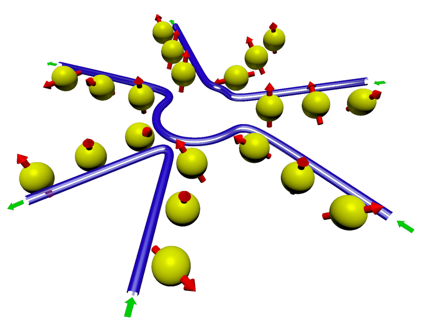
Dilute Magnetic Semiconductors for Spintronics: Mn:GaN

Frank C Langbein*[,1], Sophie G Shermer[2,4], Karol Kalna[3], Jon Evans[3,4], Greg Burwell[2,4]

[1]School of Computer Science and Informatics, Cardiff University, [2]College of Science, Physics, Swansea University, [3]College of Engineering, Swansea University, [4]Centre for Nanohealth, Swansea University

Spintronics

Semiconductor electronics has revolutionised technology. **Exploiting electron spin** in metals and especially semiconductors may give rise to a technological revolution on a similar scale with applications from spin transistors to quantum sensors and quantum computing:



- Novel and interesting **physical phenomena**,
- Many **immediate applications** (spin diodes, spinFET, etc),
- Promising **longer term applications** including novel sensors (e.g. nanoscale strain sensors), information processing and quantum simulation,
- **Bridge** between quantum 2.0 and semiconductor technology,
- Potential **quantum technology** operating at **room temperature**.

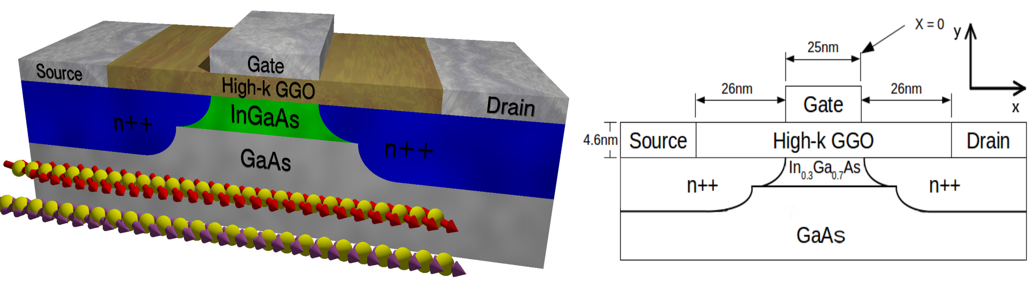
The realisation of spintronic applications relies heavily on **magnetic semiconductor materials** with suitable properties. In particular, dilute magnetic semiconductors, such as **Mn doped GaN**,show great promise of **high Curie temperatures** (220K-370K), exceeding room temperature, and a **large concentration of holes**.

Simulating Spin Transport in a FET

A **realistic device simulator to explore spin transport** in a compound semiconductor transistor with magnetic gates shows:

- **Non-uniform decay** of magnetisation between source and drain,
- **Magnetisation recovery effect** due to spin refocusing,
- Magnetisation of the drain current is **strain-sensitive**,
- **Coherent control** of the spin polarisation of the drain current via source-drain and gate voltages.

