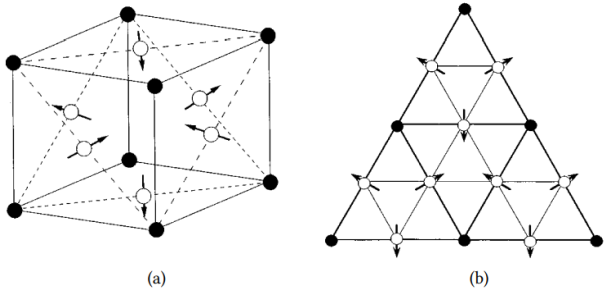
PtMn – A BEOL Compatible Antiferromagnet for MRAM

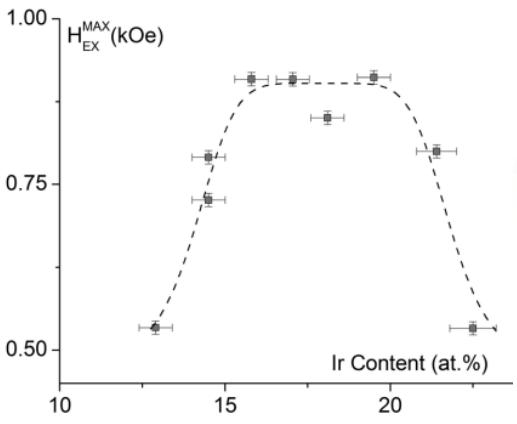
***W. Frost*[1], R. Carpenter[2], S. Couet[2], G. Vallejo Fernandez[1]**

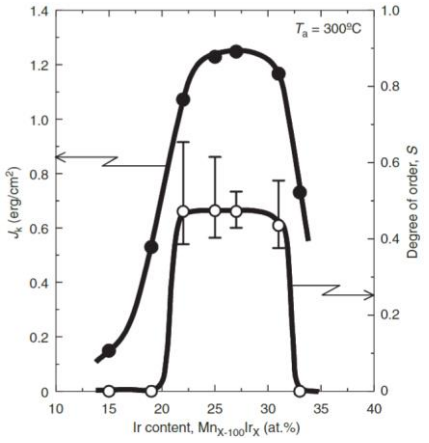
[1.] School of Physics, Engineering and Technology, University of York, Heslington, YO10 5DD, U.K.
[2.] imec, 3001 Leuven, Belgium

The Antiferromagnet $IrMn_{"3"}$

- A complicated triangular spin structure along the {111} planes.
- A good texture is therefore important.
- But this is only true in the ordered $L1_2$ phase of $IrMn_3$.
- Additionally, the ideal composition is often up for debate.



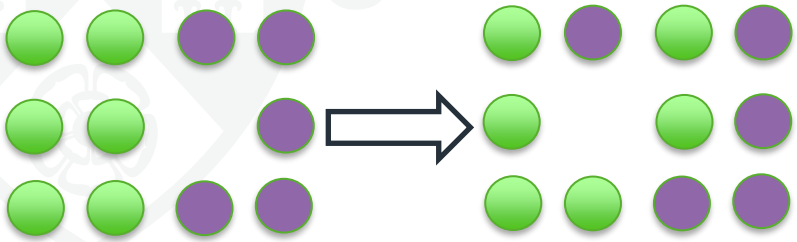


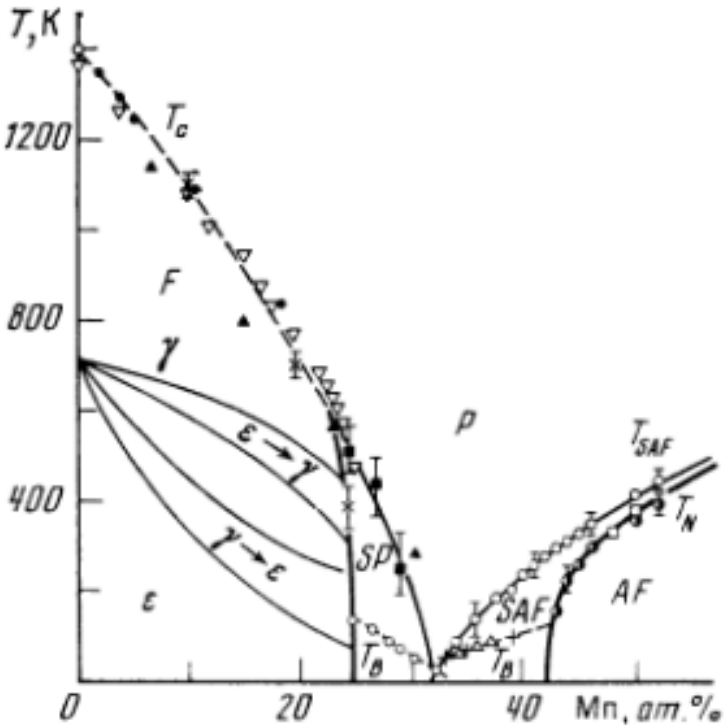


I. Tomeno, H. N. Fuke, H. Iwasaki, M. Sahashi, Y. Tsunoda, J. Appl. Phys. 86,
II. N. P. Aley, K. O'Grady, J. Appl. Phys. 109, 07D719 (2011).
III. M. Tsunoda, *et al.*, J. Magn. Magn. Mater. 304, 55 (2006).

Interfaces

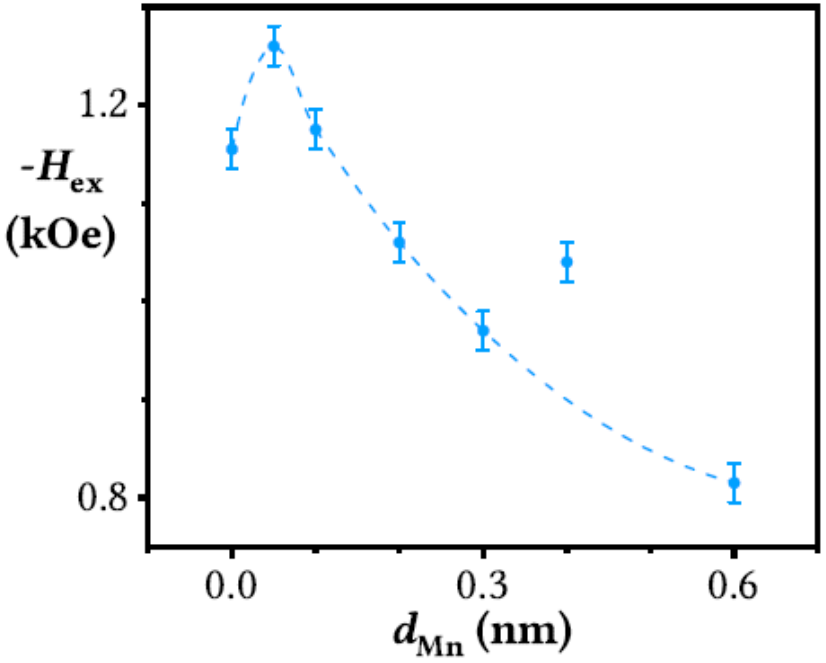
- This is further complicated by the existence of interfaces.
- The phase diagram of Co-Mn is diverse and Mn is known to readily diffuse.
- The exchange bias system must be treated as at least two systems combined – the bulk and the interface.
- The thermal stability of the system is not reliable and/or compatible with high temperature BEOL processes.

