Depinning transition for domain walls with an internal degree of freedom

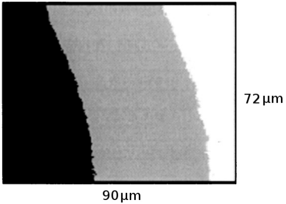
Vivien Lecomte[1], Stewart Barnes[1,2], Jean-Pierre Eckmann[3], Thierry Giamarchi[1]

[1]Département de Physique de la Matière Condensée, Genève
[2]Physics Department, University of Miami
[3]Département de Physique Théorique et Section de Mathématiques, Genève

Nancy – 14th May 2009

An example

Interfaces in magnetic films



from Lemerle *et al.*, PRL **80** 849 (1998)

Outline

1. Interface Physics
   - Systems
   - Depinning transition
   - Experiments
2. Depinning with internal degree of freedom
   - Modelisation
   - Dynamics

Interfaces

Large range of physical scales

- magnetic/ferroelecric domain walls
- growth interfaces
- contact line
- crack propagation

Common underlying description?

- Statics

  fluctuations, roughness

- Non-equilibrium dynamics

  motion of the interface

- Nature, role of disorder

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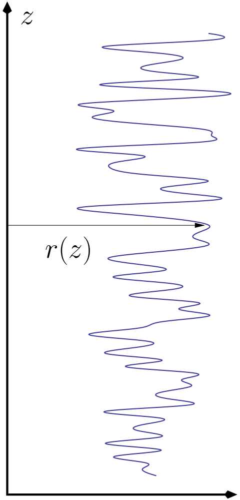
Disordered elastic systems

- Elasticity: tends to flatten the interface

$$\frac{c}{2}\int dz\,\left(\nabla r(z)\right)^2$$

- Disorder: tends to bend it

$$\int dz\,V\left(r(z),z\right)$$



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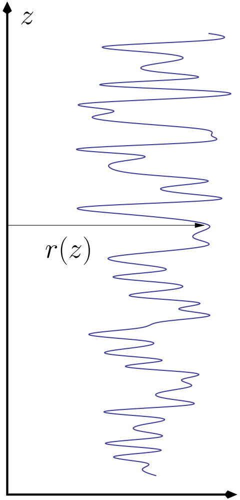

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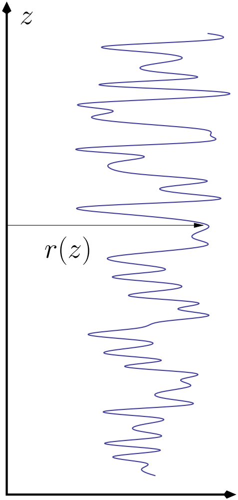

Competition btw “order” and “disorder”

Is $r(z)$ containing enough?

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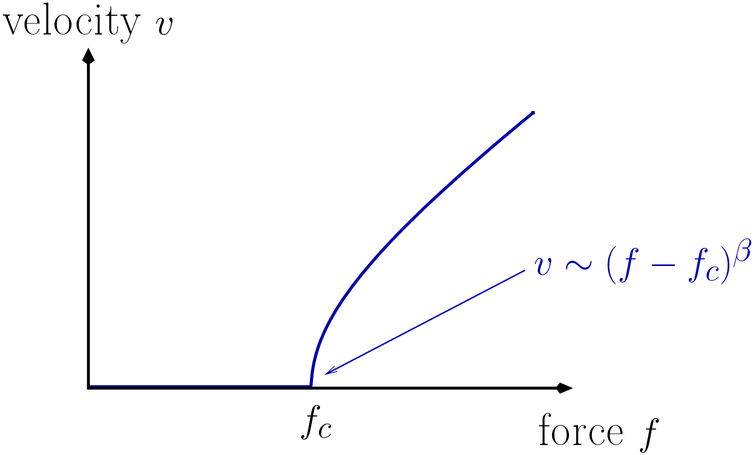
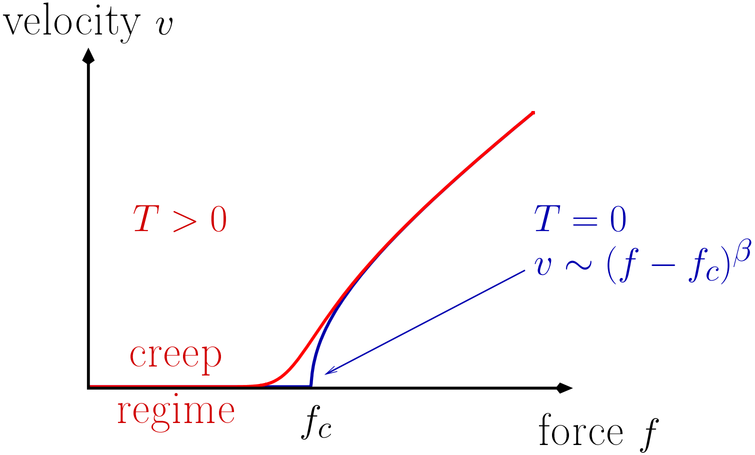
$\longrightarrow$ Have a look to the dynamics in simple examples.

