Current-driven domain wall depinning and resonance in notched Permalloy nanowires

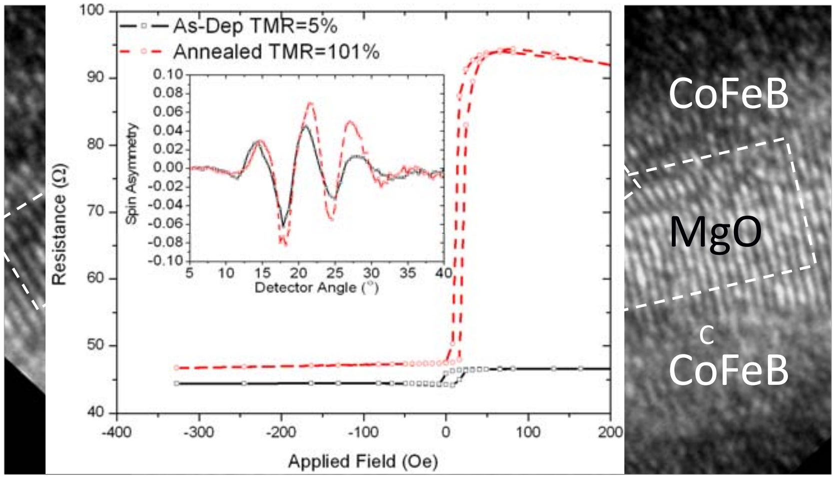
Christopher Marrows

University of Leeds, UK

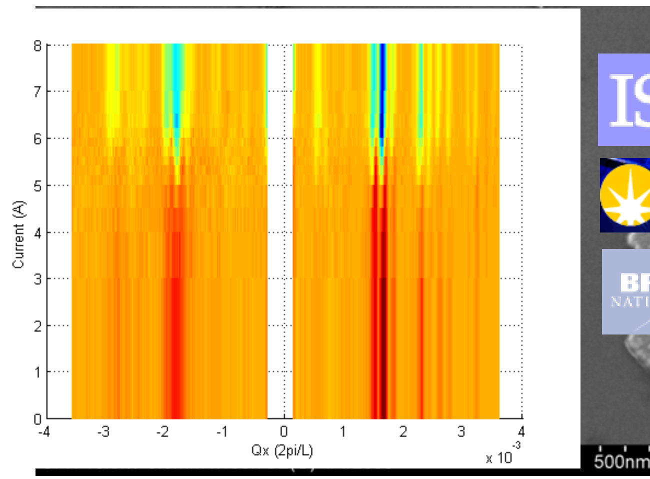
Research in CHM's group

UNIVERSITY OF LEEDS

Magnetic Tunnel Junctions

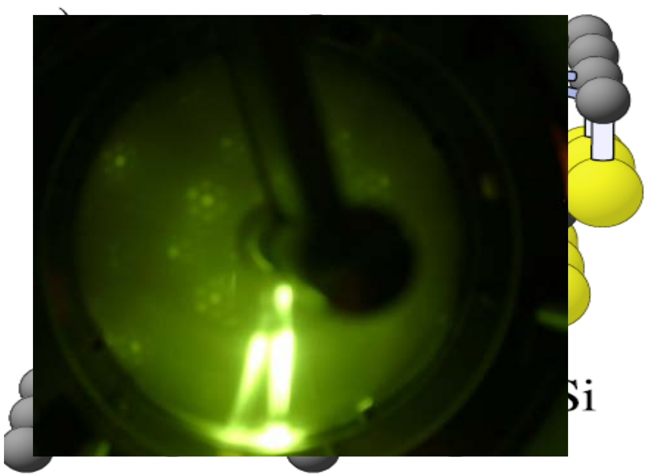


Frustrated Nanomagnet Arrays



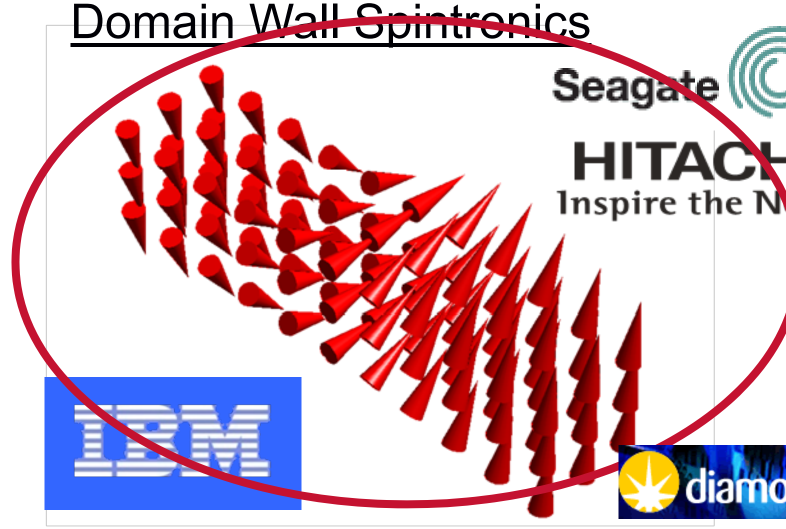
ISIS
diamond
BROOKHAVEN NATIONAL LABORATORY