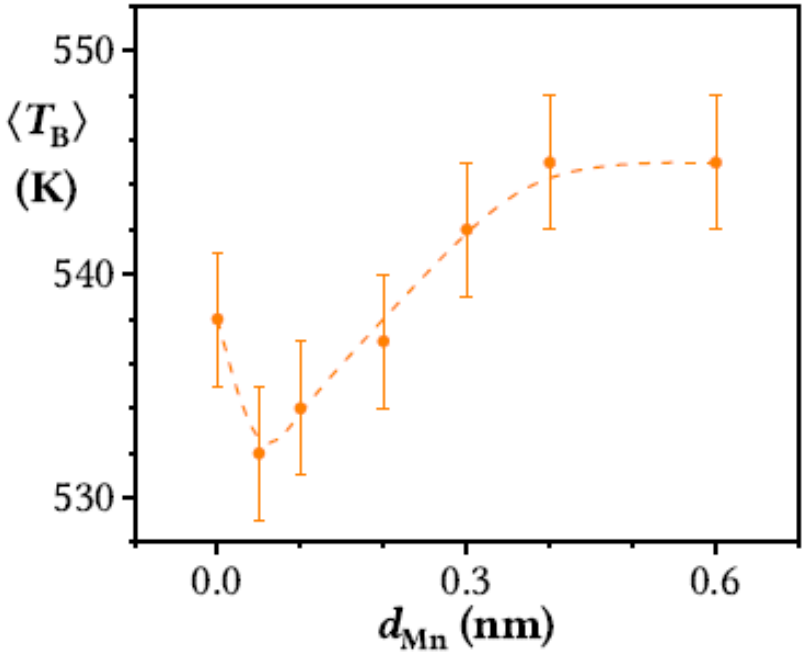




I. A. Z. Men'shikov, et al., Sov. Phys. JETP 62, 734 (1985).

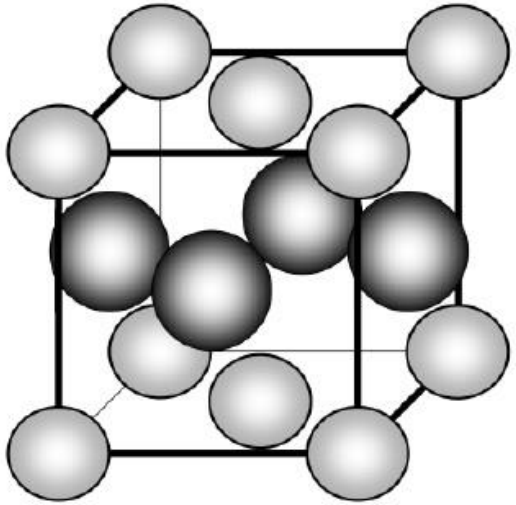
Two Inverse Trends





Alternative Materials – $L1_0$ Alloys

- Alternative AF alloys are drawing attention again to replace the ubiquitous $IrMn_x$.
- These can have a higher thermal stability than IrMn alloys and use cheaper materials.
  - High thermal stability is vital for BEOL.
  - Cu reflow process >400^{o}C for 180'.
  - Automotive applications >180^o for 10 000 hours
- Measurement of the anisotropy value is key – as well as identifying the **source** of the anisotropy.
- Many of these materials have an $L1_0$ structure.



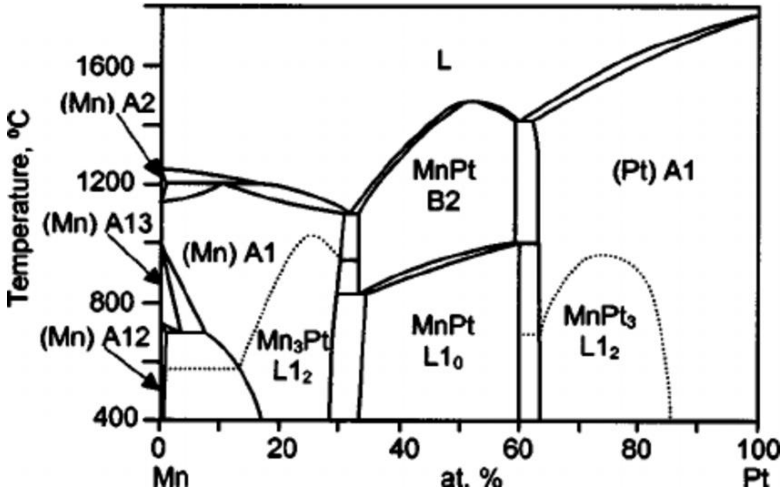
Platinum Manganese

- Platinum manganese has a “well studied” structure and has been widely investigated for its magnetic properties.

- However, its simple stoichiometry and thermal stability make it ideal for BEOL compatible application.
  - Previously shown $T_N > 700^oC$.
  - Blocking temperatures up too 400^oC.

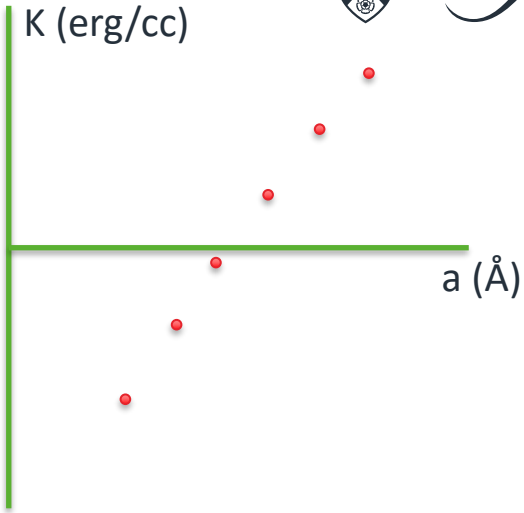
- It exists in two states in the 1:1 ratio:
  - Paramagnetic face-centred cubic
  - **Antiferromagnetic face-centred tetragonal**

- Optimising and controlling this phase transition is key – often achieved with long, high temperature anneals.



Seed Layer Variation

- Try to control sample properties by using seed layers:
  - Different lattice matching for crystallization
  - Different lattice matching for strain.
    - Linear dependence?
- Try three seed layers: Pt, Nb and Ru
  - Pt is fcc, so match {111} to PtMn-{111}
  - Ru is hexagonal, so match {002} to PtMn-{111}
  - Nb is bcc, so match of {110} to PtMn-{111}
  - Significant variation in lattice match



Seed Layer	Lattice mismatch
Pt	+ 1.84%
Nb	- 14.3%
Ru	- 0.52%

Sample preparation

- Samples were deposited in imec's Canon-Anelva system with 10 nm seed layers and 8 nm PtMn layers.

- Samples are post-annealed at (325-425)^{o}C plus 475^{o}C for Ru in a field of 5 Tesla.
  - Thermal activation of AF grains and full setting of AF layer/maximum exchange bias.
  - Enthalpy of formation for high-energy fct phase of PtMn.

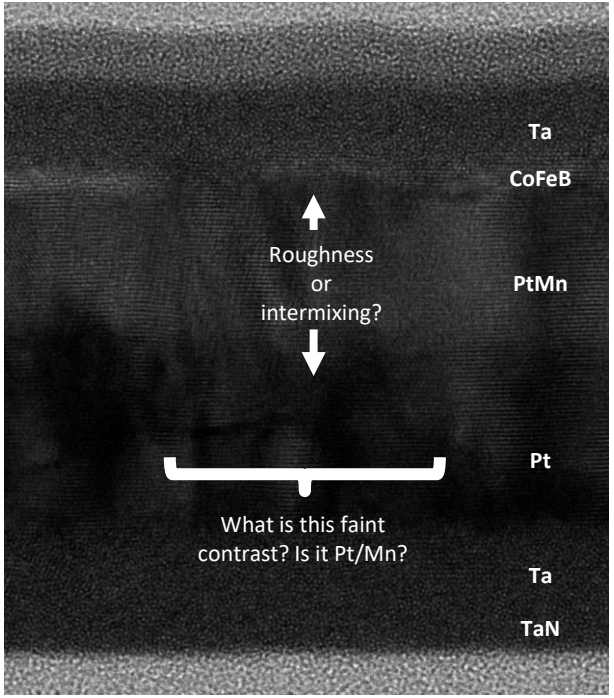
Lot	TaN [A]	Ta [A]	Pt [A]	Nb [A]	Ru [A]	PtMn [A]	20CFB [A]	Mg [A]	Ta [A]	MRT 90' 5T	Spits	Question
D02	20	50			100	80	25	6.5	50	325C	Ru Seed 325C	Anneal vs. seed dependence
D03	20	50			100	80	25	6.5	50	375C	Ru Seed 375C	
D04	20	50			100	80	25	6.5	50	425C	Ru Seed 425C	
D05	20	50			100	80	25	6.5	50	475C	Ru Seed 475C	
D06	20	50		100		80	25	6.5	50	325C	Nb Seed 325C	
D07	20	50		100		80	25	6.5	50	375C	Nb Seed 375C	
D08	20	50		100		80	25	6.5	50	425C	Nb Seed 425C	
D09	20	50	100			80	25	6.5	50	325C	Pt Seed 325C	
D10	20	50	100			80	25	6.5	50	375C	Pt Seed 375C	
D11	20	50	100			80	25	6.5	50	425C	Pt Seed 425C	

Pt Seed Layers

- Platinum has the smallest lattice mismatch and can act as a Pt source/sink for stoichiometry tuning

- However, this makes intermixing and diffusion very easy:

  - Pt: Slight into CoFe layer?
  - Mn: Pt, Ta (minor), CoFe (minor)
  - Co: whole stack
  - Fe: whole stack, more concentrated in Pt than PtMn



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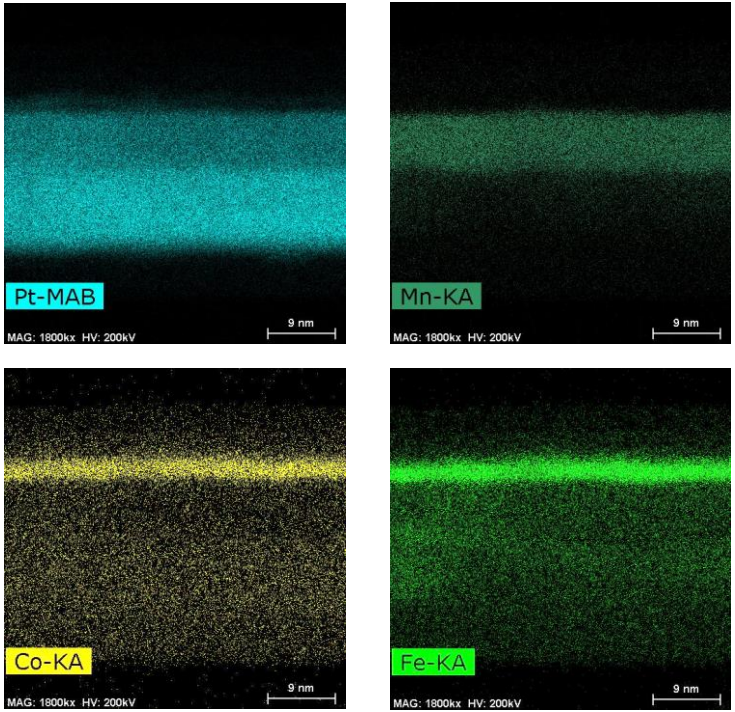

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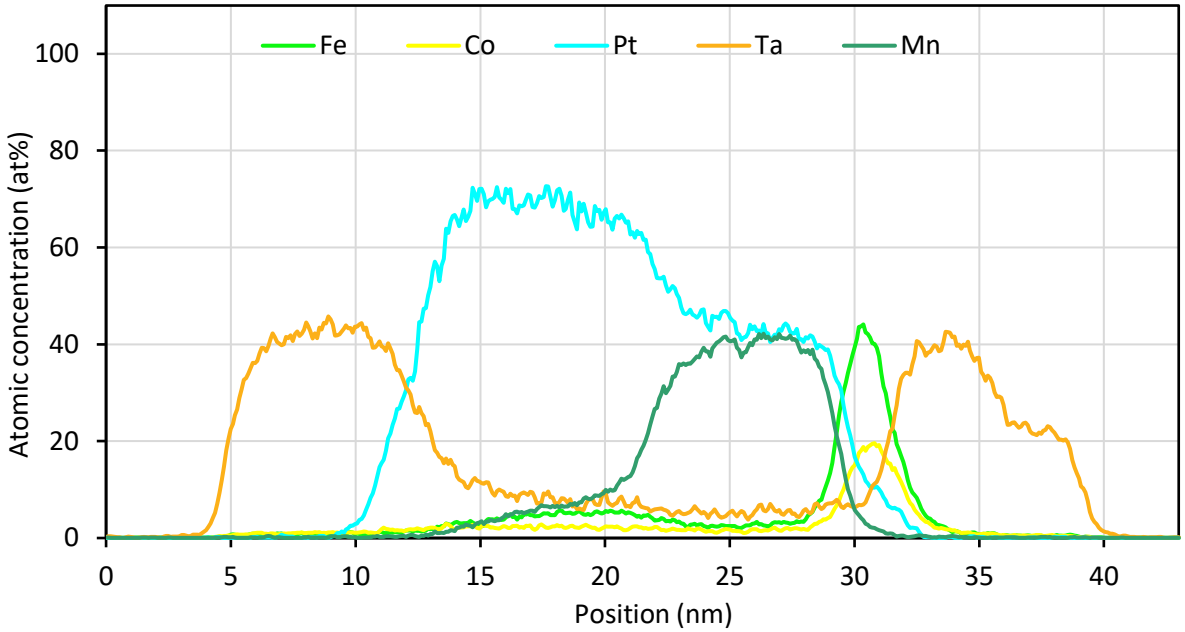
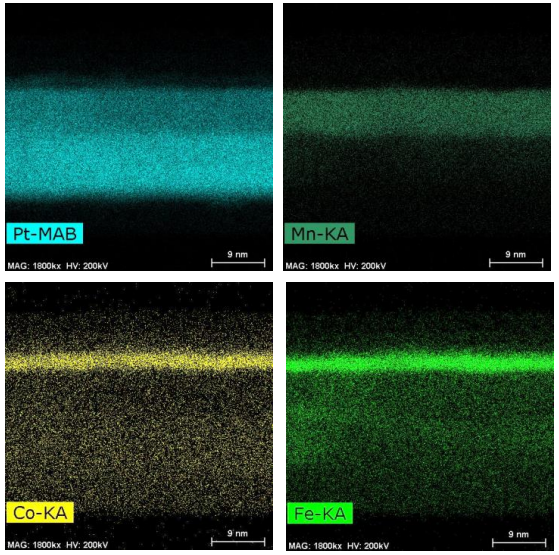
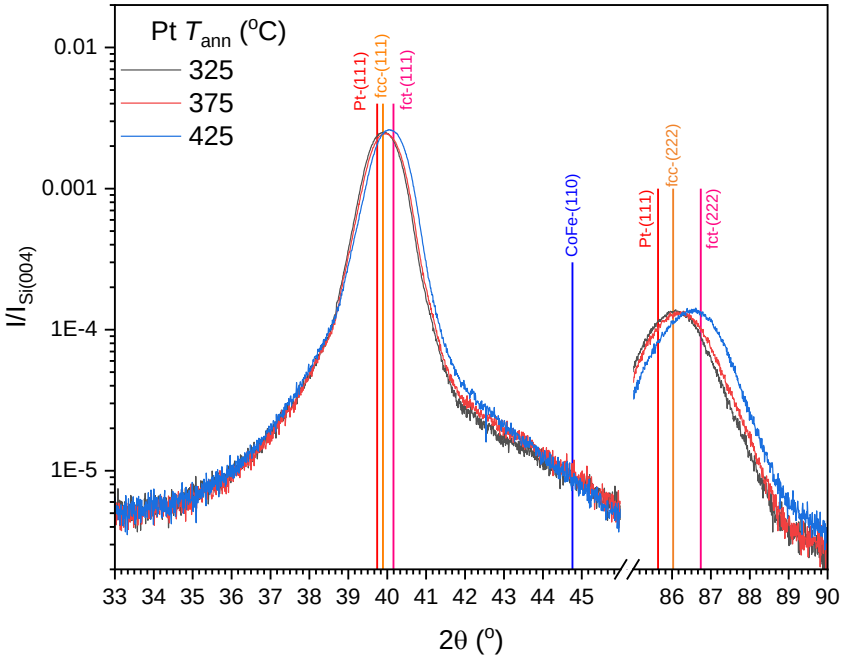




Pt Seed Layers

- Hard to differentiate the Pt and PtMn phases:
  - "Hetero"-epitaxial growth.
- A shift towards the fct-{111} position is observed at 425°C.



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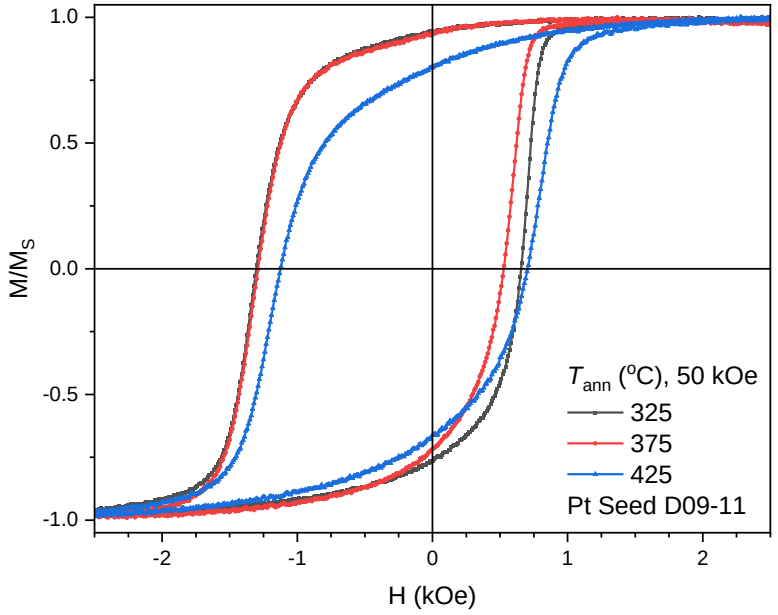
  - Consistent with work on IrMn – trends do not align.



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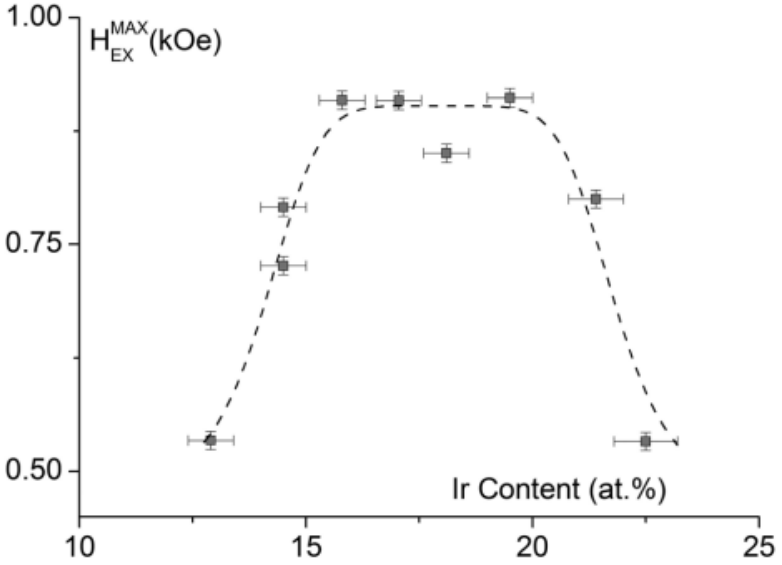

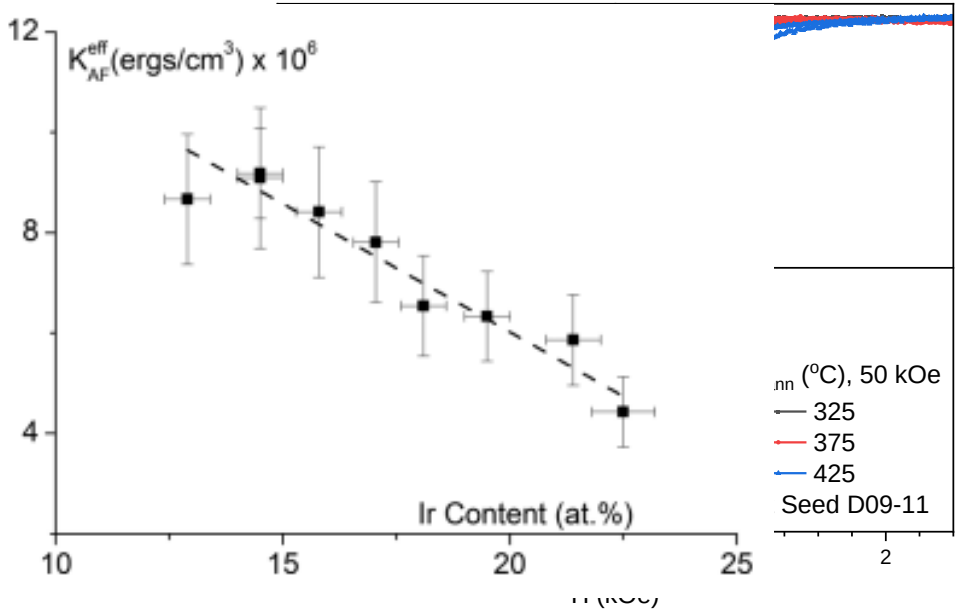

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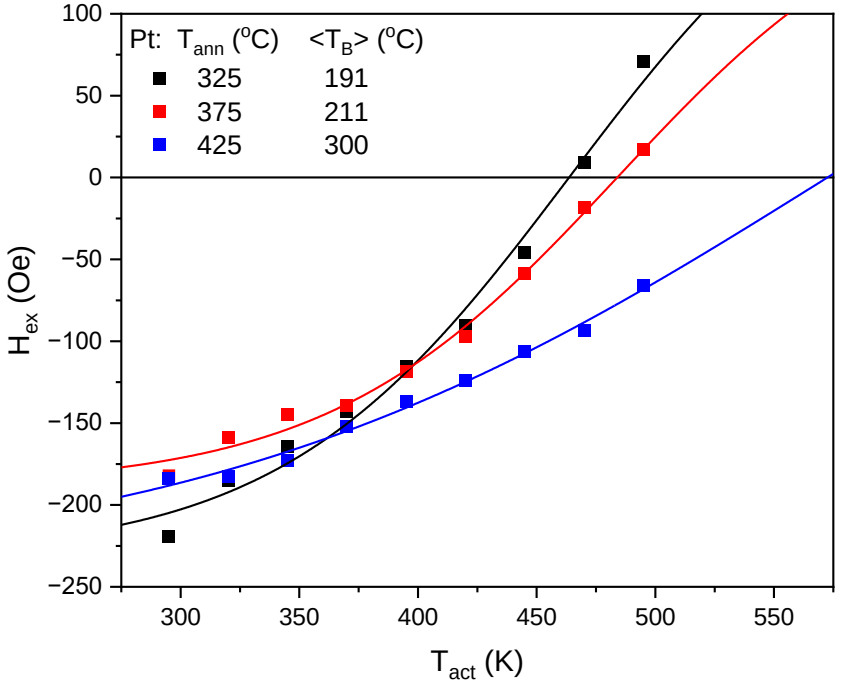
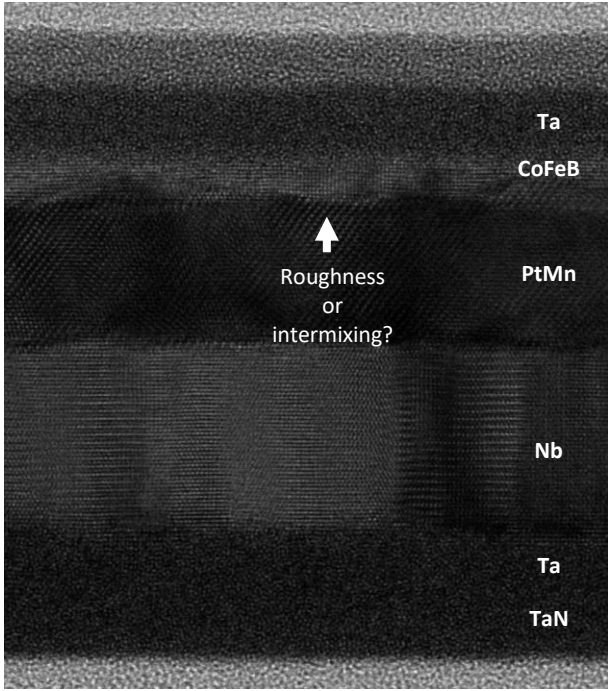
- However, a fall in the exchange bias and coercivity is observed
  - Consistent with work on IrMn – trends do not align.
- This is confirmed by a large increase in the $<T_B>$ value
  - Waiting on in-plane TEM for evaluation of k_{AF}.



Nb Seed Layers

- Nb has the largest lattice mismatch at 17.7%.
- Nb solubility of the transition metals is possibly lower than with Pt?
  - Reduced diffusion and intermixing of Mn.
  - Very low Nb/Fe and Nb/Co – more in Ta seed.



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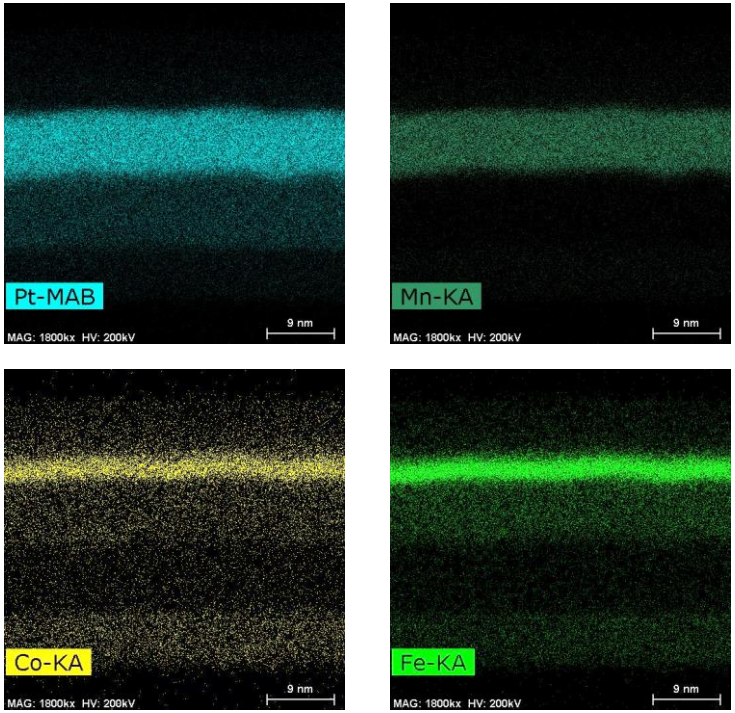

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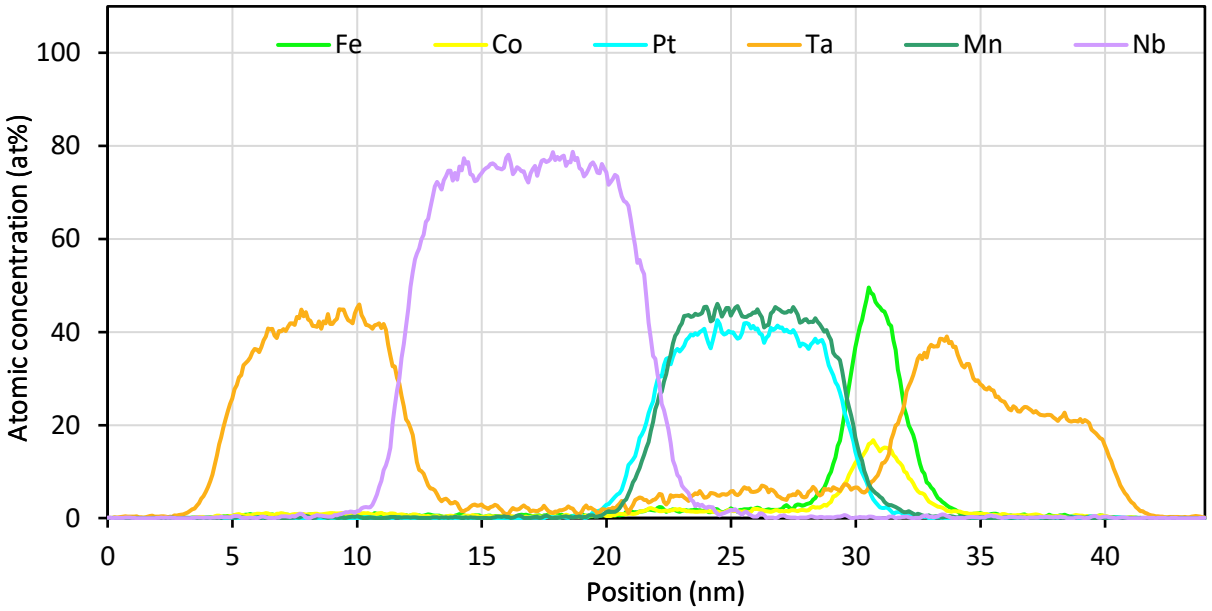
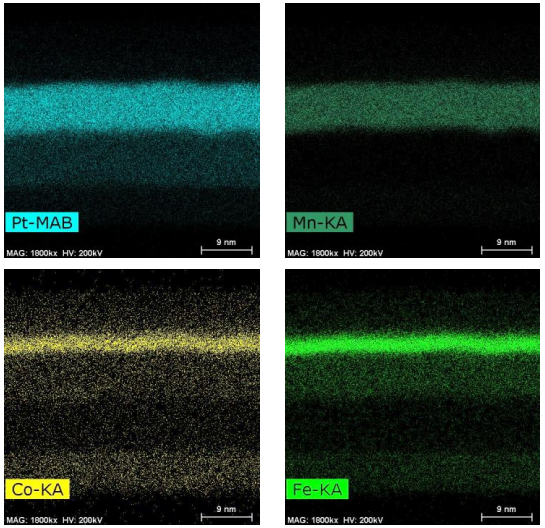
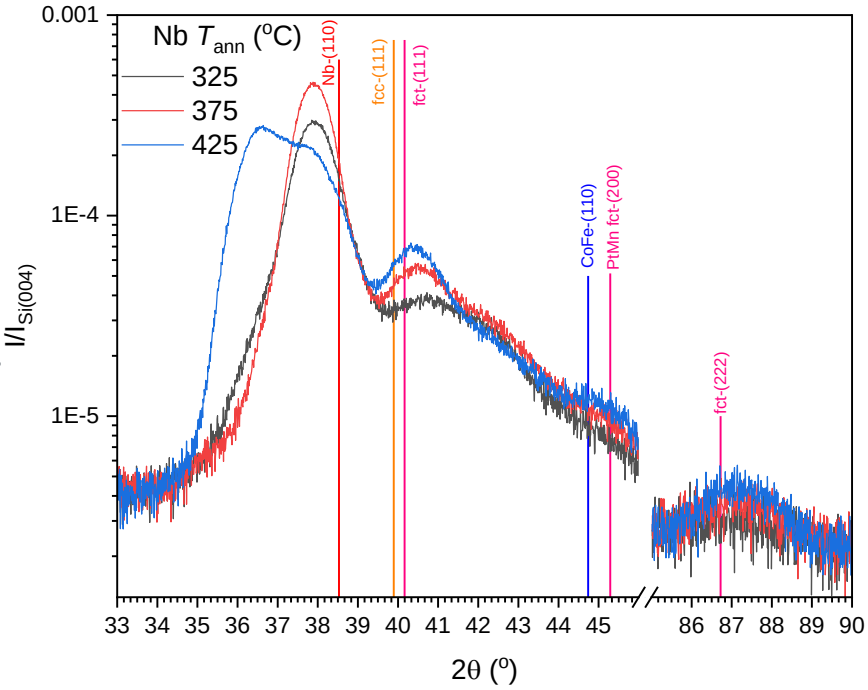




Nb Seed Layers

- System is deposited in a crystalline but strained state:
  - PtMn relaxes as T_{dep} increases to 425°C.
  - Nb undergoes partial phase transformation?
  - Nb(110) does not have match to PtMn(111)
    - Bulk ratio of PtMn(111)/Nb(110) = 0.96
  - Peak 36.5° e.g. NbPt - but limited intermixing in EDX.



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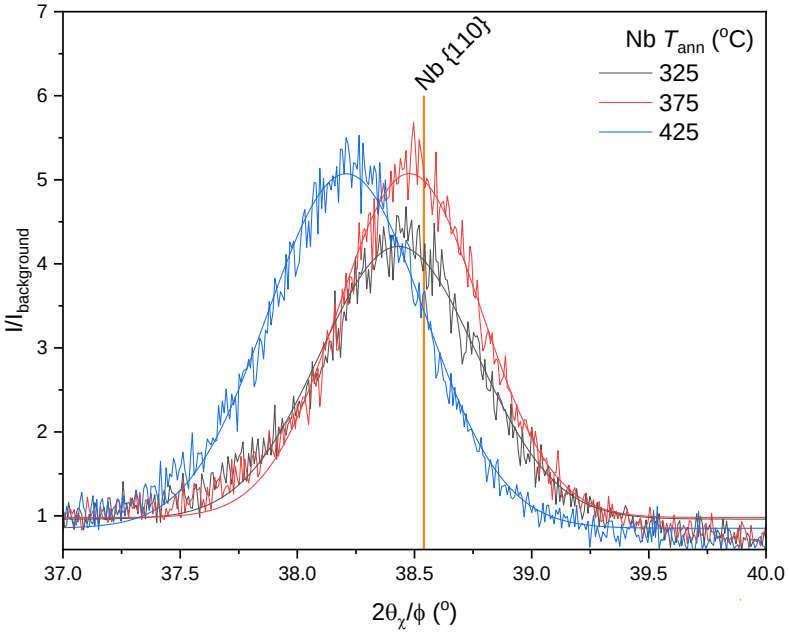
  - In-plane XRD confirms the {110} orientation of the Nb
    –Additionally means that epitaxy is far less likely



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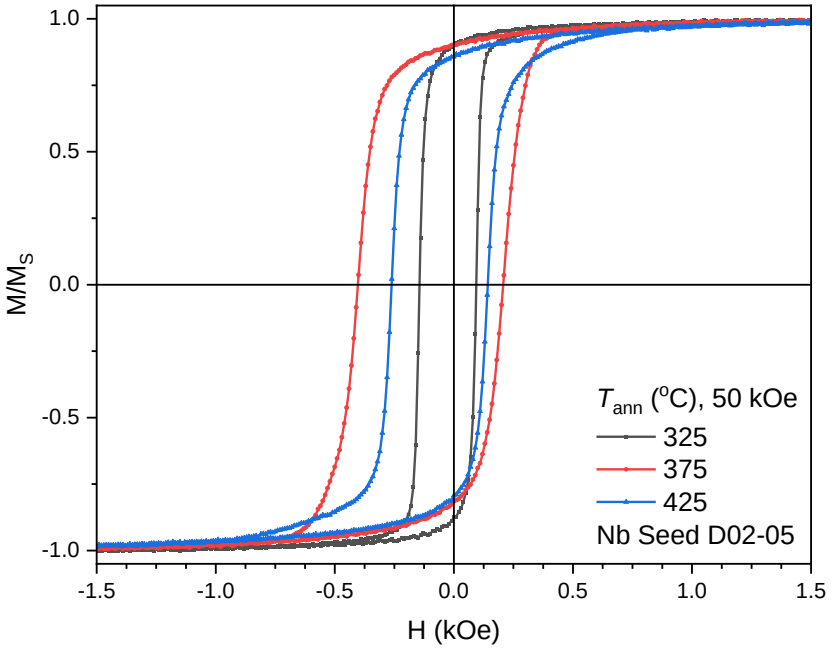
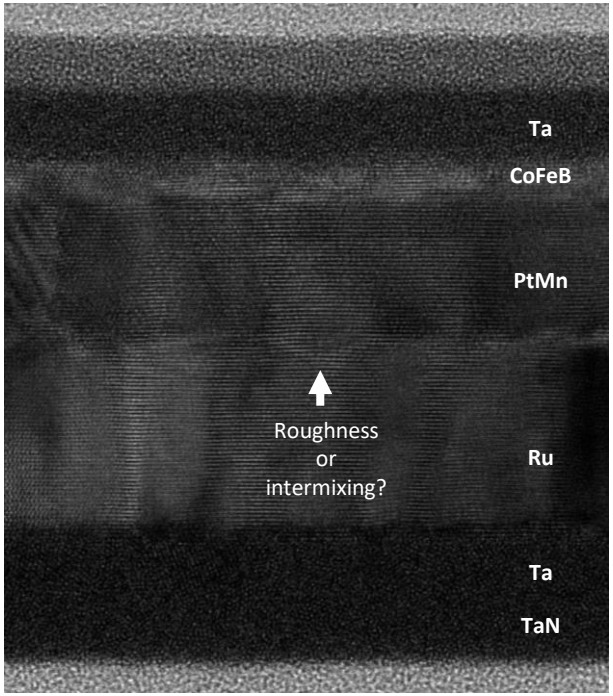
  - Peak 36.5° e.g. NbMn - but no intermixing in EDX.
- Square loops indicate loss of anisotropy, less pinning and nucleation dominated reversal.
- Loss of H_{ex} indicates lack of pinning from PtMn despite crystallinity.



Ru Seed Layers

- Ru is the hexagonal seed layer, know for columnar growth of highly ordered seed layers.

- Once again lots of diffusion of Co and Fe.
  - Fe diffuses down **grain boundaries of Ru.**
  - Co to lesser extent.
  - Mn is well contained.



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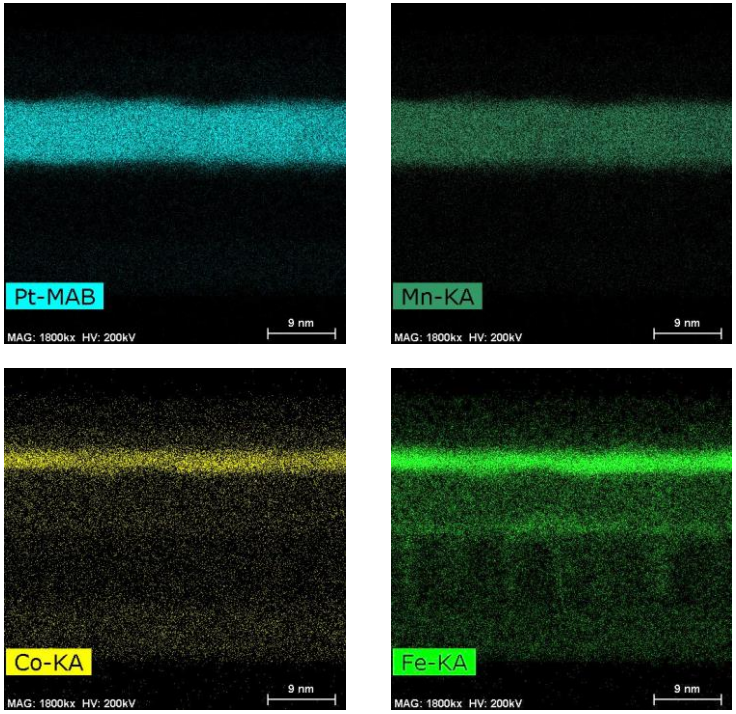

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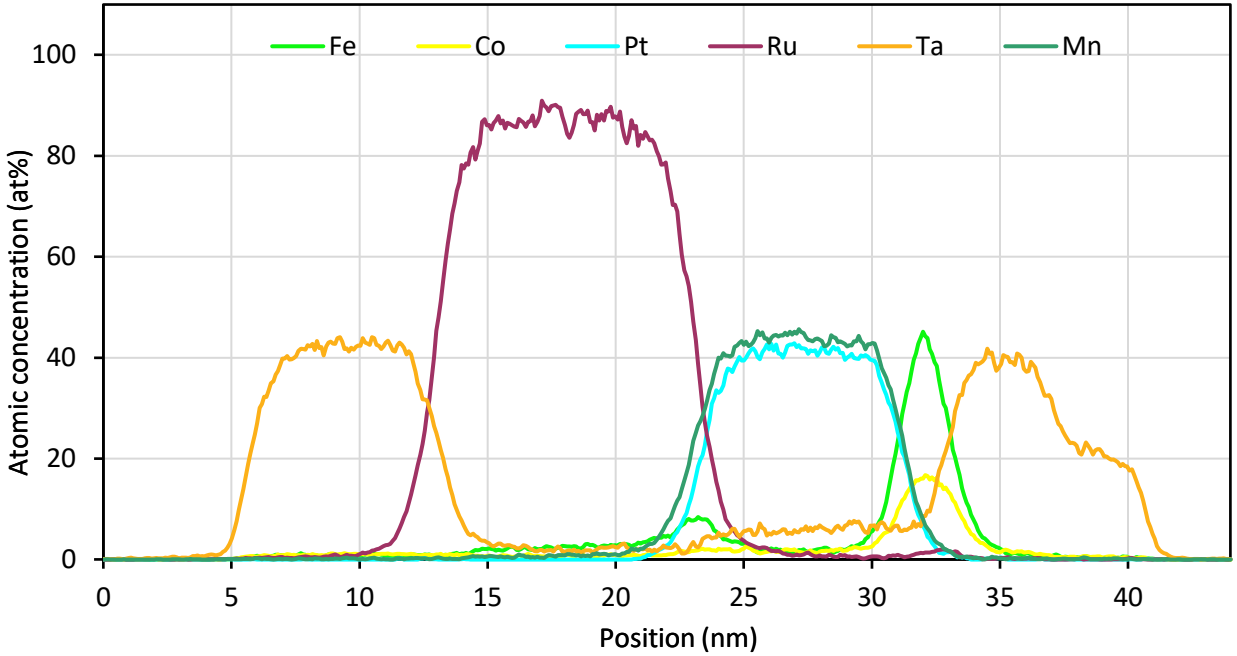

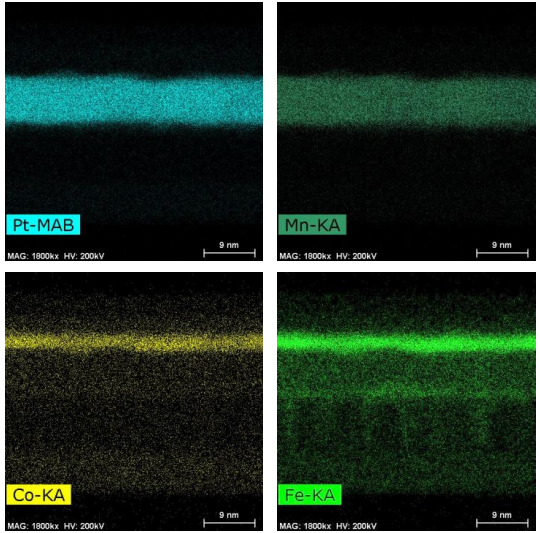

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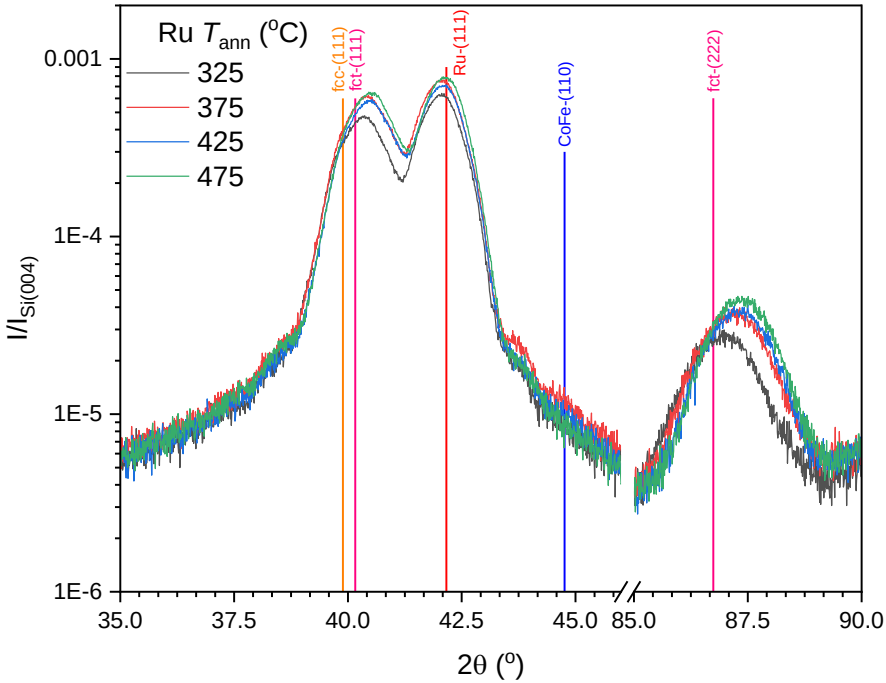
- System is deposited in a crystalline but strained state:
  - PtMn increased distortion as T_{dep} increases.
  - Significant peak shift at 375°C of 0.2% strain.
  - Still a significant fcc shoulder at all values of T_{dep}.



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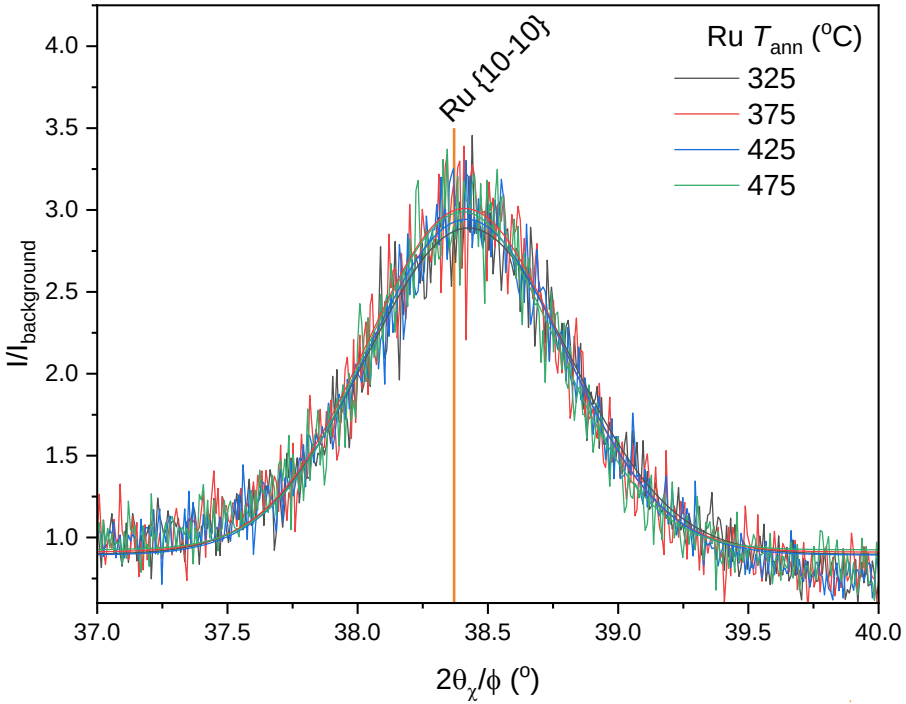

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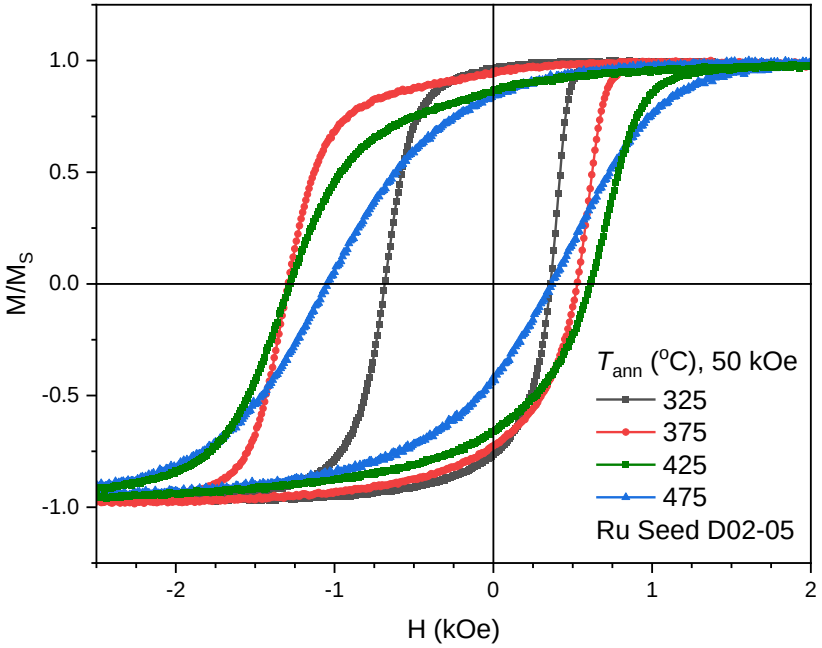

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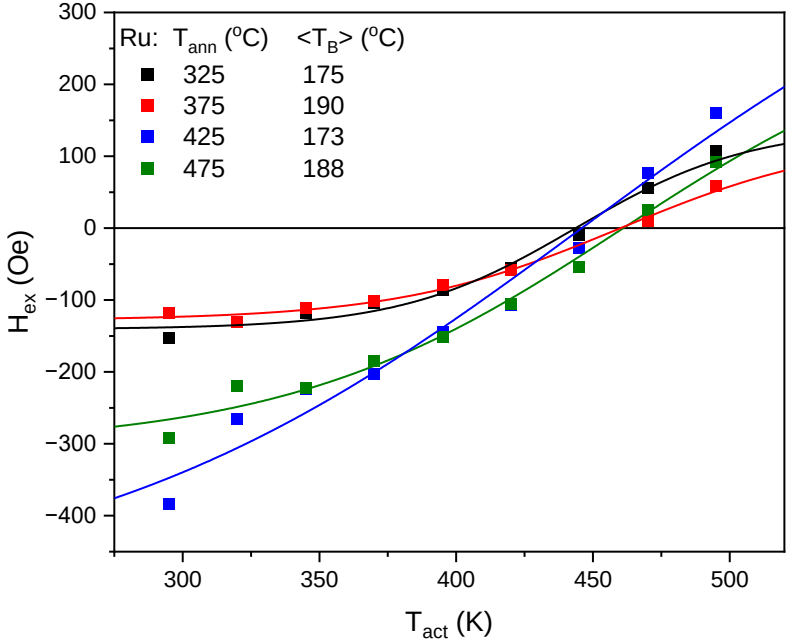
- Again, an increase in exchange bias and coercivity is observed, before a significant loop canting indicating increased anisotropy at 475°C.
  - Blocking data inconclusive without TEM data.
  - No clear trend – need to determine grain volume.



Current Status of PtMn

- Crystalline, tetragonal PtMn can be formed at lower temperatures and shorter anneal times than literature.

- Diffusion is a large issue for lighter transition elements:
  - Mn (as always)
  - Fe through grain boundaries

- Samples are thermally stable with $<T_B>$ values of 300°C:
  - Need to push further for BEOL.
  - Modify thicknesses, optimize annealing, etc.

- Further XRD to identify c/a ratio for the tetragonal fct phase we have achieved – could explain how to improve $<T_B>$ and combine with DFT calculations.