Depinning transition @ zero temperature



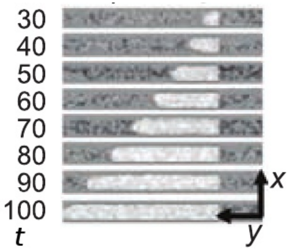
Depinning transition @ finite temperature



Comparison with experiment: ferromagnetic wire

$$v(f) \sim \exp\left[-\frac{U_c}{T}\left(\frac{f_c}{f}\right)^{\mu}\right] \qquad \text{(creep)}$$

	Field drive		Current drive	
	μ^*	σ^*	μ	σ
Experiment	1.2 ± 0.1	1.4 ± 0.1	0.33 ± 0.06	2.0 ± 0.2
Theory	1.0	1.5	0.5	1.25



from Yamanouchi *et al.*, Science **317** 1726 (2007)

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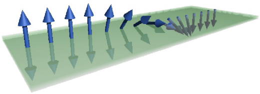
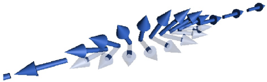
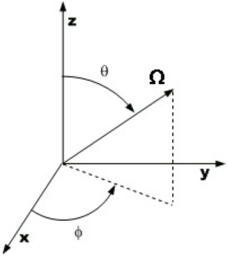
Bulk model







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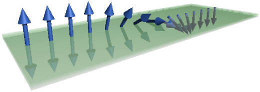
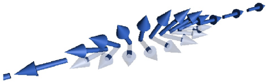
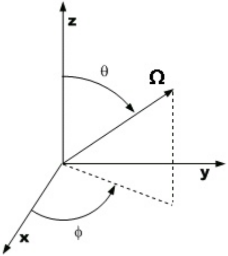




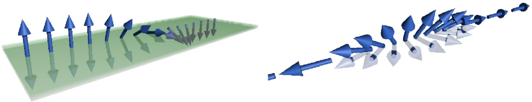
- Bulk energy

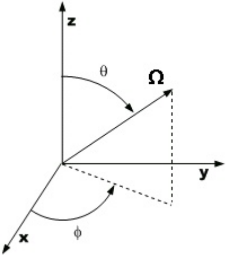
$$E = \int d^d x \left\{ J \left[(\nabla\theta)^2 + \sin^2\theta (\nabla\phi)^2 \right] + K \sin^2\theta + K_\perp \sin^2\theta \cos^2\phi \right\}$$

- Equation of motion

$$(\partial_t + v_s \cdot \nabla)\Omega = \Omega \times \left(\frac{\delta E}{\delta \Omega} + f + \eta\right) - \Omega \times \left(\alpha\partial_t + \beta v_s \cdot \nabla\right)\Omega$$

Bulk model





- Rigid wall approximation

$$\alpha\partial_t r - \partial_t\phi = \overbrace{-\cos\kappa r}^{\text{pinning}} + \overbrace{f}^{\text{external}} + \eta_1$$

$$\alpha\partial_t\phi + \partial_t r = -\frac{1}{2}K_\perp \sin 2\phi + \eta_2$$

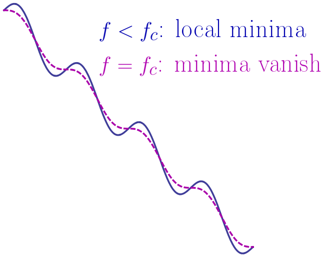
- Effective model:

Position $r(t)$ coupled to phase $\phi(t)$.

Depinning @

Large $K_\perp$: ϕ decouples from r

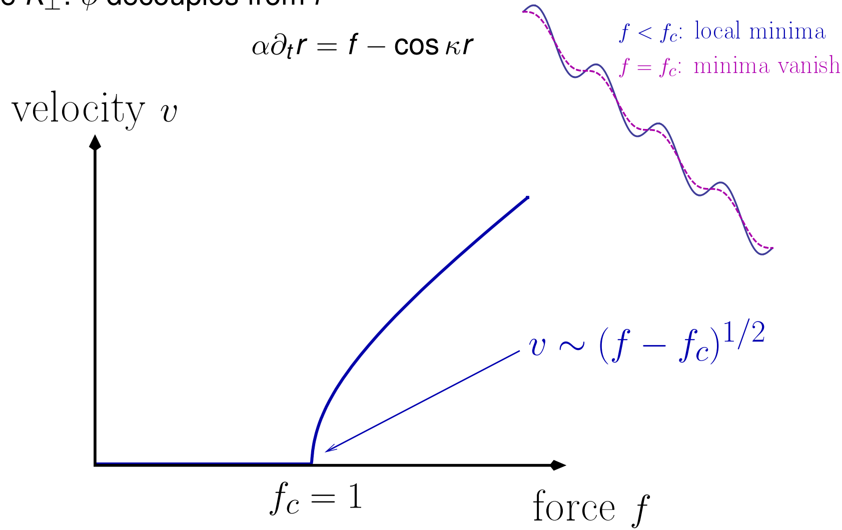
$$\alpha \partial_t r = f - \cos \kappa r$$