$In_{0.3}Ga_{0.7}As$ MOSFET



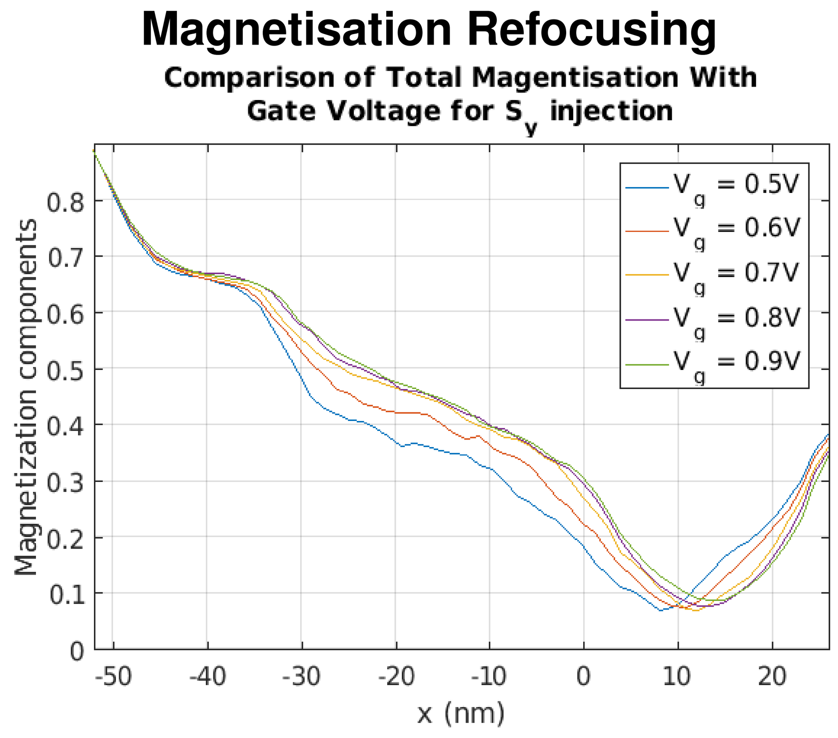
Electron spin polarisation with (red) and without (purple) strain and cross section.

A Monte Carlo simulation of an InAlAs/InGaAs HEMT was augmented to incorporate electron spin:

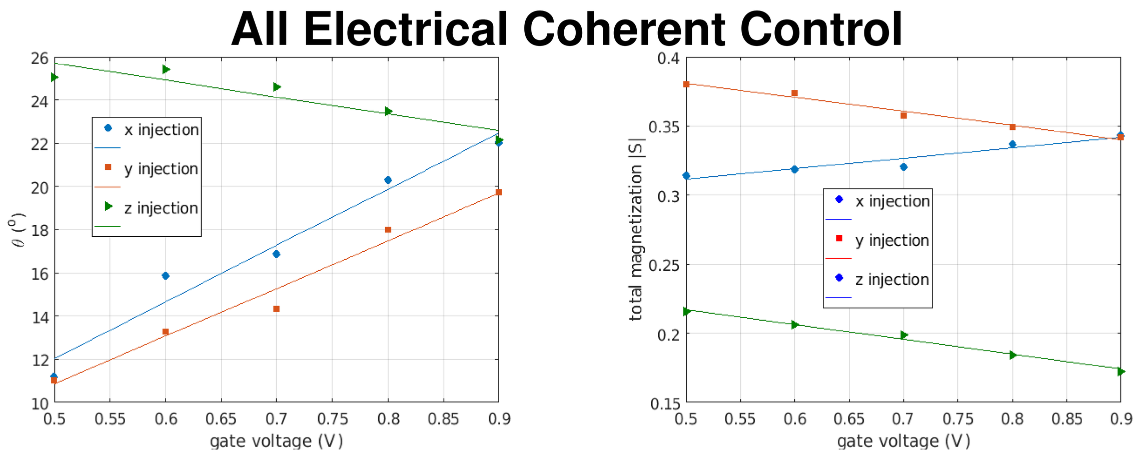
- **Dyakonov-Perel-type spin orbit coupling** (dominant in GaAs) spin dephasing was modelled using interaction Hamiltonians.
- **Dresselhaus effect**: spin coupling to an electric field due to bulk asymmetry in the crystal.
- **Rashba effect**: asymmetry in the potential due to the presence of a quantum well.

Simulation Results

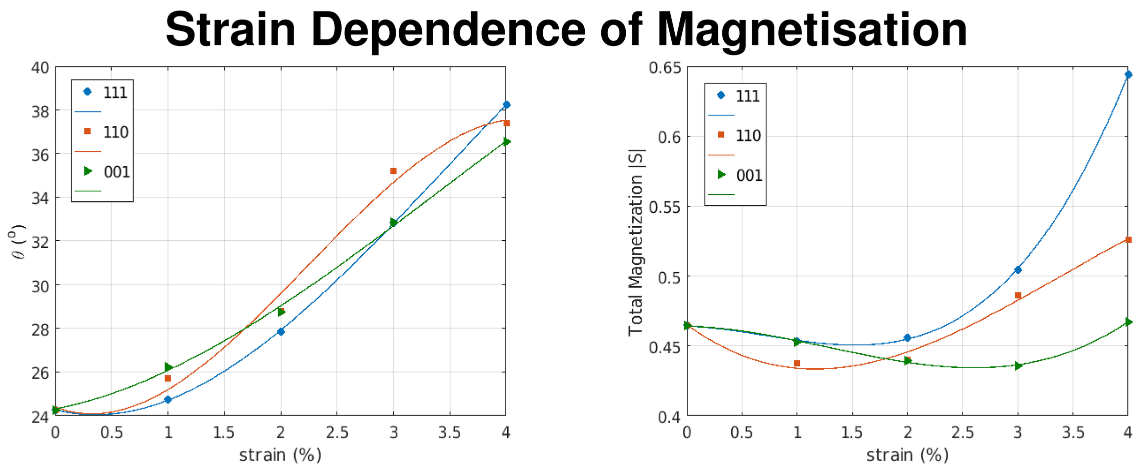
Magnetisation Refocusing



All Electrical Coherent Control



Strain Dependence of Magnetisation



Promising simulation results have prompted exploration of **magnetic materials** at room temperatures to realise such devices.

Spin-Polarised Carriers

Spintronics requires spin-polarised carriers (electrons), typically present in **ferromagnetic** materials such as

- some pure metals (Ni, Co, Fe) or
- rare-earth alloys (e.g. $Nd_2Fe_{14}B$).

Semiconductors (Si, GaAs, GaN) are normally **diamagnetic** but can become

- **paramagnetic** when **doped** with paramagnetic atoms, under the right conditions;
- **ferromagnetic**, maintaining **magnetisation** (spin polarisation) in the absence of an external B-field below **Curie temperature** T_C.

Compound semiconductors, such as GaAs and GaN, doped with Ni, Co, Mn or Cr become magnetic:

- The literature suggests **high T_C ferromagnetism**.
- Doping is possible by **thermal annealing**.

Dilute Magnetic Semiconductors: Mn:GaN

A feasibility study explores doping of GaN with Mn, funded by the Compound Semiconductor Manufacturing Hub.

Fabrication

- **Removal of top AlGaN epi-layer** to expose UID GaN layer: Cl-based dry-etch using ICP etching system to remove $\sim 100\,nm$.
- **Sputter deposition** of 100 nm of Mn on small corner pieces.
- **Thermal annealing**.

Samples Created

Sample 1: annealed at 800 °C for 6 h under 10 sccm flow of N_2 at 0.23 mbar.

Sample 2: as Sample 1, but annealed under N_2 flow at 1 bar.

Sample 3: annealed at 800 °C for 6 h, HCL wash

Sample 4: annealed at 1000 °C for 6 h

Experimental Characterisation

Structure:

- high resolution Scanning Electron Microscopy (SEM) images (surface, cross-section).

Composition: chemical composition, electronic states.

- X-Ray Photoelectron Spectroscopy (XPS); quantitative, detection limit: 1/1000.
- Energy-Dispersive X-Ray Spectroscopy (EDX).

Magnetic properties:

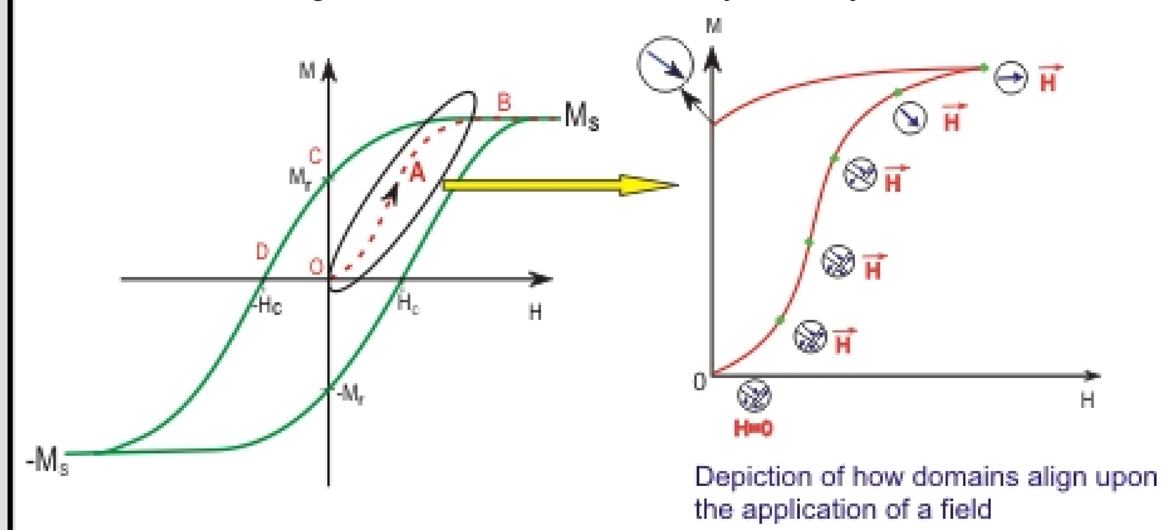
- DC-SQUID magnetometry.
- Anomalous Hall Effect measurements.
- Susceptibility-based MRI.

Magnetic domains:

- magnetic Atomic Force Microscopy (AFM).

Signatures of Ferromagnetism

- Spontaneous magnetisation below Curie temperature T_C.
- Remanent magnetisation M_r, coercivity and hysteresis.



DC SQUID magnetometry

- Hysteresis curves $M(B)$.
- Remanent magnetisation M_r (vibration at $B = 0$).
- Determination of T_C by measuring $M_r(T)$.

Problems with DC SQUID Magnetometry

Utility of DC superconducting quantum interference device (SQUID) data has been **questioned**, e.g. Liu 2005: *Eventually if ZnO and GaN based DMS advances to the point where reliable Hall measurements can be made, the anomalous Hall effect would be a reliable means of determining whether the material is ferromagnetic and what the Curie temperature is.*

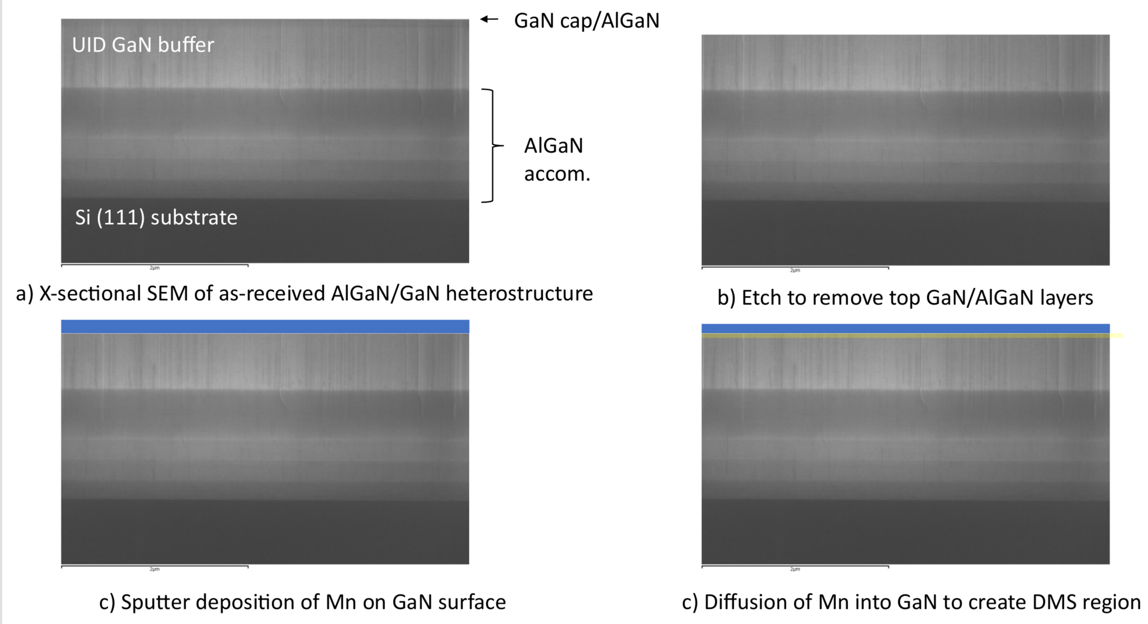
- DC magnetometry hysteresis curves might result from clusters of ferromagnetic atoms (magnetic impurities).
- It does not require spin-polarised carriers.

⇒ Transport measurements are needed.

Anomalous Hall Effect (AHE)

Several authors have argued that the **AHE would be a reliable signature** of true ferromagnetism and spin-polarised carriers.

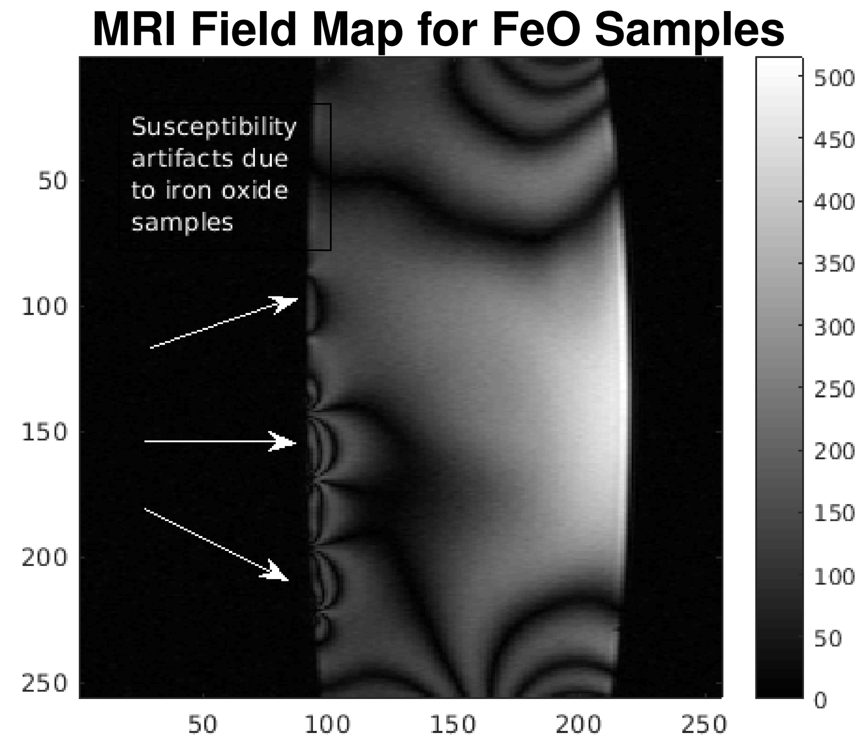
AlGaN/GaN Heterstructure SEM X-Section



Susceptibility-Based MRI

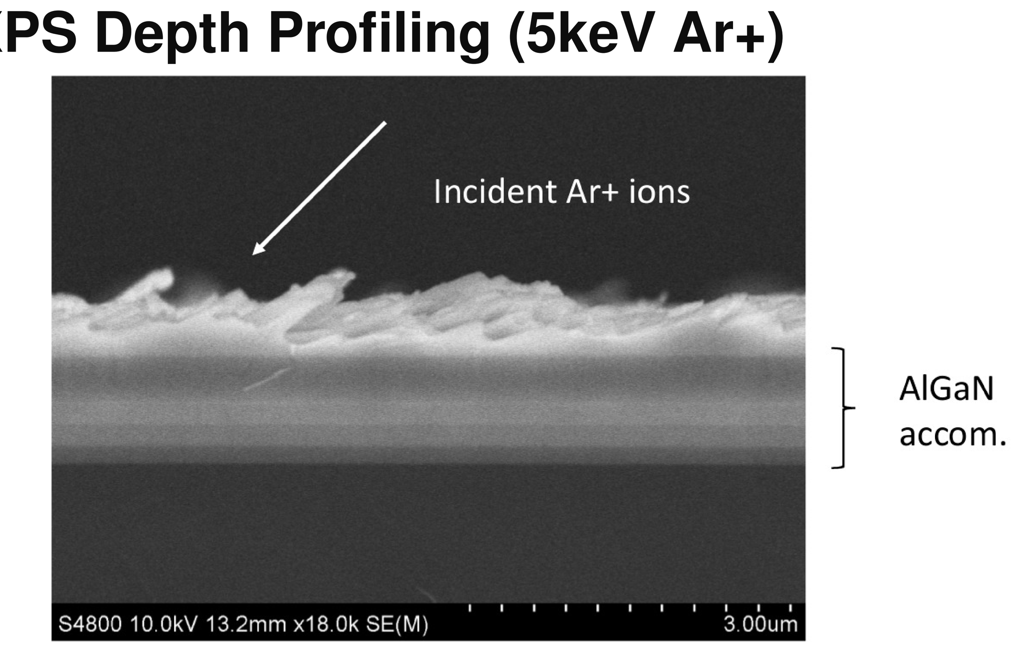
- Standard MRI relies on magnetic response of hydrogen nuclei.
