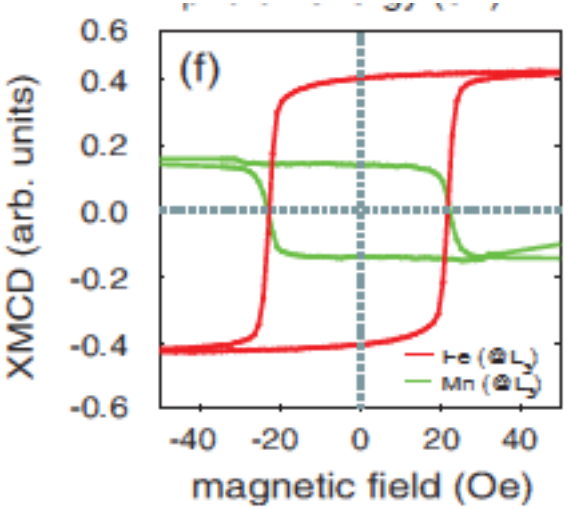
Towards room temperature diluted magnetic semiconductors?

**(Ga,Mn)As** $T_C$ increases with %Mn but currently limited to ≈190K




Room temperature ferromagnetism observed at the (Ga,Mn)As interface in bilayer structures




Maccherozzi *et al.*
Phys. Rev. Lett. 101, 267201 (2008)

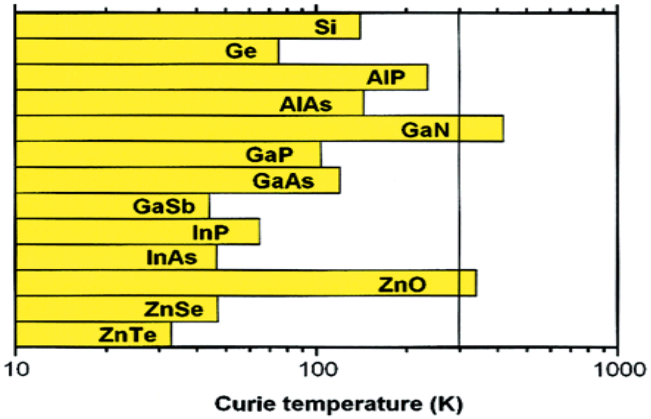
Olejnik *et al.*
Phys. Rev. B 81, 104402 (2010)

# Future directions

Towards room temperature diluted magnetic semiconductors?

**Other material systems**

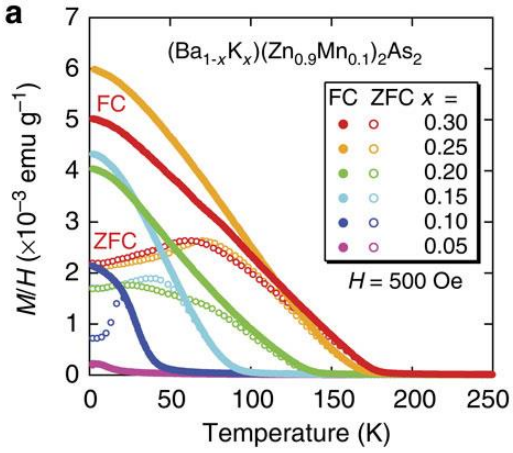
Widely cited article: Dietl *et al.* Science 287, 1019 (2000)




- Predicts $T_C$ > 300K assuming delocalized hole-mediated ferromagnetism

- Some promising results for oxides (*e.g.*, $TiO_2$), but not well-understood

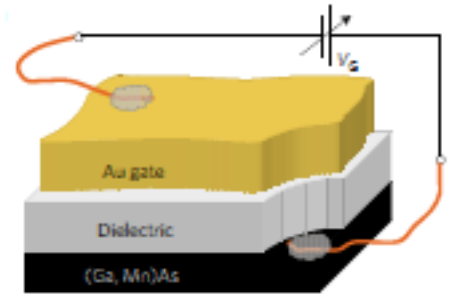
- Wide material space still to explore, *e.g.* "122" compounds
Zhao *et al.* Nature Comms. 4, 1442 (2013)

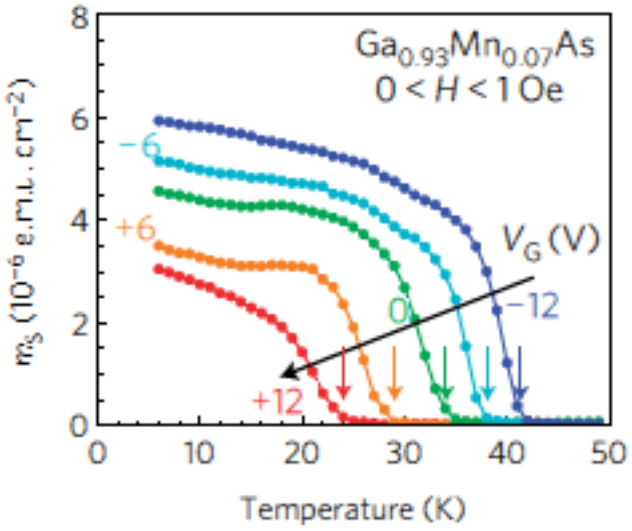


# Future directions

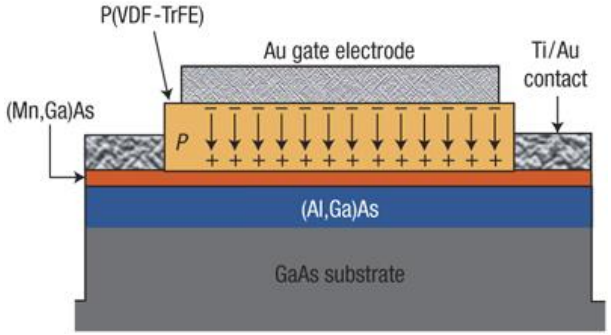
## Exploration of spintronic phenomena

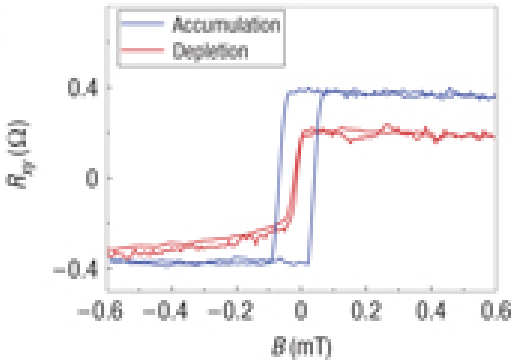
*e.g.* electrical control of magnetism




Sawicki *et al.* Nature Phys. 6 22 (2010)




Stolichnov *et al.* Nature Mater. 7 464 (2008)

# Summary

The University of Nottingham

- Mn-doped GaAs is a ferromagnetic semiconductor, with magnetic properties that are closely tied to the nature and concentration of charge carriers and magnetic ions

- Understanding the nature of defects in this material is essential for understanding, utilizing and optimizing its properties

# Acknowledgements


Richard Campion, Mu Wang, Pete Wadley, Bryn Howells, Bryan Gallagher, Andy Rushforth
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Joerg Wunderlich, Andrew Ferguson
*Hitachi Cambridge Laboratory*



EPSRC
Engineering and Physical Sciences Research Council

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS