A New Paradigm for Exchange Bias in Polycrystalline Films

K. O'Grady, L. E. Fernandez-Outon and G.Vallejo-Fernandez

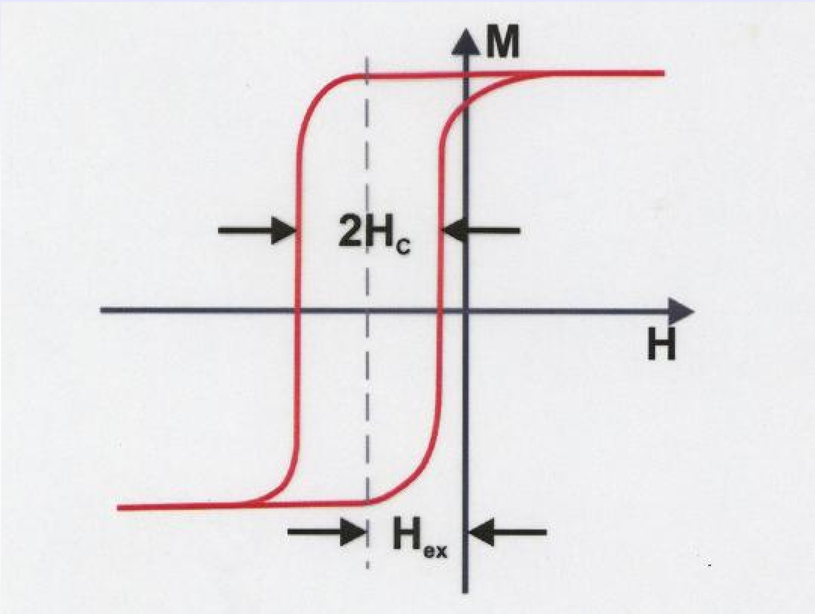
Department of Physics, The University of York, Heslington, York, YO10 5DD, UK.

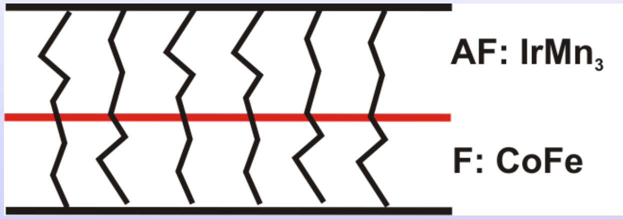
Acknowledgements: A. Goodman, T. J. Hughes, W. J. Antel, J. D. Dutson, S. Manzoor, T. Deakin, R. W. Chantrell, U. Nowak, B. Hillebrands, M. J. Carey.
Seagate Technology N. Ireland, HGST San Jose, WD Fremont, EU RTN NEXBIAS.

Magnetics Society Distinguished Lecture 2010

Exchange Bias

- Exchange bias was first reported in 1956 by Meiklejohn and Bean.
- The effect occurs when an antiferromagnet (***AF***) is in contact with a ferromagnet (***F***).
- This can be engineered in thin films.
- It can also occur if films or particles of Co or Ni are oxidised to give a surface of NiO or CoO.
- If the *AF* is field-cooled through T_N a shifted loop and increased H_c occur.

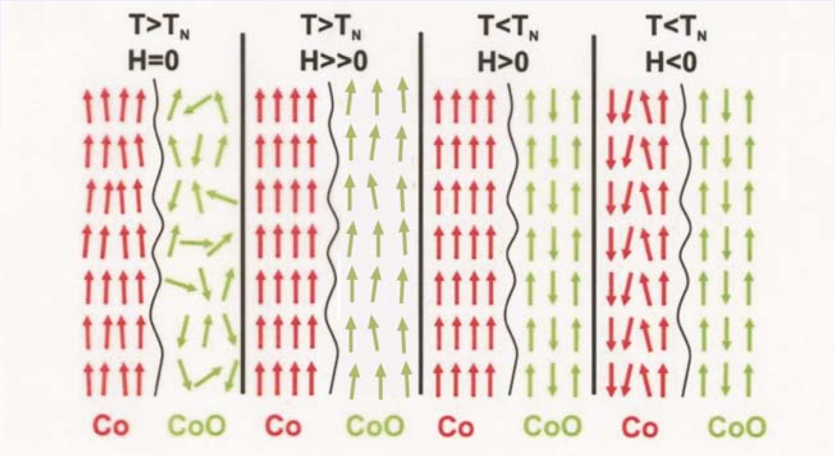


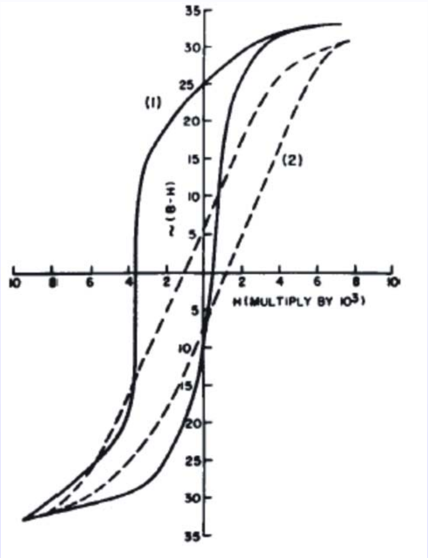


W. H. Meiklejohn and C. P. Bean, *Phys. Rev.* **102** p.1413 (1956).

FM/AFM Coupling

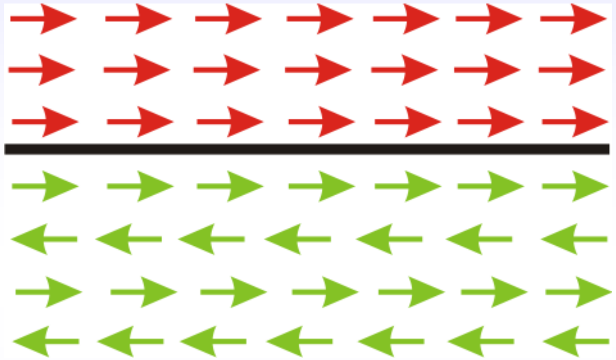
- CoO is a classical superexchange-based *AF*.
- Neighbouring (111) planes align antiparallel with $T_N \sim 290$ K
- Hence in oxidised small Co particles there is an interface between a *F* and an *AF* material.
- The loop shifts by H_{ex}.
- H_c increases dramatically.

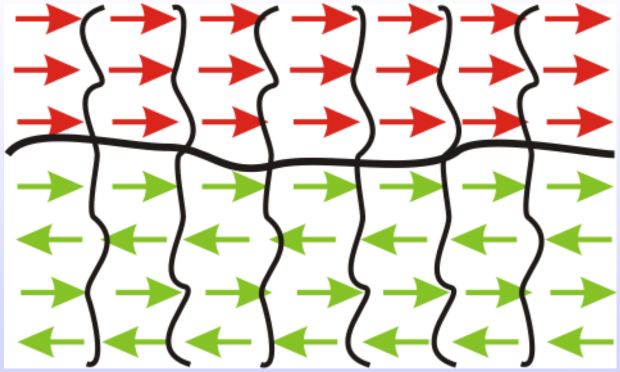




Early Theories

- Meiklejohn and Bean calculated the shift assuming a perfect interface but were > 10x out.
- An uncompensated spin interface model by Néel also failed.
- There have been several complex models predicting domain walls in the AF with marginal success.
- The only successful model was a granular model due to Fulcomer and Charap based on Stoner-Wohlfarth theory.





W. H. Meiklejohn and C. P. Bean, *Phys. Rev.* **102** p.1413 (1956).

L. Néel, *Ann. Phys. Paris* **2** p.61 (1967).

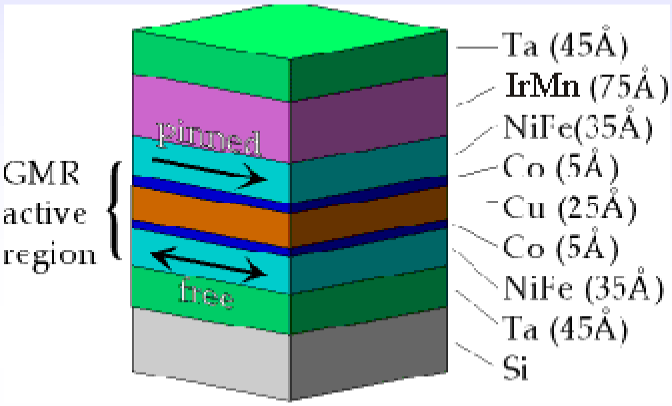
R. L. Stamps, *J. Phys. D: Appl. Phys.* **33** p.R247 (2000).

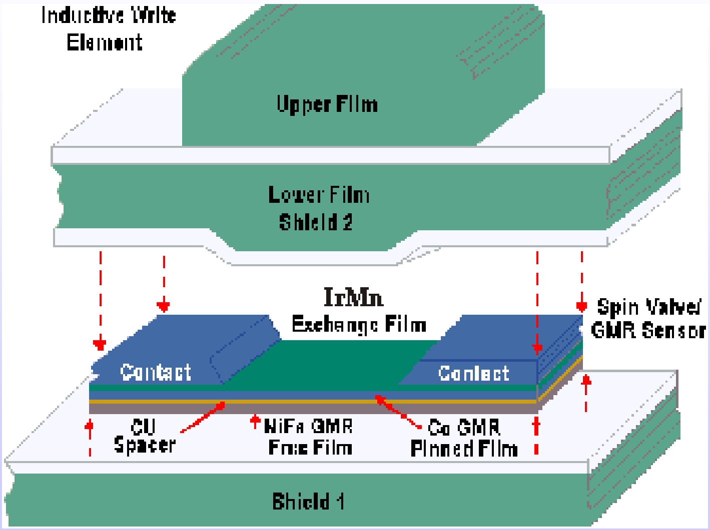
U. Nowak, K. D. Usadel, J. Keller, P. Miltényi, B. Beschoten and G. Güntherodt, *Phys. Rev. B* **66** 014430 (2002).

E. Fulcomer and S. H. Charap, *J. Appl. Phys.* **43** p.4190 (1972).

Technical Importance

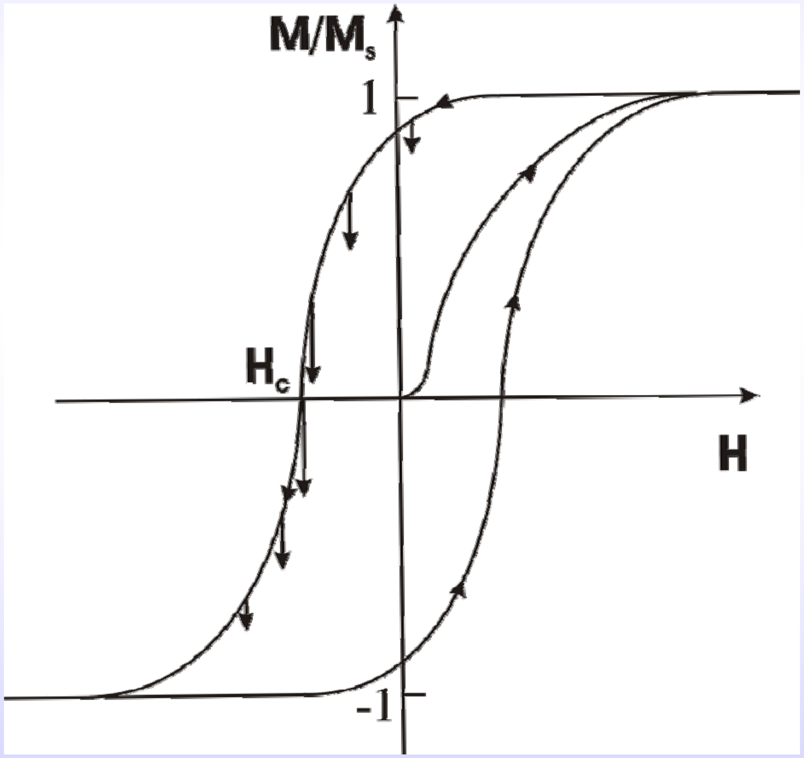
- From 1956 to ~1990, Exchange Bias (EB) was of academic interest only.
- With the discovery of GMR and the development of spin-valves EB was used to align the pinned layer.
- An understanding of how EB works and can be controlled was then essential.
- For example, early spin-valve heads used NiO as the *AF* and had to be reset.
- All GMR, TMR and Spin Electronic devices require or will require Exchange Bias.





Time Dependent Effects

- All magnetic materials exhibit time dependent effects because hysteresis is a non-equilibrium phenomenon.
- In a ferromagnet, time dependence occurs around the coercivity leading to a sweep-rate dependence of H_c.
- Time dependence occurs because of thermal activation over energy barriers.
- The energy barriers are due to anisotropy effects or domain wall pinning.



Nature of Relaxation

- Relaxation over a single barrier is described by the Néel Arrhenius law

$$\tau^{-1} = f_0 \exp\left(\frac{-\Delta E}{k_B T}\right) \quad f_0 = \text{attempt frequency}$$

- Note that the origin of the barrier is not specified.

- In real materials there is a distribution of barriers so that approximate ln(*t*) behaviour is observed.

$$M(t) = M_0 \pm S(H) \ln t$$

- *S(H)* depends on the value of the energy barrier distribution *f(ΔE)* at the critical value being activated.

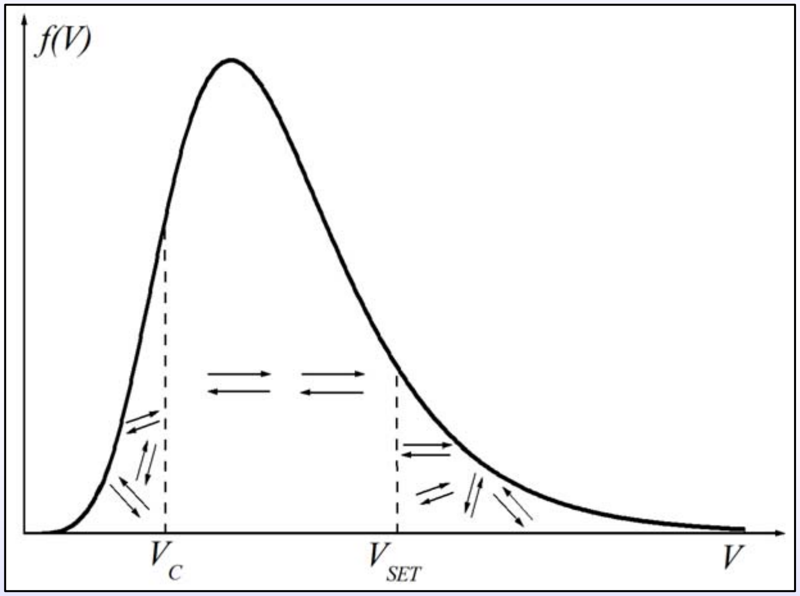
$$S(H) = 2M_s k_B T f\left(\Delta E(H,T)\right)_{\Delta E_c(H,T)}$$

R. Street, and J. C. Wooley, *Proc. Phys. Soc.*, **A62** p.562 (1949)

P. Gaunt, *J. Appl. Phys.*, **59** p.4129 (1986)

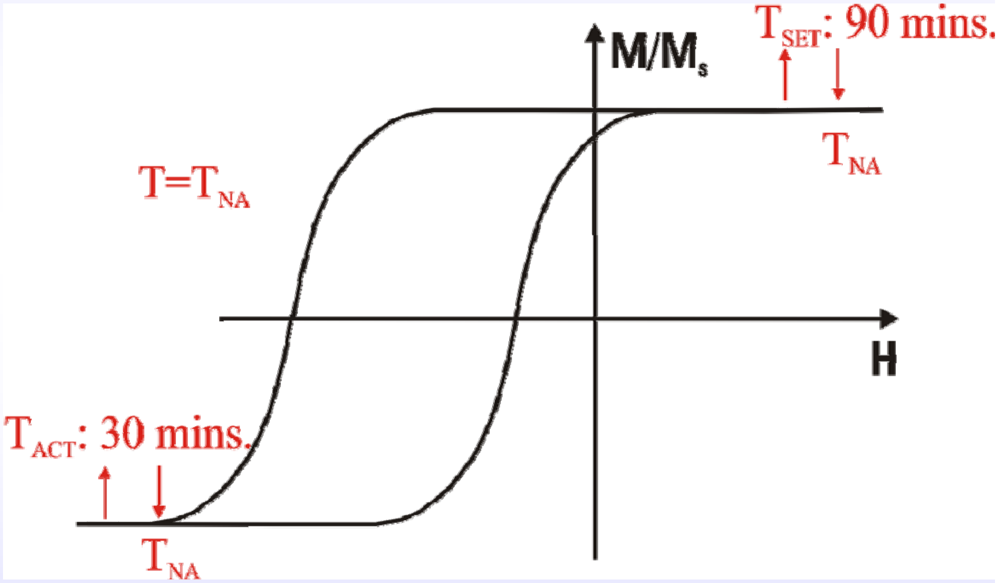
Time Dependence in *AF*s

- In polycrystalline films the ***AF*** is ‘set’ below T_N to avoid damage to the structure.
- The ***AF*** is ordered by the exchange field from the F layer.
- This is done by field annealing using thermal activation giving an ln(*t*) process.
- Temperature causes parts of the ***AF*** to disorder and only the stable grains cause H_{ex}.
- Also in IrMn (T_N=690K) the ‘setting’ of the AF is often incomplete.



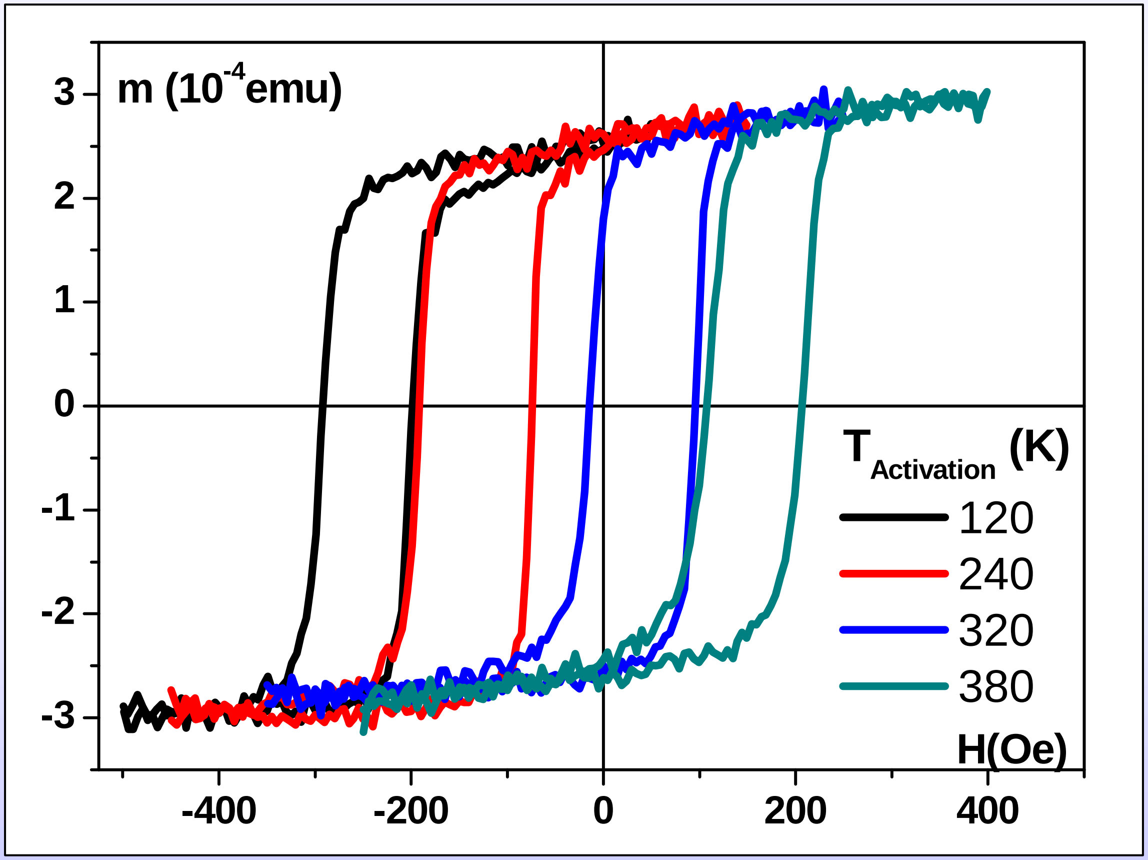
York Protocols

- The *AF* is set at T_{SET} for 90 minutes.
- Sample cooled to T_{NA}.
- Sample heated to T_{ACT} for 30 mins.
- Sample measured at T_{NA}.

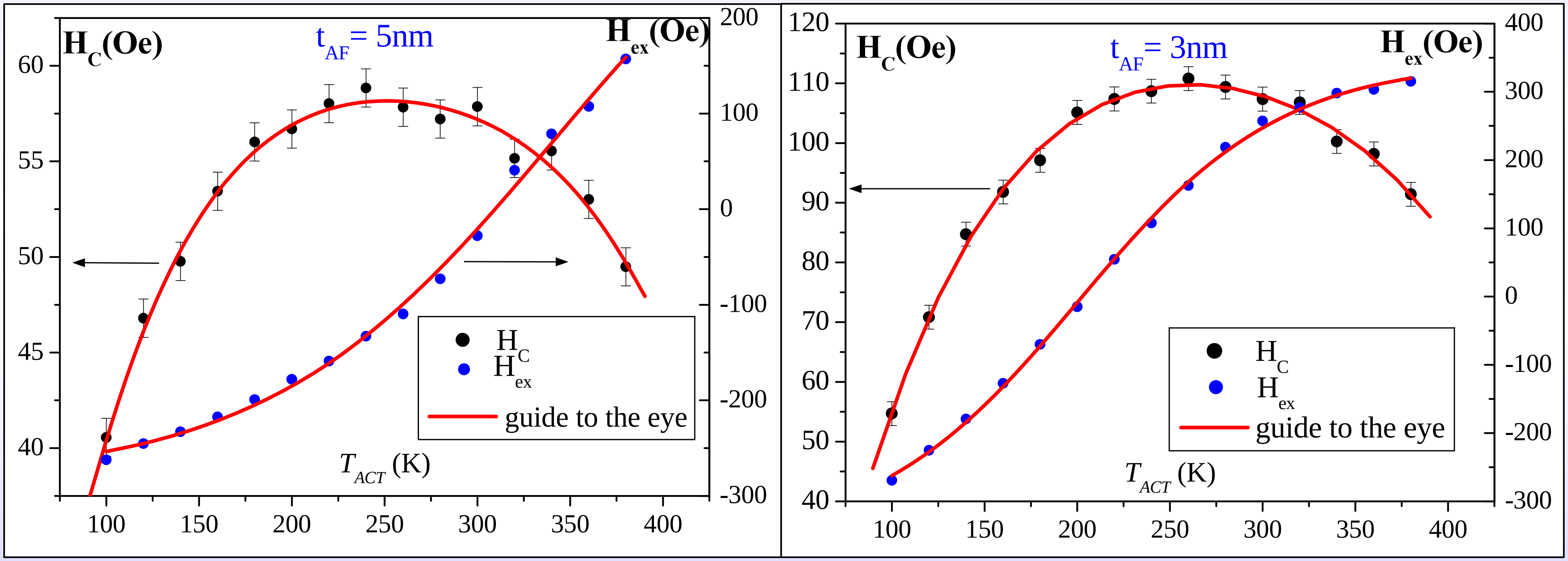


L. E. Fernandez-Outon, K. O'Grady, and M. J. Carey, *J. Appl. Phys.*, **95** p.6852 (2004)

Reversal in IrMn(5nm)/CoFe(10nm)



H_C and H_{ex} IrMn(t_{AF})/CoFe(10nm)

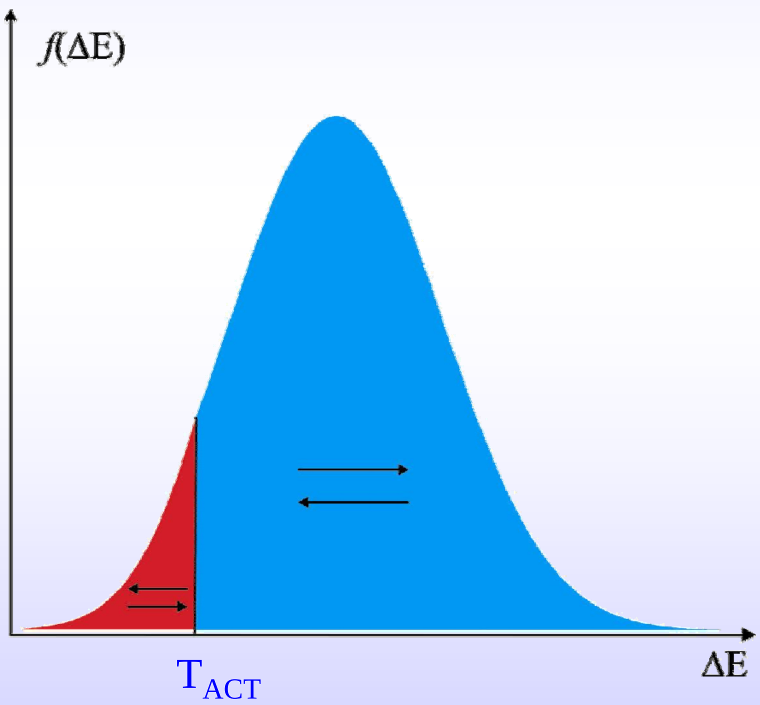


Features of Exchange Bias

- H_{ex} is controlled by the ordered *AF*.
- H_{ex} and H_c are not related.
- Ordering is controlled by thermal activation.

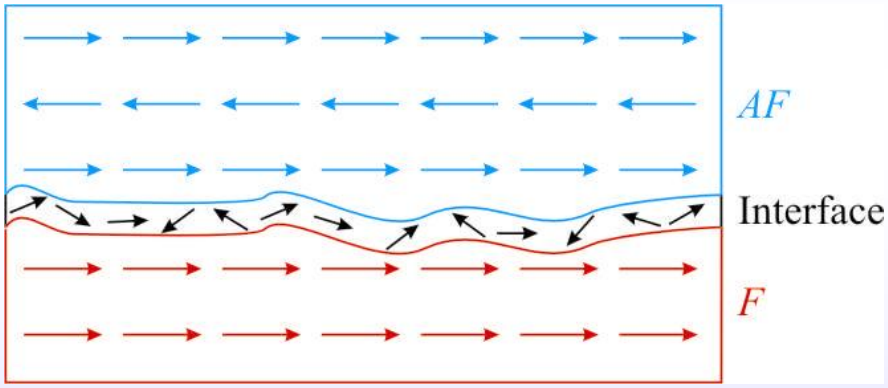
$$H_{ex} \propto \int_{\Delta E_c(T_{ACT})}^{\infty} f(\Delta E)\, d\Delta E - \int_{\Delta E_c(T_{NA})}^{\Delta E_c(T_{ACT})} f(\Delta E)\, d\Delta E$$

- $f(\Delta E)$ appears to scale with the grain volume.



Nature of the Energy Barrier

- For several years there has been no clear model of ΔE in *AF*s.
- Some, but not all, features can be explained using *AF* domain structures and computer models.
- All models predict H_{ex} values to large by orders of magnitude.
- We proposed a simple model based on granular reversal of H_{ex} modulated by disordered interfacial spins.



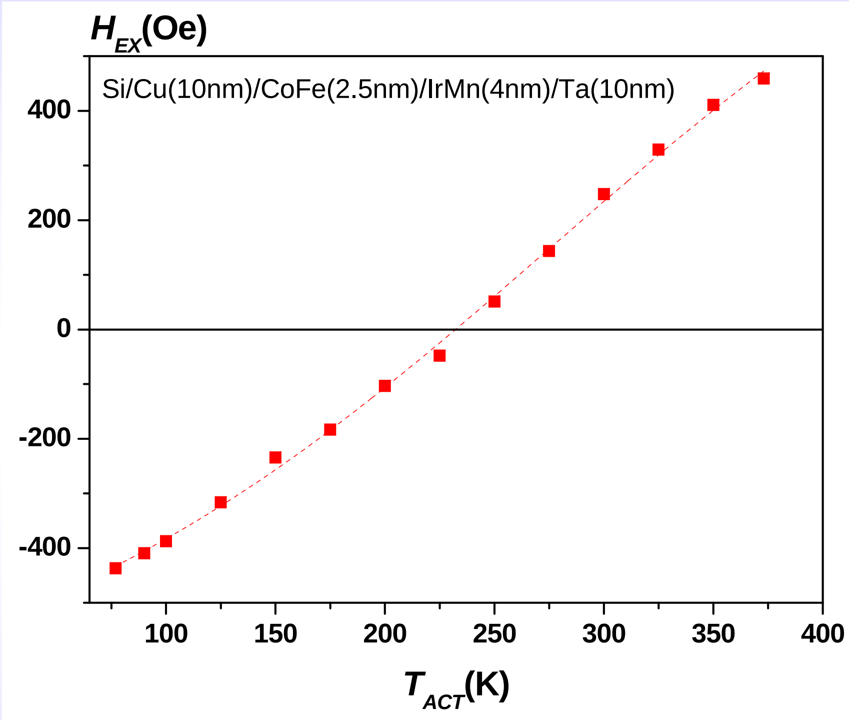
$$\Delta E = K_{AF}V$$

Determination of K_{AF}

- We have calculated K from the zero point in the $H_{ex}(T)$ data.

- The factor 1800 arises due to activation for 30 minutes and <V> is obtained from TEM analysis of >500 grains.

$$K_{AF}(T_B) = \frac{\ln(1800 f_0) k_B T_B}{<V>} \qquad f_0 = 10^9 s^{-1}$$



- The value of $K(T)$ was obtained using:

$$K_{AF}(T) = K_{AF}(0) \cdot \left[1 - \frac{T}{T_N}\right]$$

$<T_B>$: K_{AF} (236K) = 6.3×10^6 ergs/cc

RT : K_{AF} (295K) = 5.5×10^6 ergs/cc

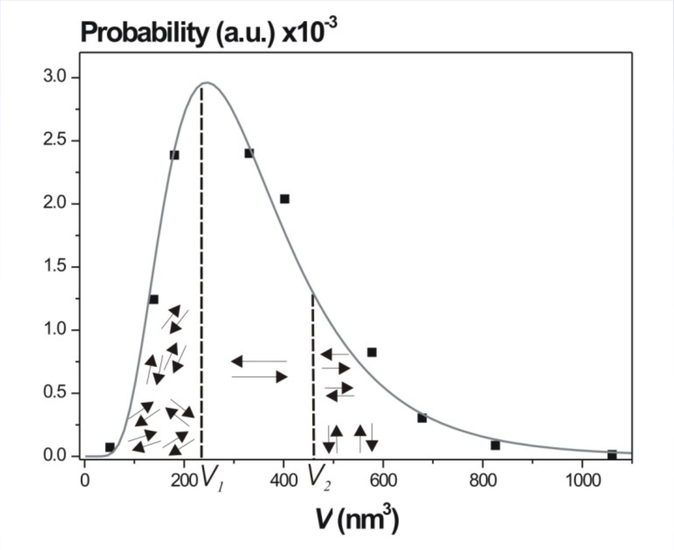
T_{SET} : K_{AF} (373K) = 4.4×10^6 ergs/cc

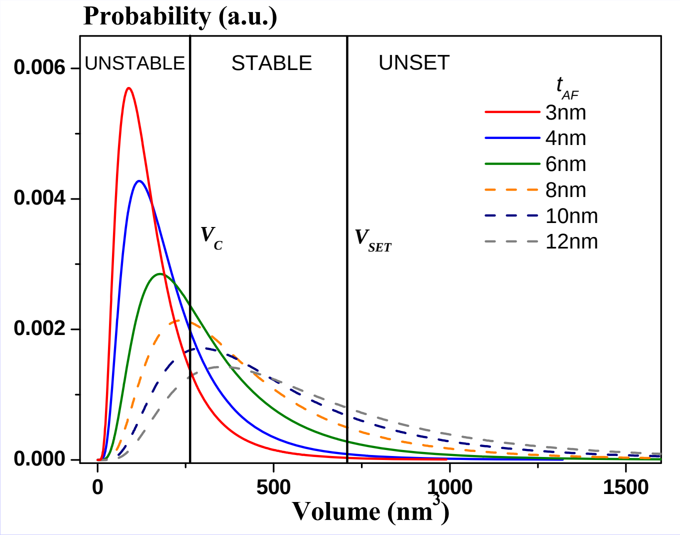
Grain Size Dependence of EB

- Since the *AF* is 'set' by thermal activation all large grains may not be set at $T<T_N$.
- Small grains will be disordered by thermal energy above T_{NA}.
- Hence H_{ex} will be due to the stable and set fraction at finite temperatures.

$$H_{ex} \propto \int_{V_C(T_{meas})}^{V_{set}(T_{set})} f(V)\,dV$$

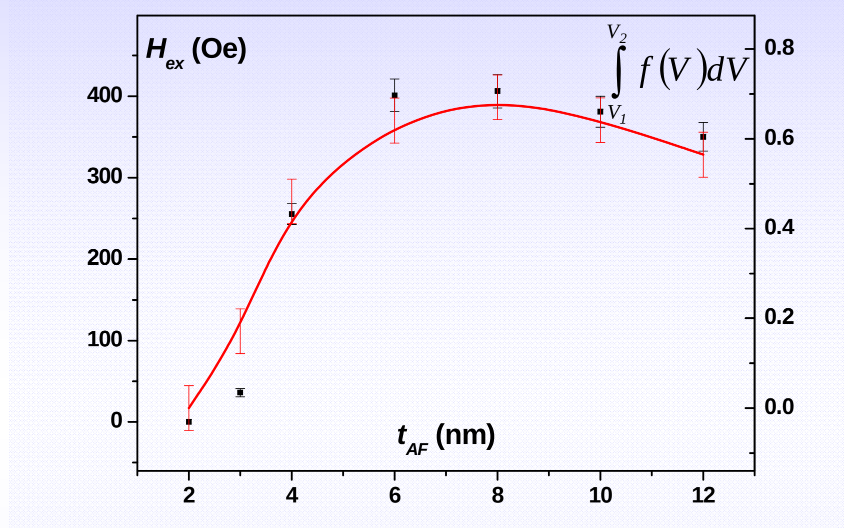
- Grain volume was varied via the *AF* thickness t_{AF} and the grain size.

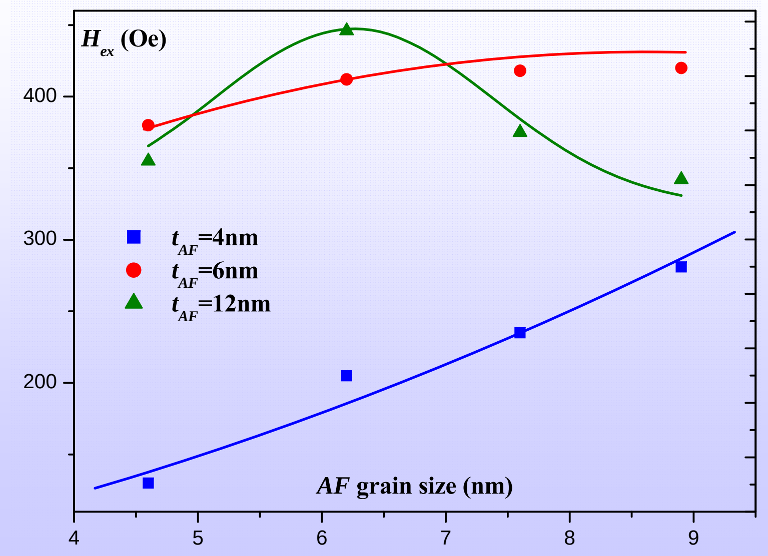




H_{ex} and Grain Volume

- At room temperature it is known that H_{ex} can increase or decrease with t_{AF}.
- This is due to the "stable and set" fraction of the volume distribution changing.
- The grain volume distribution can account for both variations.
- The fit between the integral and $H_{ex}(t_{AF})$ is excellent.
- The fitting is better than that from domain wall models.





G. Vallejo-Fernandez, L.E. Fernandez-Outon and K. O'Grady, J. *Phys. D: Appl. Phys.* **41** 112001 (2008)

Other Predictions

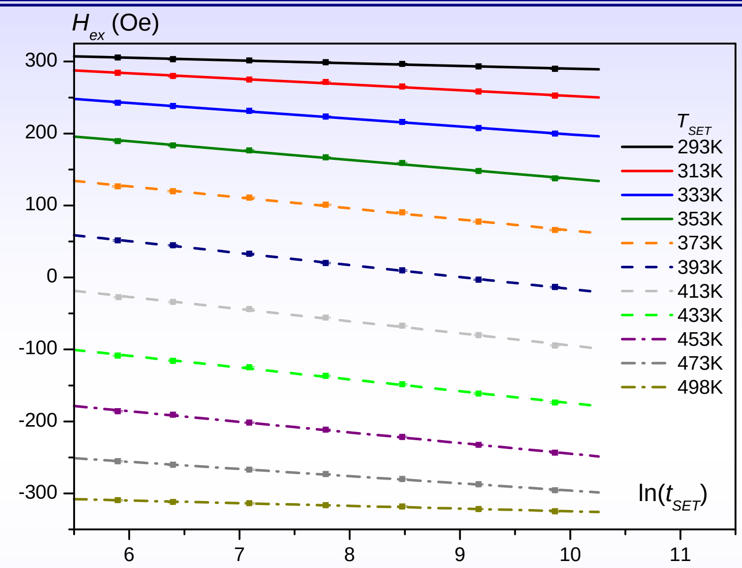
- The fit of the simple grain model to size and thickness curves is not sufficient to validate the model.

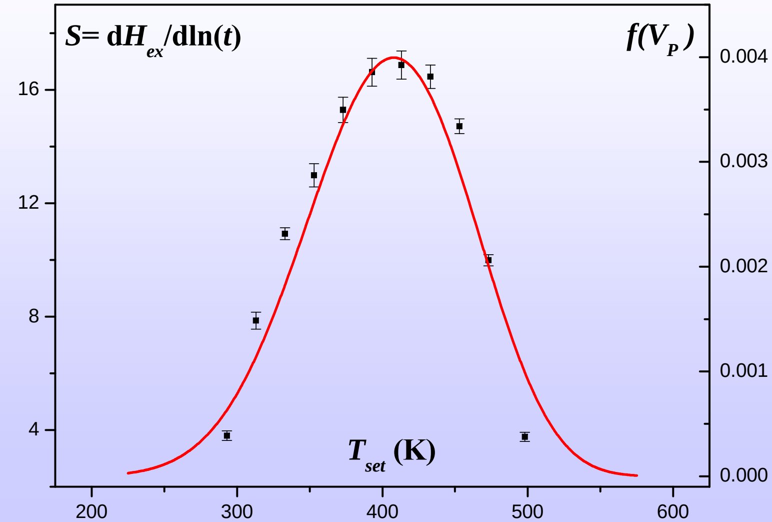
- We have also looked at the setting process because of its importance in applications.

- Because of the form of the time dependence we predict

$$S \propto f\left(\Delta E_C\right)\Big|_T \propto f\left(V_P\right)\Big|_T$$

- Again the simple model works and gives the correct form.





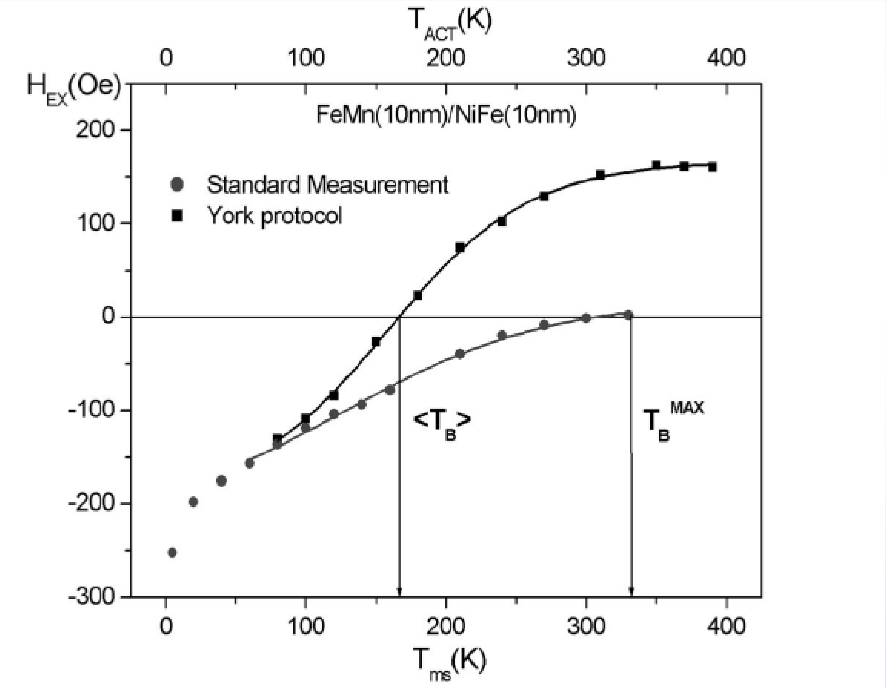
G. Vallejo-Fernandez, N.P. Aley, L.E. Fernandez-Outon and K. O'Grady, *J. Appl. Phys*. **104** 033906 (2008).

Interfacial Spin Order

- We have observed a dramatic increase in H_{ex} at low temperatures.
- As the bulk of the *AF* is stable, this must be due to changes at the interface.

$$H_{ex} \propto C^{*}(?,?)\int_{V_c}^{V_{set}} f(V)\,dV$$

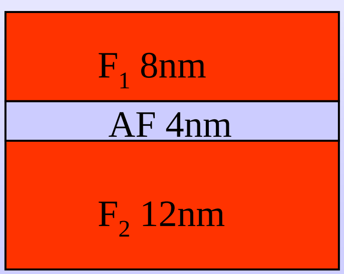
- We know that $C^{*} < 1$ to fit the results.
- The low temperature data indicate a change in order similar to that in spin glass freezing.

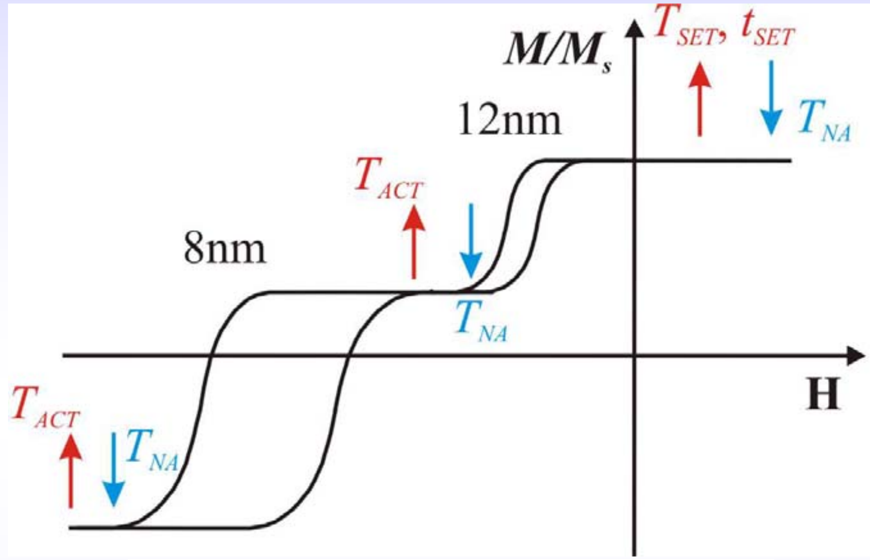


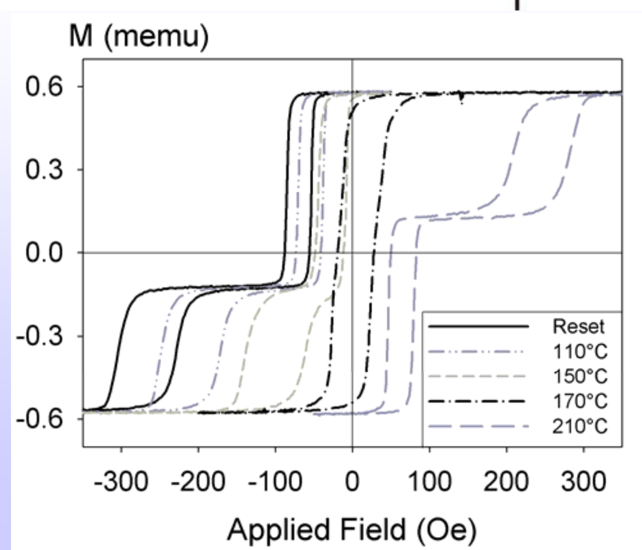
L.E. Fernandez-Outon, G. Vallejo-Fernandez, S. Manzoor, B. Hillebrands and K. O'Grady, *J. Appl. Phys.* **104** 093907 (2008).

Interfacial Spin Effects

- We have done an experiment on trilayer systems with different *F*.
- This systems produces two distinct hysteresis loops.
- The *AF* can be thermally activated as before.
- Both loops shift as the bulk and interfaces are reordered.

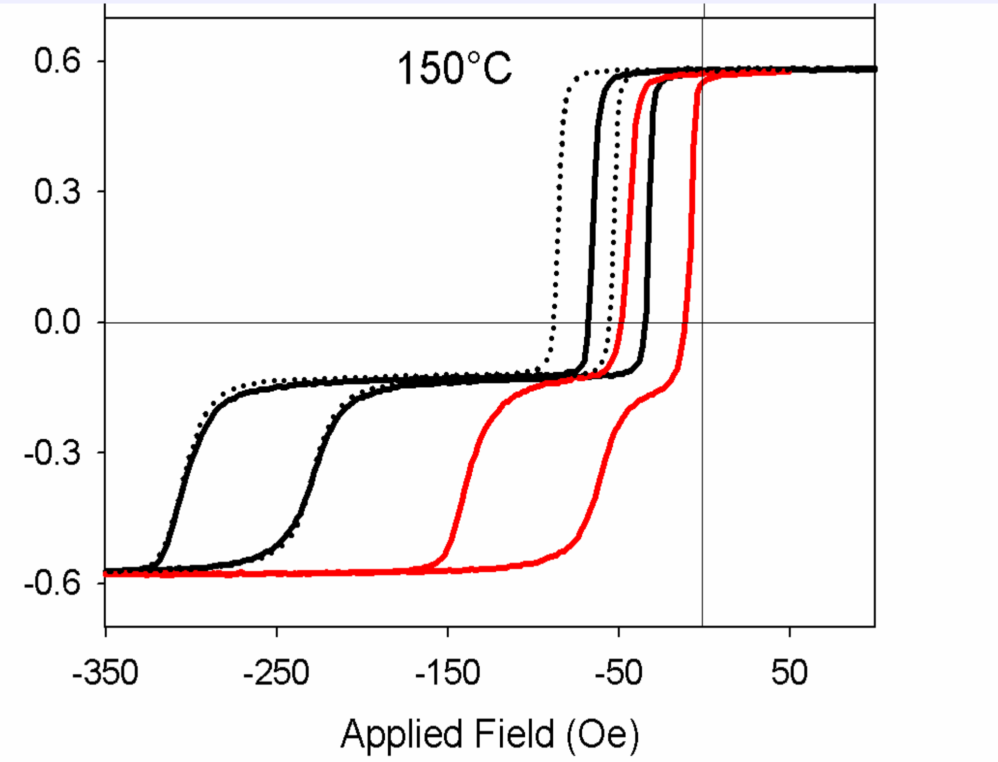






Single Interface Activation

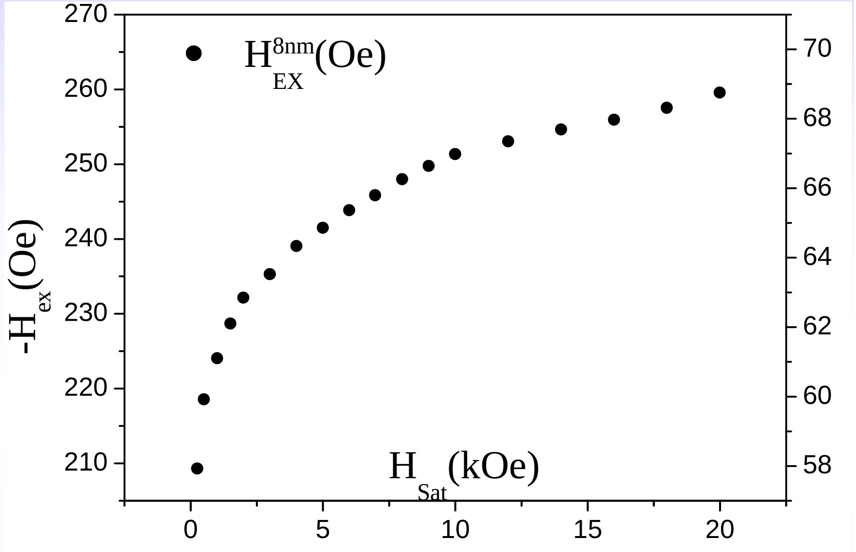
- We can also activate the *AF* at one interface only so that only the 12 nm layer is measured.
- This shifts only the loop for the 12nm layer and to a lesser degree.
- The loop for the 8 nm layer is not moved at all.

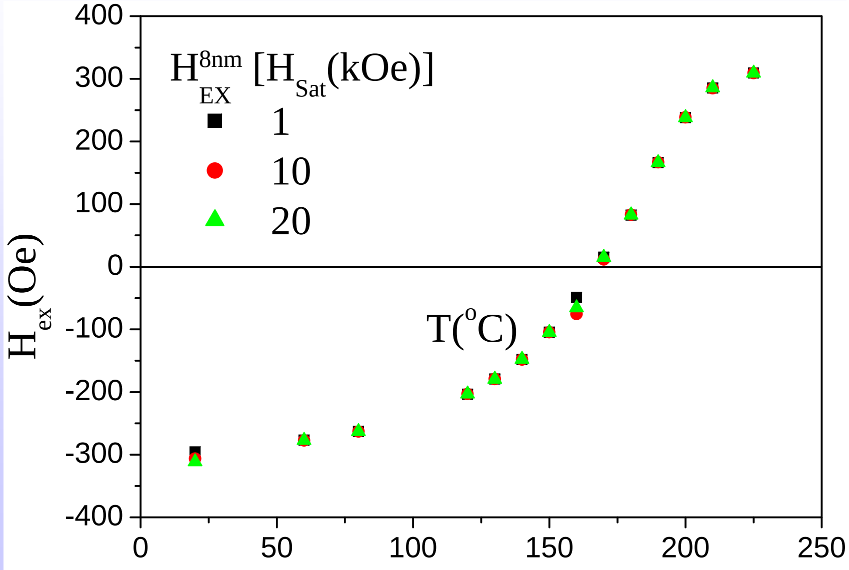


J. D. Dutson, C. Huerrich, G. Vallejo-Fernandez, L. E. Fernandez-Outon, G. Yi, S. Mao, R. W. Chantrell and K. O'Grady *J. Phys. D: Appl. Phys.* **40** 1293 (2007)

Field 'Setting' of Interfaces

- Interfacial spins can also be set by high fields.
- At low fields (*H* < 500 Oe) the exchange field from the F layer aligns the interfacial spins.
- Higher fields increase H_{ex} due to improved interfacial spin alignment.
- We know this is not a bulk *AF* effects since $f(T_B)$ is unaffected.

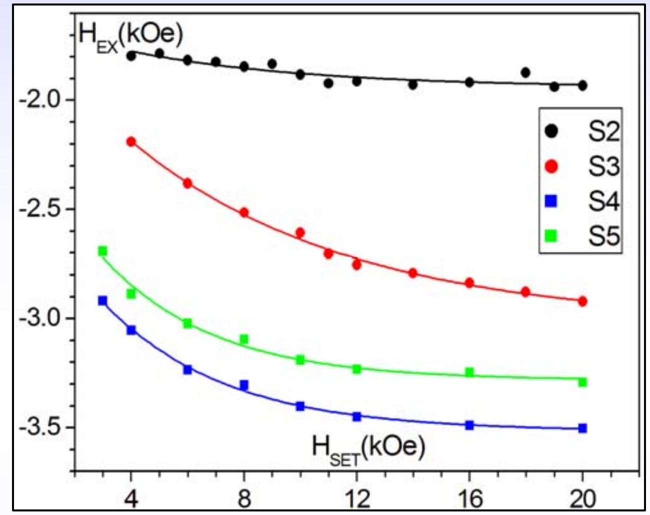




L.E. Fernandez-Outon, G. Valleje-Fernandez and K. O'Grady, *J. Appl. Phys.* **103** 07C106 (2008)

Interfacial Spin Effects

- The state of order of the interfacial spins, represented by $C^*(H,T)$, is altered by the application of H_{set}.
- The F/AF coupling is due to the order of the interfacial spins.
- When the coupling is strong H_{ex} is larger and H_c smaller.
- Increasing H_{set} increases H_{ex} but does not change $\langle T_B \rangle$.
- H_c < 20% H_{ex} for our samples. (3% for S2)



H_{ex} (kOe) measured after setting at H_{set}	SAMPLE			
	S2	**S3**	**S4**	**S5**
H_{ex}(4kOe)	-1.796	-2.188	-3.537	-2.887
H_{ex}(20kOe)	-1.936	-2.922	-3.700	-3.292
ΔH_{ex} (%)	8	37	14	14
H_c(kOe)	0.055	0.540	0.200	0.130
H_C/H_{ex}(%)	2.8	18.5	5.4	3.9

Design of *AF*s

- The width of $f(T_B)$ means that it is difficult to have a stable system that can be set.

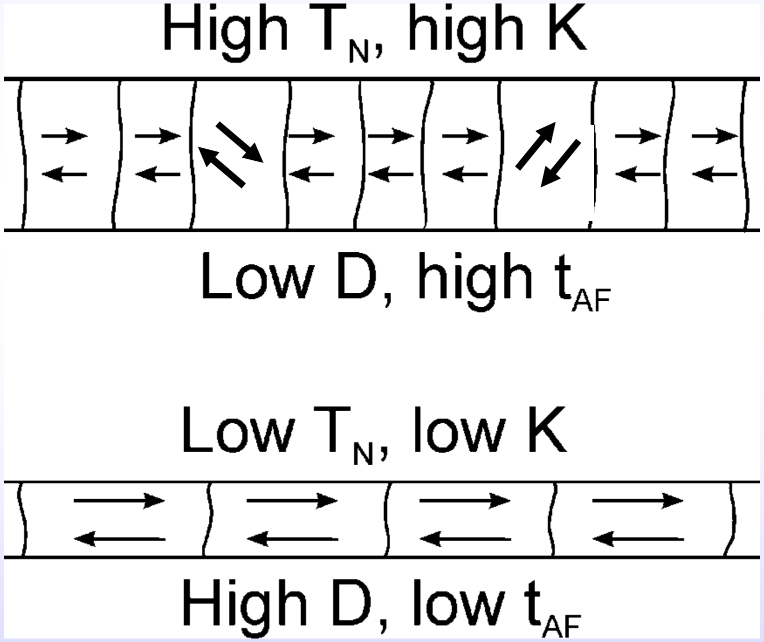
- It would be best to set at:

$$T > T_N$$

- That would lower K and T_B unless large grains were used.

$$\langle T_B \rangle \propto \Delta E = KV(1\text{-}H^*/H^*_K)^2$$

- The ideal would be low T_N and T_B with large grains and low t_{AF}.



Conclusions

- We now have an understanding of the blocking process and interface required to get optimum H_{ex}.

$$H_{ex} = H_{ex}^{i} C^{*}\left(H_{set}, T\right)\int_{V_c}^{V_{set}} f\left(V\right) dV$$

- This is the first formulaic description of exchange bias.
- It is unlikely that a grain size distribution could be made sufficiently narrow to meet the setting and stability requirements.
- This can be overcome by setting above T_N and using big grains to avoid thermal instability.
- It is not yet clear how interfacial spin order can be controlled other than by field setting.