Epitaxial Graphene



intel

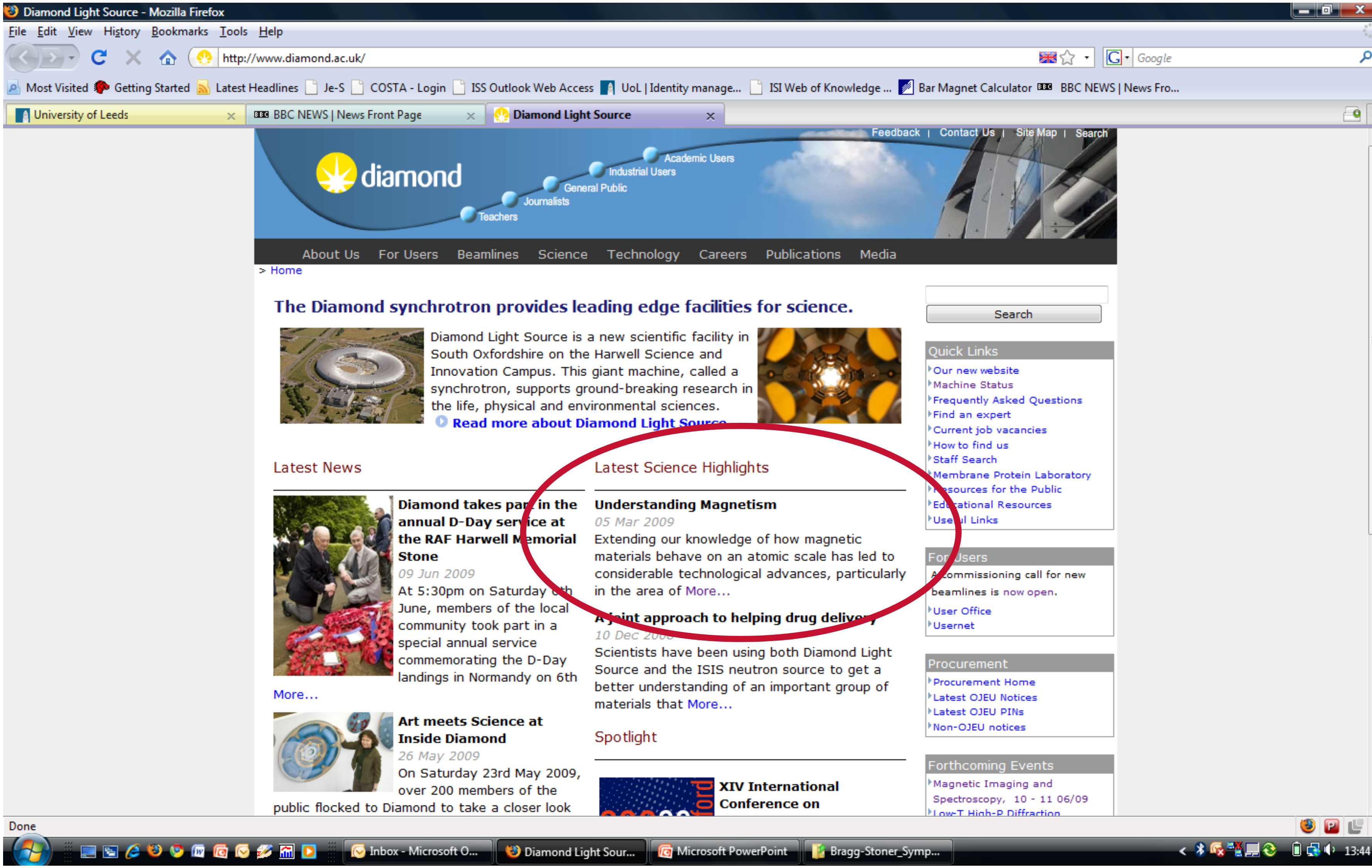
Domain Wall Spintronics



Seagate
HITACHI Inspire the Next
IBM
diamond

Diamond Website

UNIVERSITY OF LEEDS



Acknowledgements

UNIVERSITY OF LEEDS

S. Lepadatu and M. C. Hickey

University of Leeds

A. Vanhaverbeke and R. Allenspach

IBM Rüschlikon

A. Potenza, H. Marchetto, and S. S. Dhesi

Diamond Light Source

D. Atkinson

University of Durham

T. R. Charlton and S. Langridge

ISIS, STFC Rutherford Appleton Laboratory

O. Wessely and D. M. Edwards

Imperial College London

Spin@RT

•- A UK consortium for Room Temperature Spintronics -

EPSRC Engineering and Physical Sciences Research Council

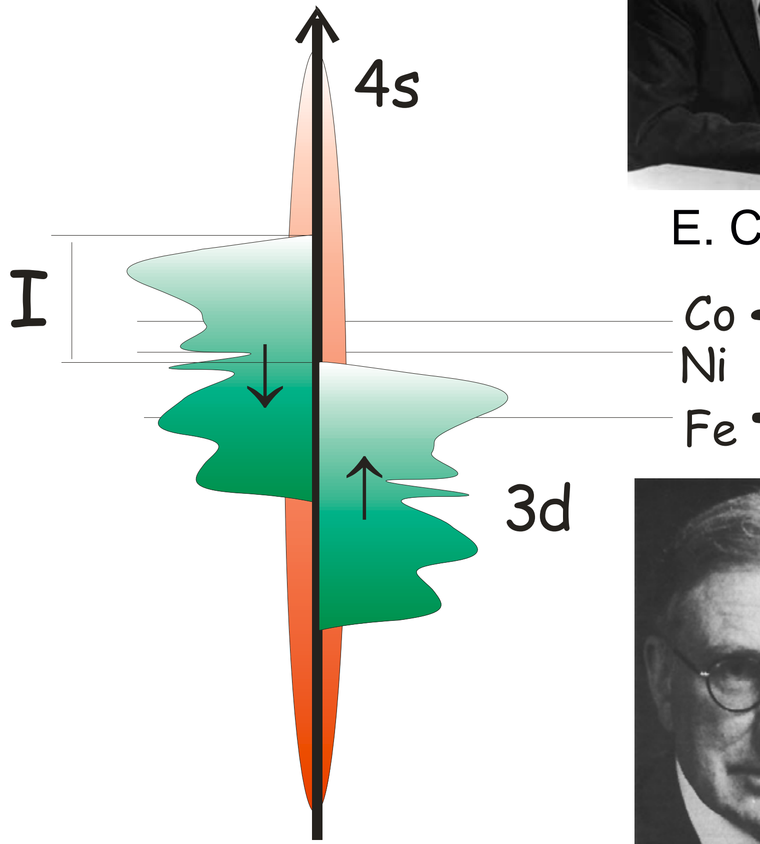
European Science Foundation

SETTING SCIENCE AGENDAS FOR EUROPE

Spin-Polarised Conduction

- Band structure is exchange split: Stoner model (1938).
- Most important idea in spintronics: spin sub-bands conduct in parallel (Mott 1936).
- Different spins have different m^*, v_F, k_F, $g(E_F)$, so different conductivity σ.
- Assume no spin flips (or τ_{sf} very long).
- Polarisation P = spins per charge carrier

$$ID(\epsilon_F) > 1$$



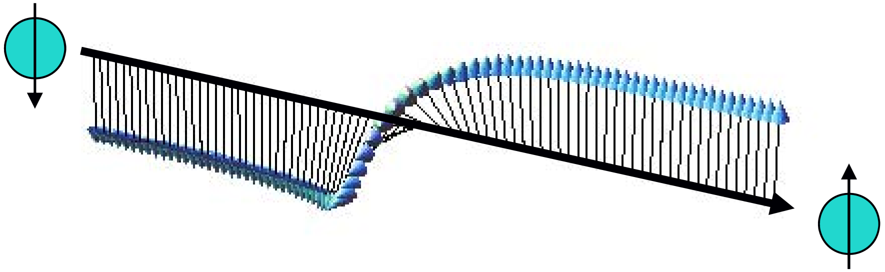
E. C. Stoner

N. F. Mott

Domain Walls

UNIVERSITY OF LEEDS

- Domain walls are where magnetization rotates: topological defects
- Thickness determined by material parameters $$\delta_{\mathrm{W}} = \pi\sqrt{\frac{A}{K}}$$
- Spin-polarised currents interact with domain walls, since quantization axis changes
  - Walls affect current flow: magnetoresistance
  - Current flow affects walls: spin-transfer torque (rate of change of angular momentum)



Review: C. H. Marrows, Advances in Physics **54**, 585 (2005)

Resistance of domain walls

- Magnetisation rotates around electron as it traverses wall

$$\omega_{\mathrm{wall}} = \frac{\pi v_{\mathrm{F}}}{D}$$

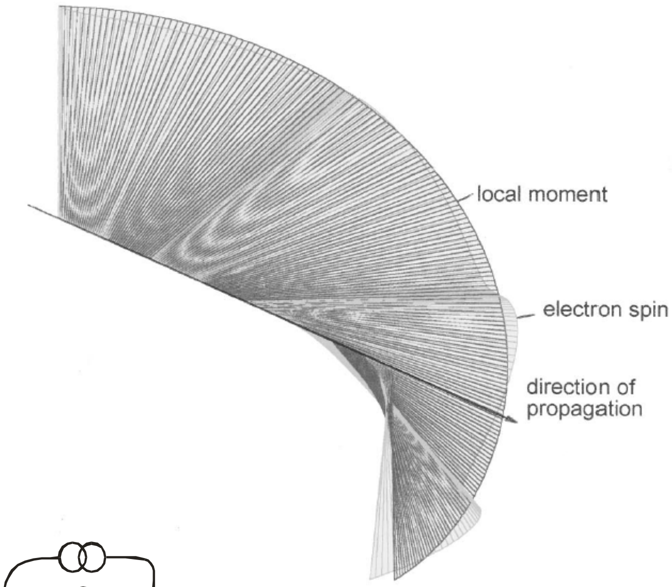
- Spin precesses around magnetisation

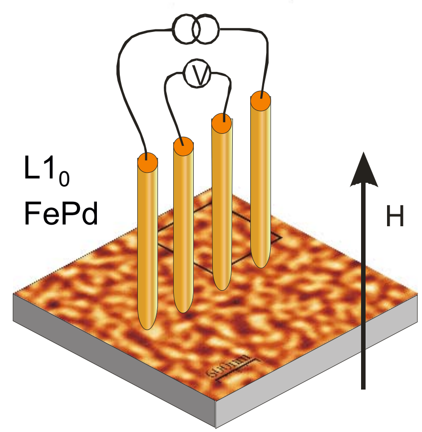
$$\omega_{\mathrm{Larmor}} = \frac{J}{\hbar}$$

- Small departures from adiabaticity lead to mixing of spin channels => higher resistance

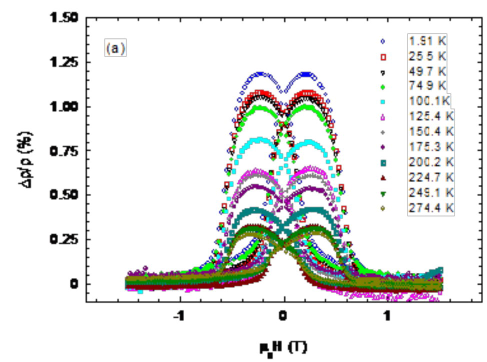
$$\frac{\Delta R}{R} = \frac{2P^2}{(1-P)^2}\left(\frac{2\pi\hbar v_{\mathrm{F}}}{J}\right)^2 \frac{1}{D^2}$$

Viret *et al.*, Phys. Rev. B (1996)





~8 nm wide walls



Marrows and Dalton, Phys. Rev. Lett. (2004)

Spin Transfer Torques

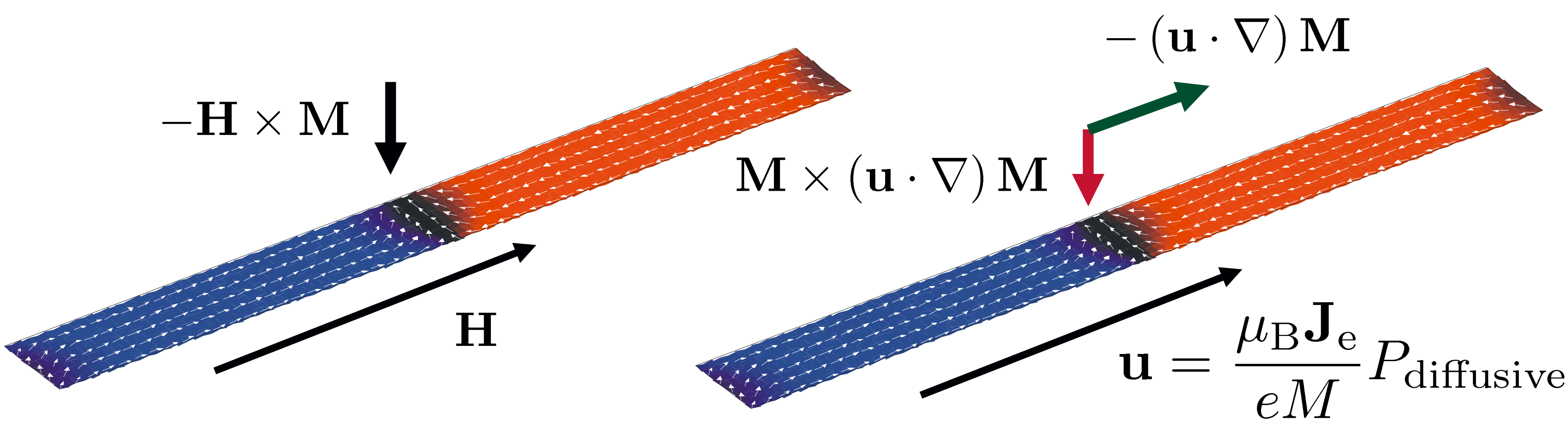
UNIVERSITY OF LEEDS

Modified LLG equation given by A. Thiaville *et al.*, Europhys. Lett. **69** 990 (2005)

$$\frac{d\mathbf{M}}{dt} = -\gamma_0 \mathbf{H} \times \mathbf{M} + \alpha \mathbf{M} \times \frac{d\mathbf{M}}{dt} - (\mathbf{u} \cdot \nabla)\,\mathbf{M} + \beta \mathbf{M} \times (\mathbf{u} \cdot \nabla)\,\mathbf{M}$$

γ_0 = gyromagnetic ratio, α = Gilbert damping constant, β = 'non-adiabaticity' parameter

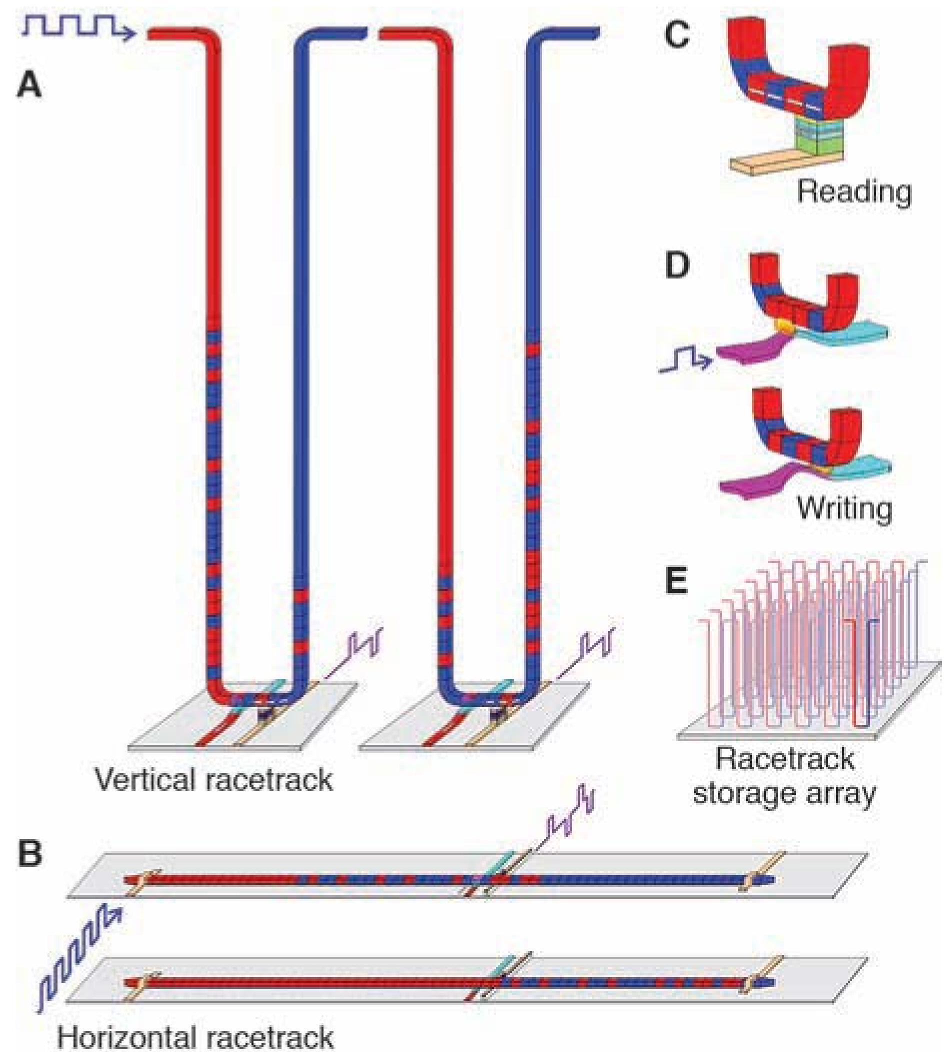
Implemented in OOMMF code from Antoine Vanhaverbeke http://www.zurich.ibm.com/st/magnetism/spintevolve.html



Racetrack memory

UNIVERSITY OF LEEDS

- Combine MTJ reader with CIDW motion to produce 3D ‘storage class’ memory
- Entirely solid-state => intrinsically reliable
- Compete on cost with hard-disks



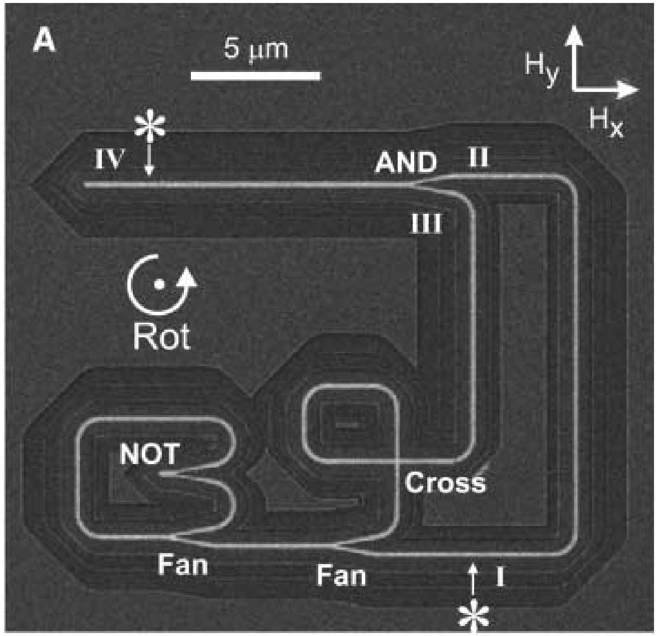
Stuart Parkin, IBM Almaden
Science 320, 190 (2008)

IBM

DW Logic

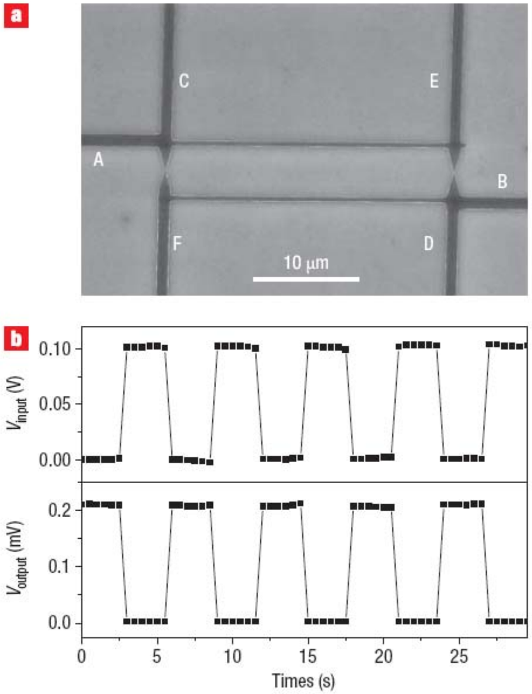
UNIVERSITY OF LEEDS

Field Driven



Allwood et al., Science **309**, 1688 (2005)

Current Driven

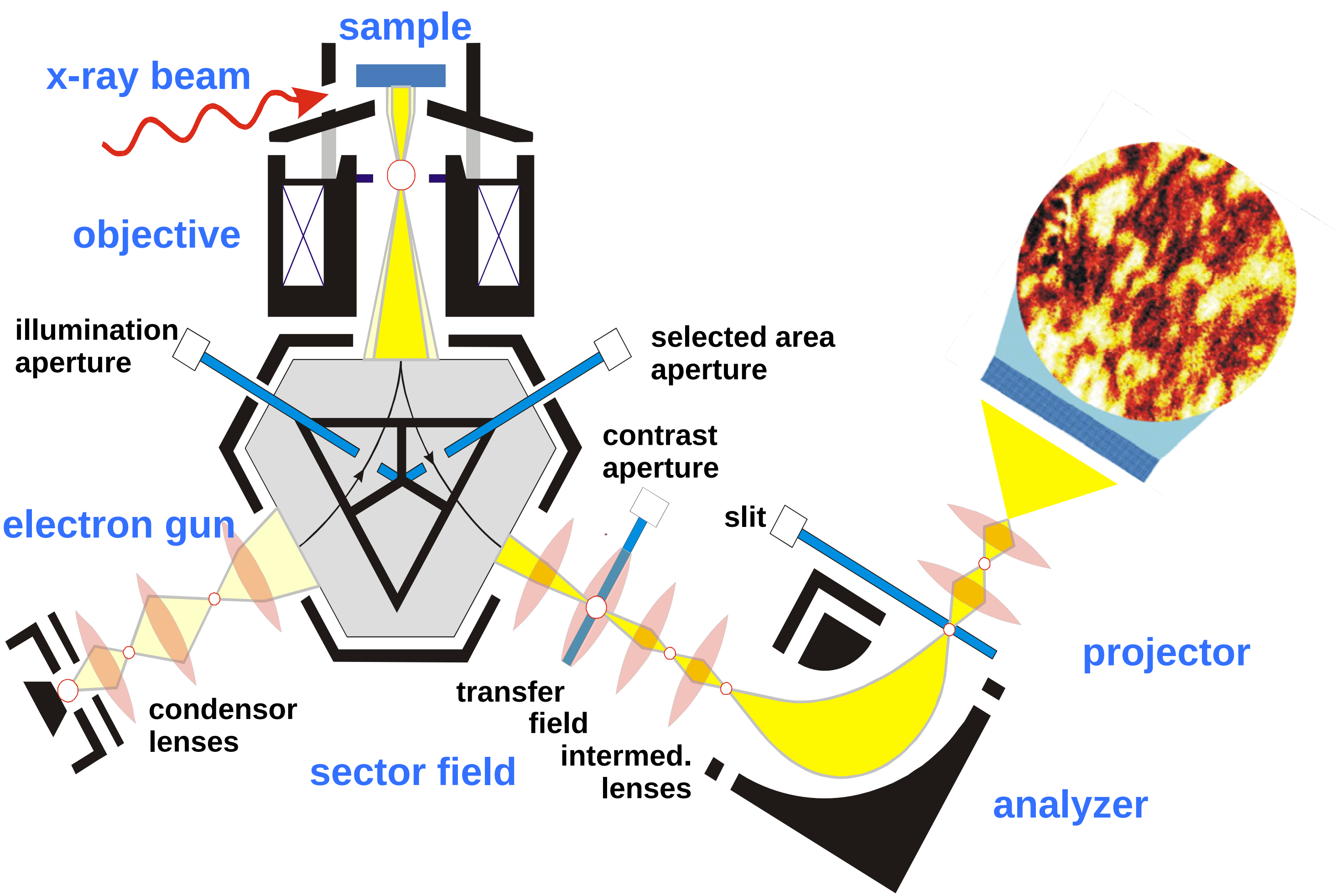


Xu et al., Nature Nanotechnology **3**, 97 (2008)

- Architecture intrinsically combines logic and storage
- Chameleon processor (Compton and Huack, ACM Computing Surveys (2002))

Photoemission Electron Microscopy (PEEM)

UNIVERSITY OF LEEDS

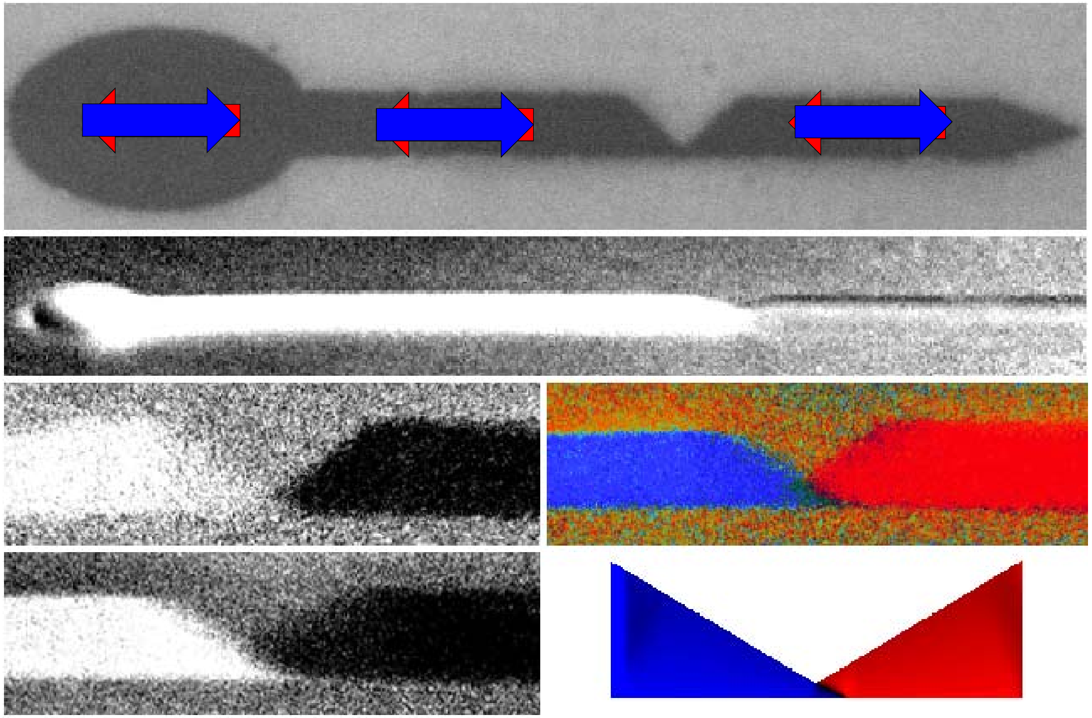


Courtesy of S.S. Dhesi (Diamond Light Source)

Sample Design

UNIVERSITY OF LEEDS

Wall nucleates in elliptical injection pad → Wall pins in patterned notch → Wall annihilates at pointed end



SEM

XMCD PEEM

Raw PEEM — Vector Map

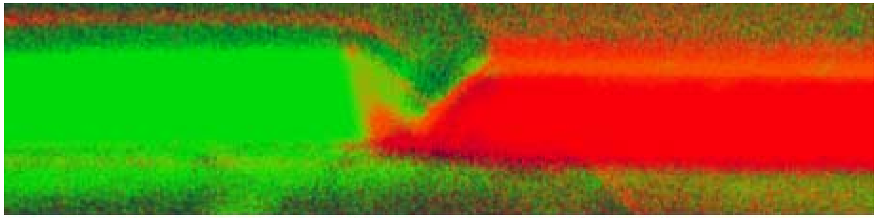
Raw PEEM — Simulation

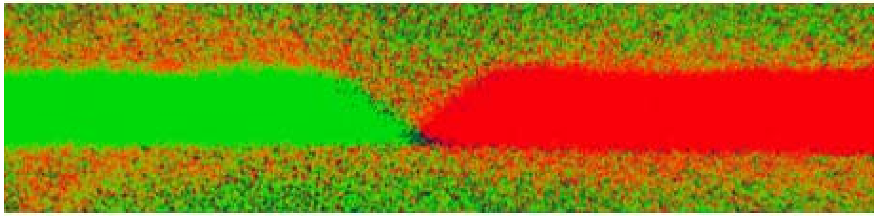
Typical injection fields: 10-15 Oe   Typical depinning fields: 15-20 Oe

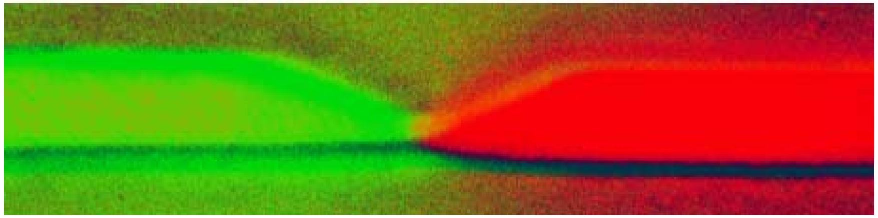
Electron beam lithography, sputter ~20 nm Permalloy, 1-2 nm Al or Au cap, lift off

XMCD PEEM & Micromagnetics

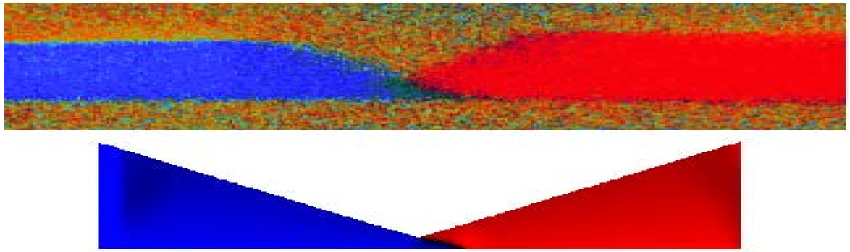
UNIVERSITY OF LEEDS







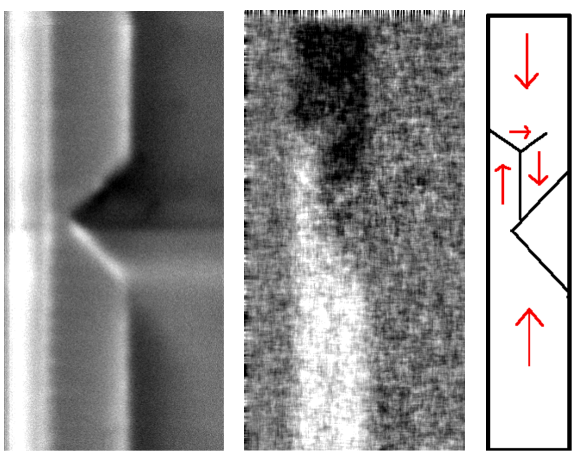
- **2µm long notch** : vortex domain wall pinned in one side of the notch
- **3µm long notch** : vortex domain wall pinned close to centre of notch
- **5µm long notch** : domain wall pinned close to centre of notch



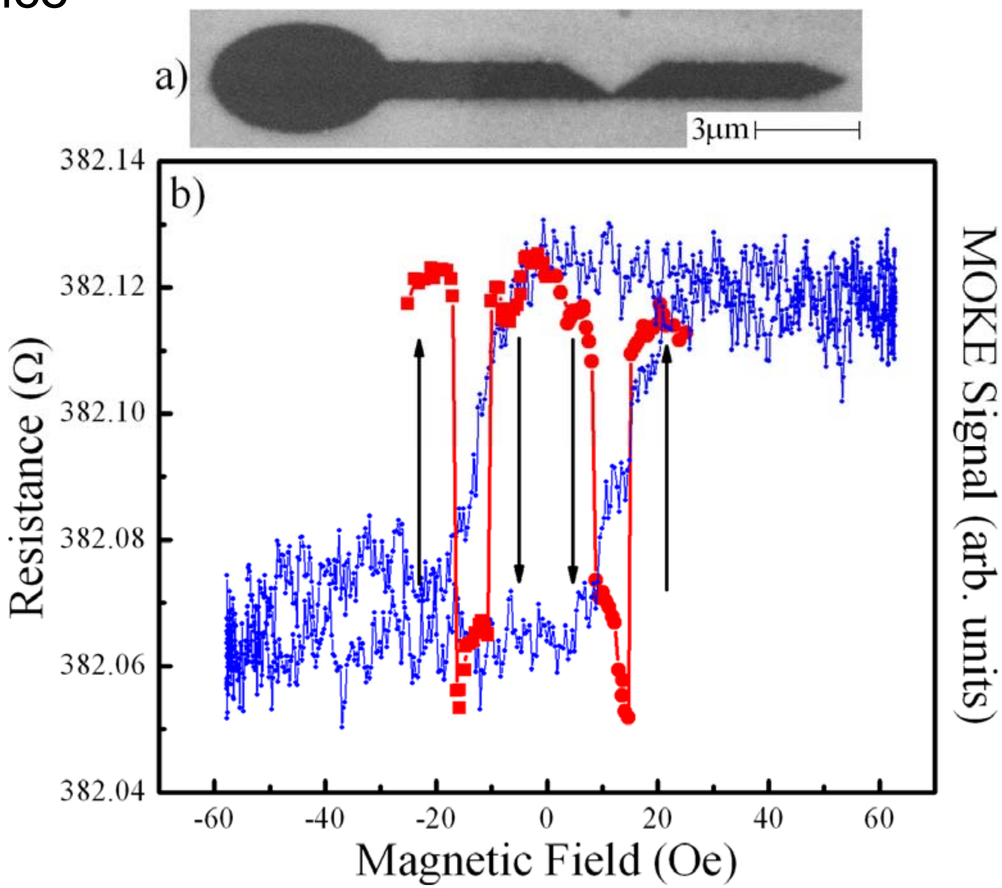
- Micromagnetic simulation of domain wall pinning using OOMMF – vortex domain wall introduced in left hand side of notch and system left to relax in a 10Oe field

Longitudinal MR

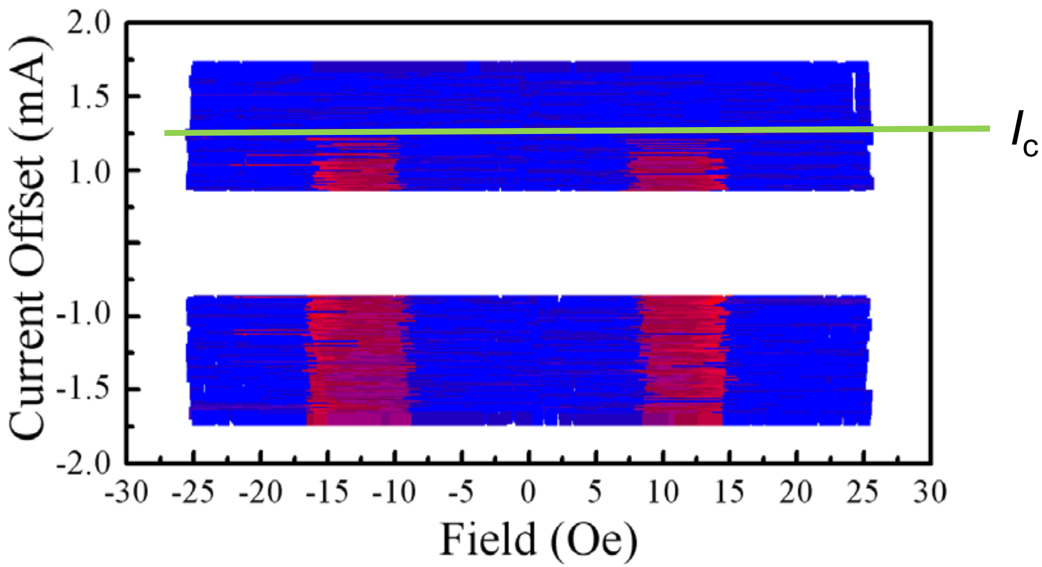
- Anisotropic magnetoresistance can be used to detect
  - Entry of wall into notch
  - Compression of wall (reversible)
  - Depinning of wall (irreversible)



SEMPA



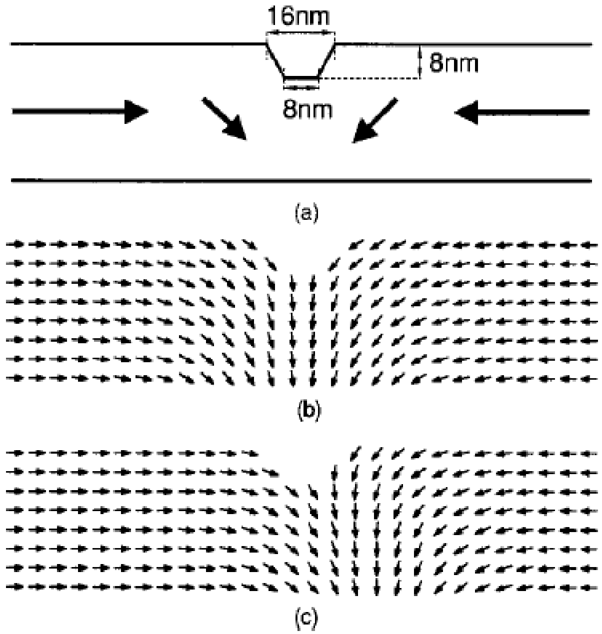
Current-Induced Domain Wall Depinning

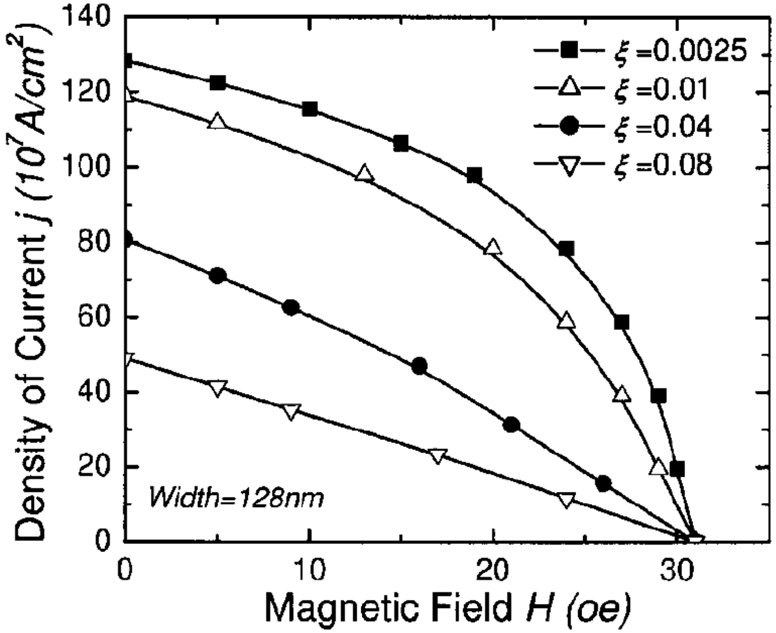


- Longitudinal MR measurements as a function of dc current offset and normalized
- Wall is not pinned above a critical dc current I_c
- DW pinning suppression in one direction only – rules out Joule heating as cause

Field-Current Depinning Boundary

UNIVERSITY OF LEEDS



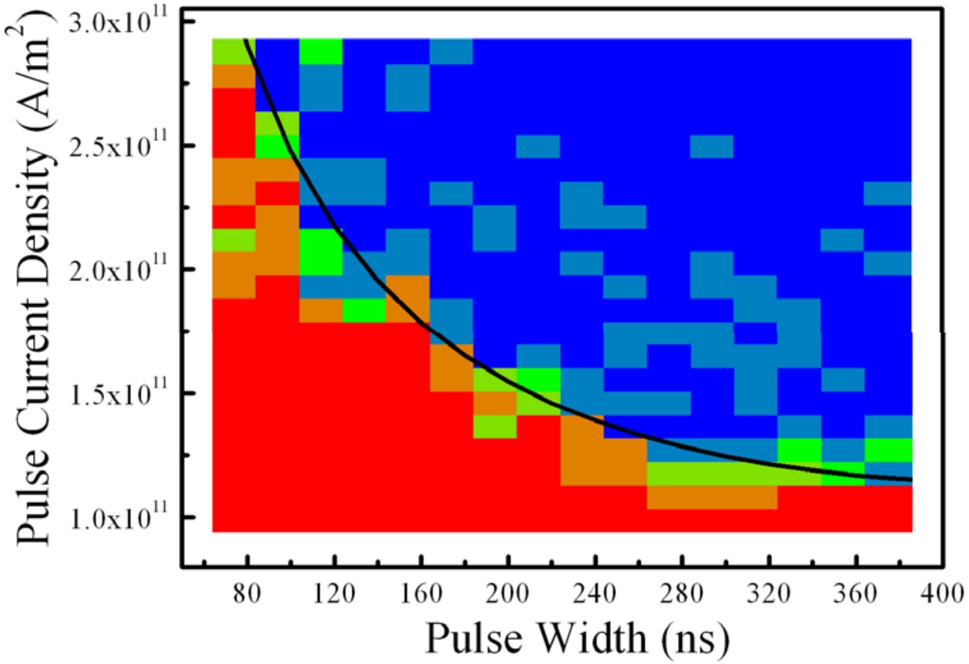


- Depinning boundary as a function of field
- Shape depends on strength of non-adiabatic 'field-like' term
- Nonadiabaticity parameter, $\xi = \beta$, obtained by curve-fitting results from micromagnetics simulations.

J. He, Z. Li, S. Zhang, J. Appl. Phys. 98, 016108 (2005)

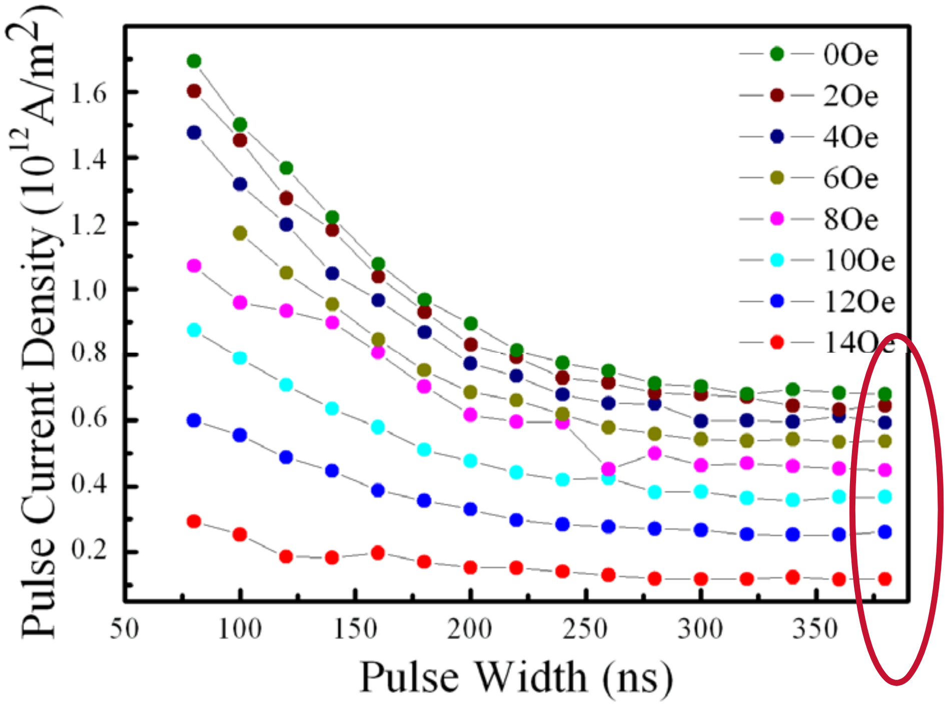
Pulsed Current Measurements

UNIVERSITY OF LEEDS



- DW depinning probability map at 14 Oe field for a 3 μm length notch
- Threshold current density increases monotonically with decreasing pulse width

Experimental Depinning Boundaries



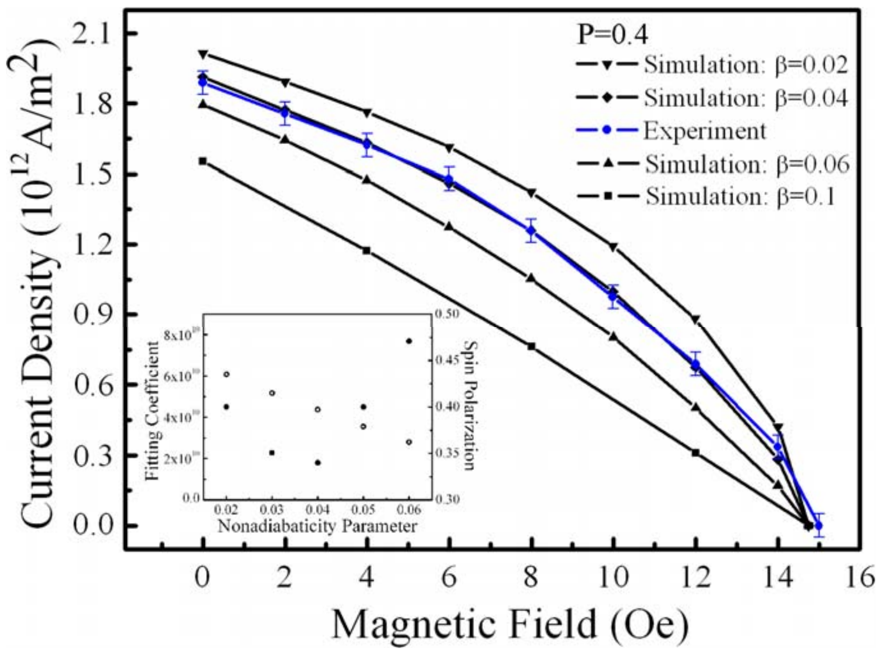
$$\Phi = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right]$$

J_c roughly independent of duration

- Depinning boundaries obtained as a function of longitudinal field
- Critical current density values increase with decreasing magnetic field
- Mean critical current values obtained by curve fitting using the cumulative Gaussian distribution function

Simulated Depinning Boundaries

UNIVERSITY OF LEEDS



- Micromagnetic simulations including the adiabatic and nonadiabatic spin torque terms in the LLG equation (code from Antoine Vanhaverbeke at IBM, http://www.zurich.ibm.com/st/magnetism/spintevolve.html)
- Starting state as obtained from XMCD imaging

$$\frac{d\vec{M}}{dt} = -|\gamma|\vec{H}_{eff}\times\vec{M} + \alpha\vec{M}\times\frac{d\vec{M}}{dt} + u\vec{M}\times(\vec{M}\times\frac{\partial\vec{M}}{\partial x}) + \beta u\vec{M}\times\frac{\partial\vec{M}}{\partial x}$$

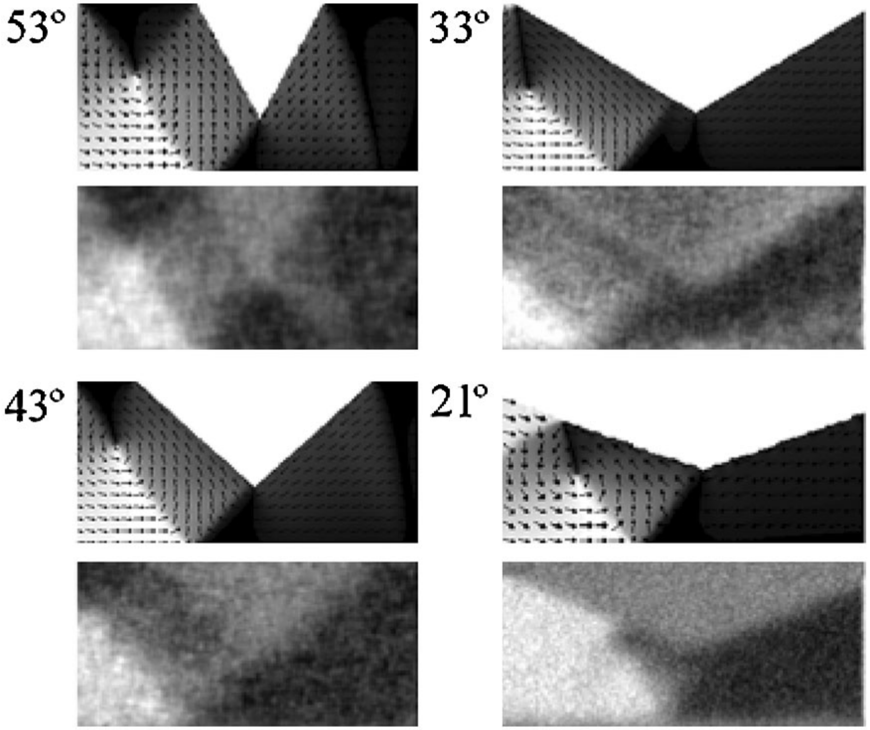
- Experimental depinning boundary as a function of field compared with simulated depinning boundaries for different values of β – best fit gives **β = 0.040 ± 0.005, P = 0.40 ± 0.02.**
- Finite temperature effects : reduction of spin-torque efficiency with increasing temperature [1] and thermal activation effects leading to reduction of critical currents and depinning fields [2]
- Used α = 0.02, so β ≠ α [3]

[1] M. Laufenberg et al., Phys. Rev. Lett. 97, 046602 (2006)
[2] P. Dagras et al., J. Phys. D: Appl. Phys. 40, 1247 (2007)
[3] L. Heyne et al., Phys. Rev. Lett. 100, 066693 (2008)

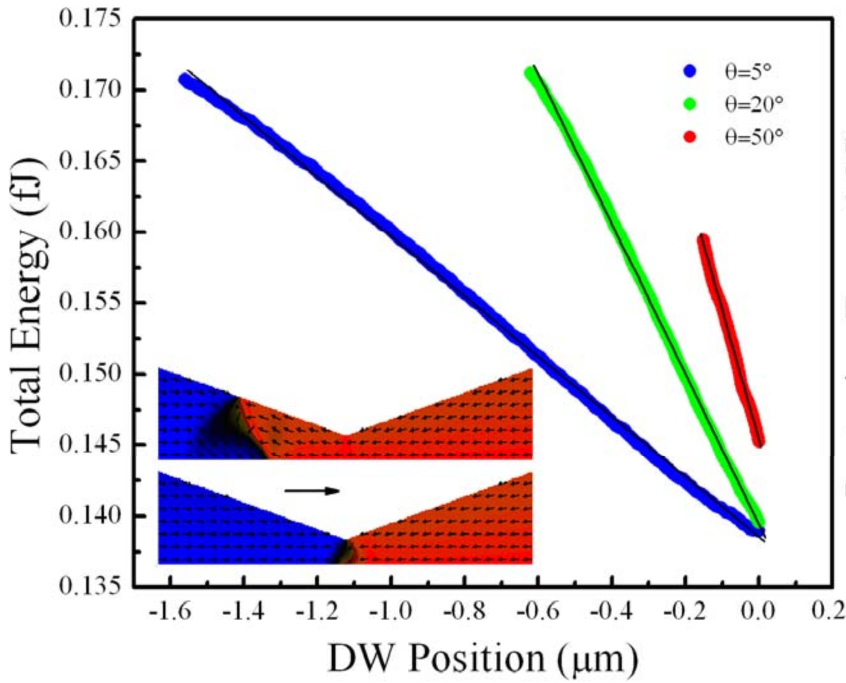
Variable Notch Profile

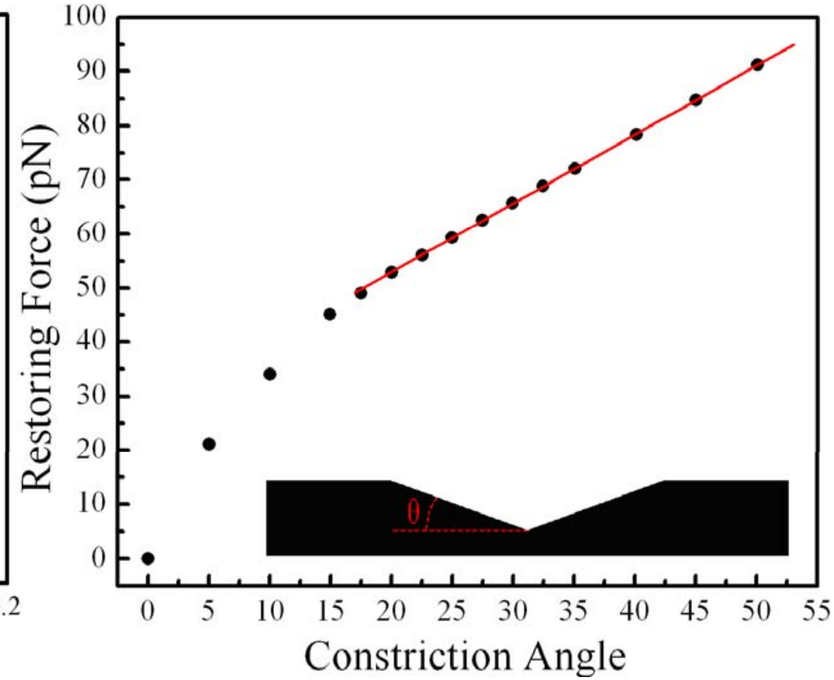
UNIVERSITY OF LEEDS

- Lithographically pattern different notch profiles
- Observe detailed wall structures using SEMPA
- Can reproduce various different wall structures in notches using OOMMF simulations



Micromagnetic Simulations



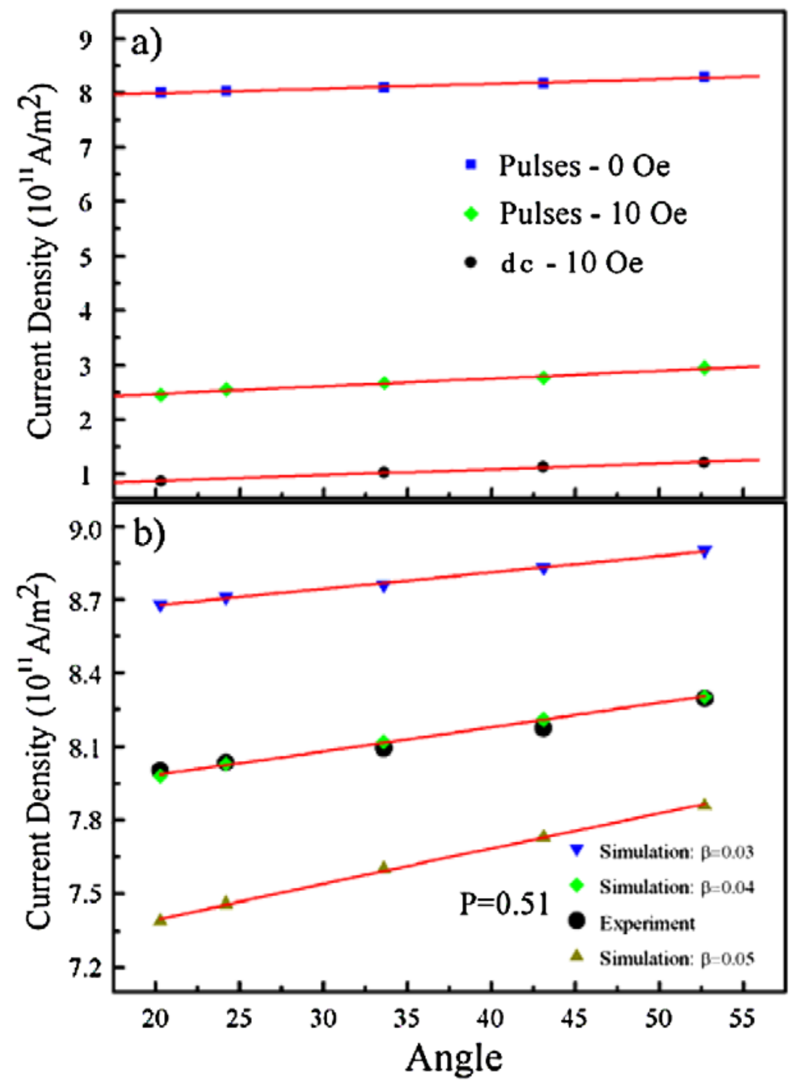


- DW artificially inserted at one end of half-bowtie and system left to relax
- DW relaxes and then slides towards constriction centre due to restoring force of pinning potential gradient $\partial E/\partial x$
- Restoring force calculated as a function of constriction angle - restoring force linear with angle above 17.5°

Current-Induced Domain Wall Depinning

UNIVERSITY OF LEEDS

- Apply current continuously
  - $J_c \sim 10^{11}$ A/m^2
- Apply current for 380 ns at field
  - $J_c \sim 2.5\times10^{11}$ A/m^2
- Apply current for 380 ns at zero field
  - $J_c \sim 8\times10^{11}$ A/m^2
- All show linear dependence of J_c on notch angle: **control of restoring force**
- Simulations of zero field data in OOMMF (Vanhaverbeke extended version)
- Best fit to zero field data gives β **= 0.040 ± 0.005,** P **= 0.51 ± 0.02**.

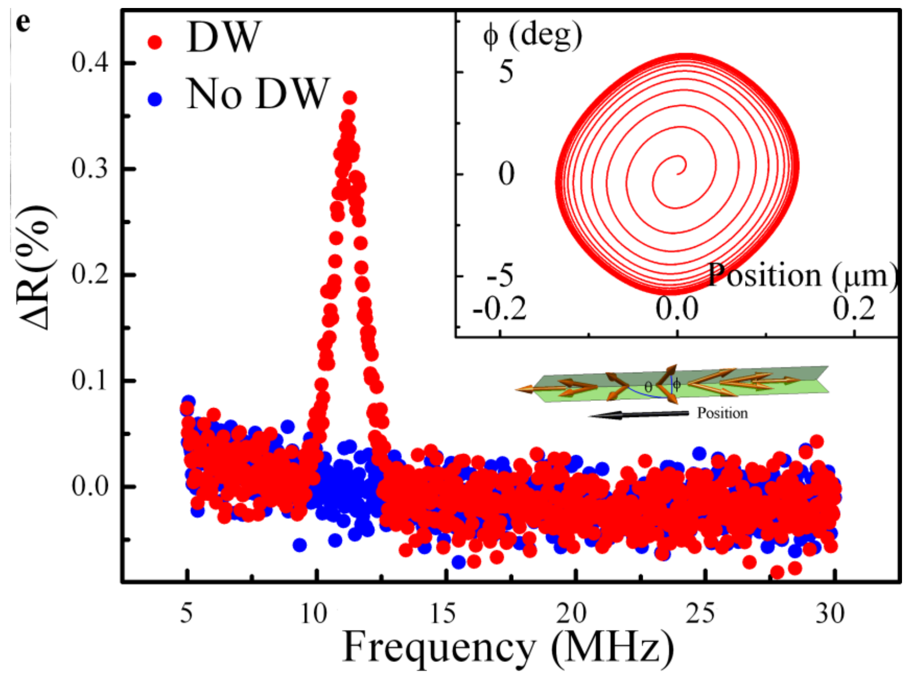


Domain Wall Oscillations

UNIVERSITY OF LEEDS

- Restoring force will always return wall to centre of notch: driven oscillator for ac current (Saitoh et al., Nature 432, 203 (2004)).
- Resonant peak in S_{11} reflection signal for VNA observed when wall is present in centre of notch
- Convert to resistance change: energy dissipated as wall oscillates.
- Derive analytical model from Lagrangian dynmaics.
- Use co-ordinates wall position q and tilt angle ϕ used to model oscillation.
- Obtain and solve equations of motion.

1 μm triangular notch



$$\left(\dot{q} - \alpha\Delta\dot{\phi}\right) S(q) = -\frac{\gamma}{2M_\mathrm{s}}\frac{\partial E}{\partial \phi} + \frac{J(q)\mu_\mathrm{B} P}{eM_\mathrm{s}} S(q)$$

$$\left(\dot{\phi} + \frac{\alpha}{\Delta}\dot{q}\right) S(q) = \frac{\gamma}{2M_\mathrm{s}}\frac{\partial E}{\partial q}$$

$S(q)$ = local wire cross-section; $J(q)$ = local current density; Δ is ϕ-dependent wall width

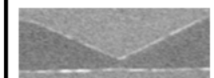
Linear notches

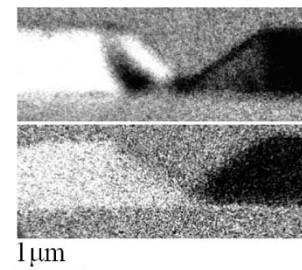
UNIVERSITY OF LEEDS

- Lots of examples of this shape in literature

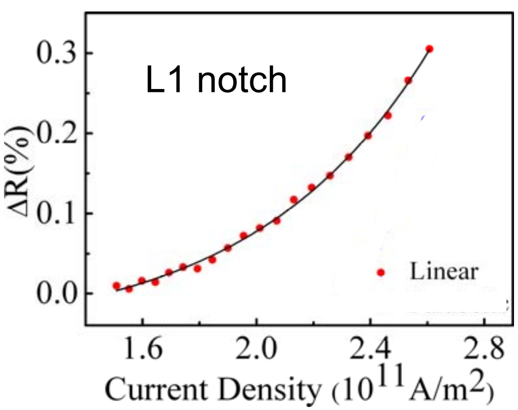
e.g. Bedau et al. Phys. Rev. Lett. 99, 146601 (2007); Phys. Rev. Lett. 101, 256602 (2008); Im et al. Phys. Rev. Lett. **102**, 147204 (2009)

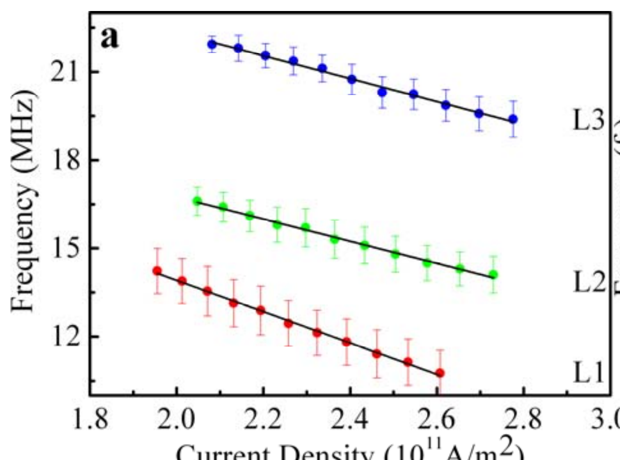
- Amplitude ΔR not linear in current density: threshold observed.

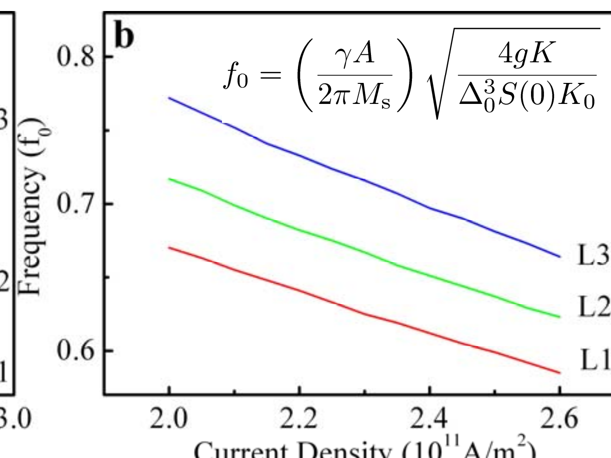
Linear Pinning Potentials : $y = g\|x\|$					
	**L1**	**L2**	**L3**	**L4**	**L5**
g	0.36	0.45	0.6	0.9	1.8



- No resonance observed for vortex wall (L4 and L5).
- Resonant frequency depends on notch angle (restoring force).
- Varies with driving current density: **anharmonic** (theory agrees).

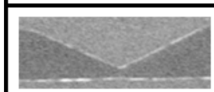
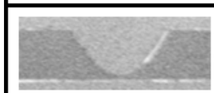


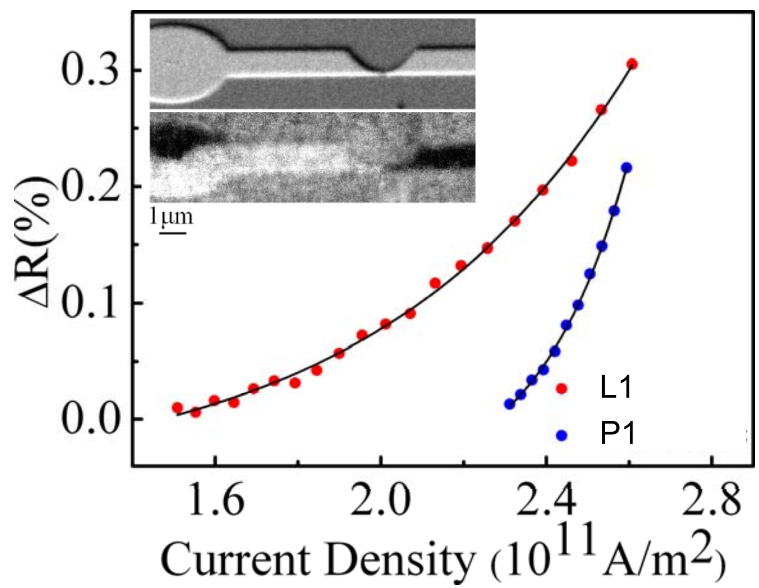




Linear and parabolic notches

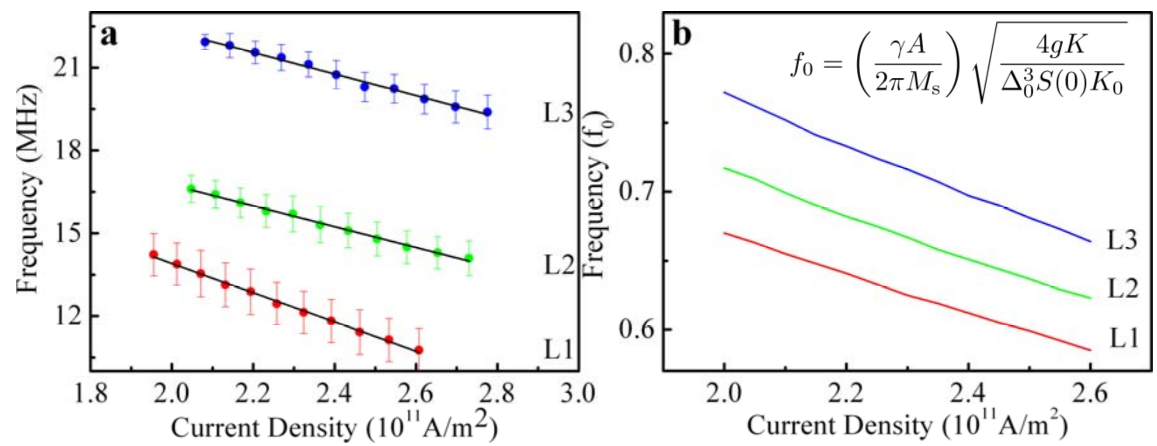
- Need a better notch shape: a parabola would be harmonic if pinning potential given by *S*(*q*).
- Fabricated five more samples.
- SEMPA shows that all five have walls in centre of notch.
- Amplitude ΔR still shows threshold current density.

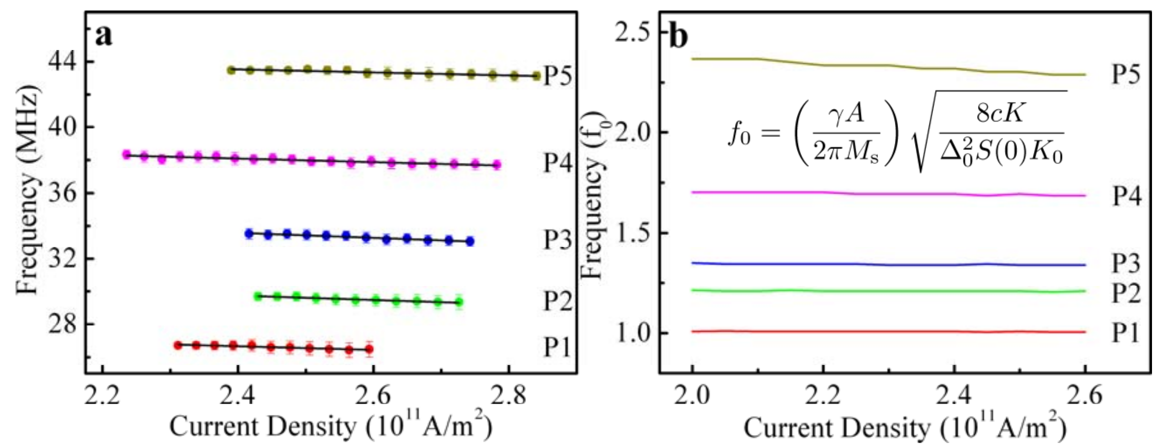
Linear Pinning Potentials : $y = g\|x\|$					
	**L1**	**L2**	**L3**	**L4**	**L5**
g	0.36	0.45	0.6	0.9	1.8
Parabolic Pinning Potentials : $y = cx^2$					
	**P1**	**P2**	**P3**	**P4**	**P5**
$c/10^6$	0.5	0.73	0.91	1.49	3.25



Linear and parabolic notches

- Frequency behaviour much improved: well-defined eigenfrequencies for parabolae.
- Q-factors improve by factor of 2-3 over linear notches.
- Resonant frequency can be engineered by notch shape.
- Good qualitative agreement with theory.





Conclusions

UNIVERSITY OF LEEDS

• Field-current depinning boundary can be used to measure non-adiabatic torque contribution.

- Yields $\boldsymbol{\beta}$ **= 0.040** ± **0.005, *P* = 0.40** ± **0.02** for Permalloy.
- S. Lepadatu *et al.*, Phys. Rev. B **79**, 094402 (2009)

• Depinning current can be engineered by controlling restoring force form geometry.

- Yields $\boldsymbol{\beta}$ **= 0.040** ± **0.005, *P* = 0.51** ± **0.02** for Permalloy.
- S. Lepadatu *et al.*, Phys. Rev. Lett. **102**, 127203 (2009)

• Eigenfrequency of pinning potential determined by shape and steepness of notch.

- Could be used to address different notches along a single wire in e.g. a memory array.