- Larmor precession frequency of protons $\omega_p \propto B$.
- Magnetisation of sample near water probe disturbs B_0 field.
- **Change in the Larmor frequency** can be measured with high precision to produce susceptibility maps (unlike DC-SQUID or AHE measurement) but has low spatial resolution.

MRI Field Map for FeO Samples

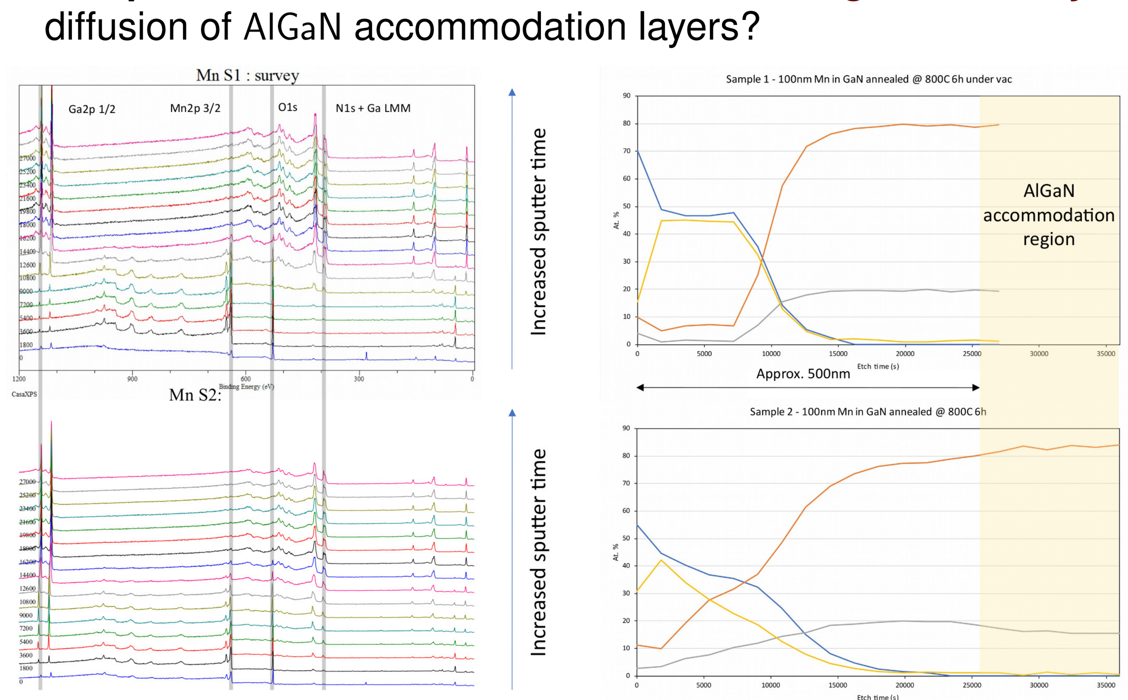


Correlate data with DC SQUID measurements.

XPS Depth Profiling (5keV Ar+)

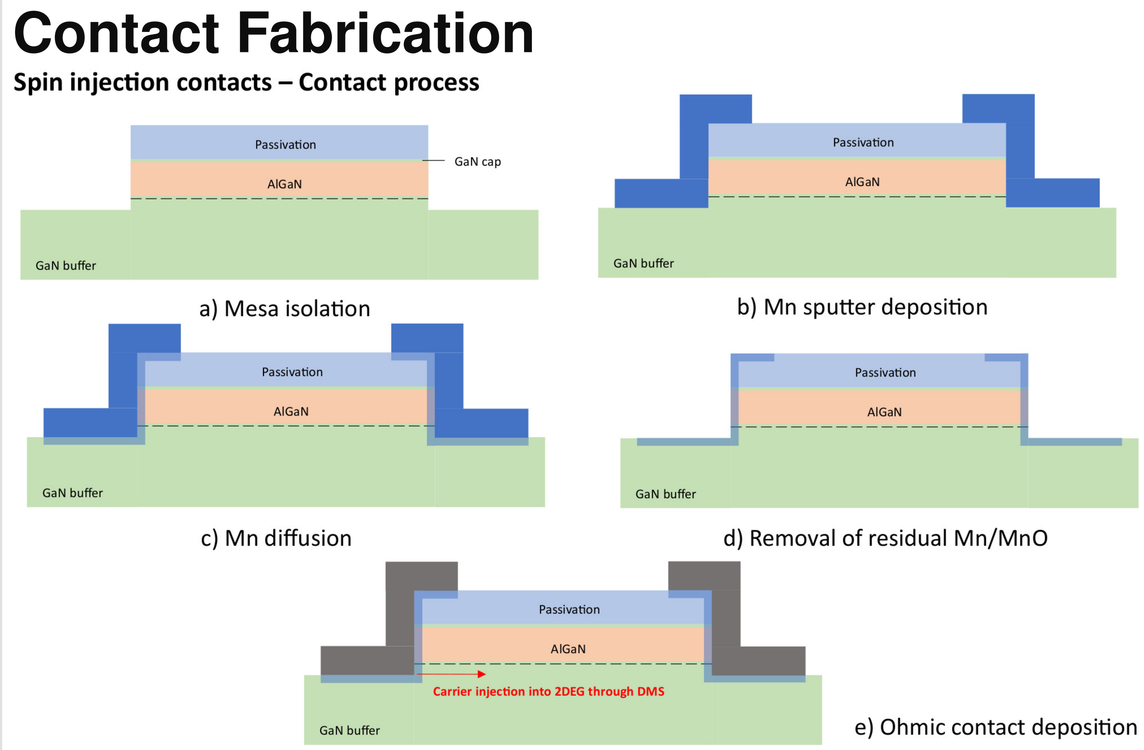


- Mixing between Mn (MnO) and GaN layers
- **Sample 1,2: MnO surface layer, negligible diffusion** MRI results suggest **negligible magnetic susceptibility**.
- **Sample 3**: **Mn below detection limit**
- **Sample 4**: **diffusion of Mn** into GaN but **damage to GaN layer**, diffusion of AlGaN accommodation layers?



Contact Fabrication

Spin injection contacts – Contact process



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[2] B. Thorpe, K. Kalna, F.C. Langbein, S.G. Schirmer. Spin Recovery in the 25nm Gate Length InGaAs Field Effect Transistor. *Int. Workshop Comp. Nanotech*, 168, 2017.

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