Depinning @ zero temperature

Large $K_\perp$: ϕ decouples from r

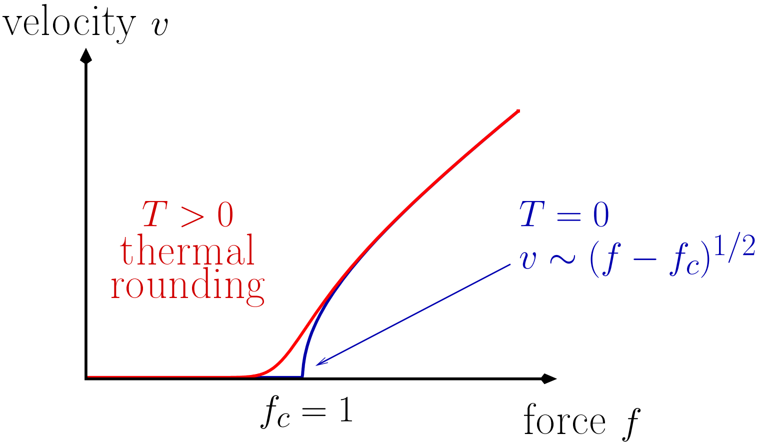
$$\alpha \partial_t r = f - \cos \kappa r$$



Depinning @ finite temperature

Large $K_\perp$: ϕ decouples from r

$$\alpha \partial_t r = f - \cos \kappa r + \eta$$



Depinning @ zero temperature

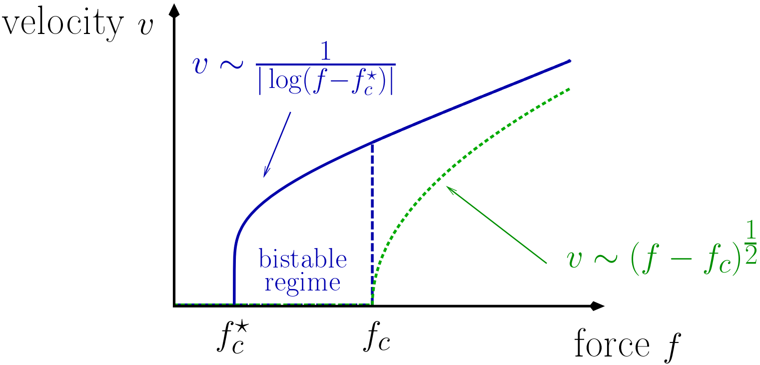
Smaller $K_\perp$: ϕ matters

$$\alpha\partial_t r - \partial_t\phi = f - \cos\kappa r$$
$$\alpha\partial_t\phi + \partial_t r = -\frac{1}{2}K_\perp \sin 2\phi$$

Depinning @ zero temperature

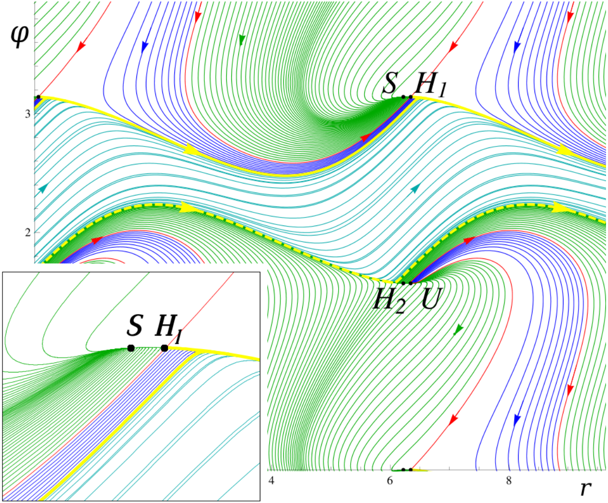
Smaller $K_\perp$: ϕ matters

- Dramatic change in the depinning law: $v \sim \frac{1}{|\log(f - f_c^\star)|}$



- Depinning at lower critical force: $f_c^\star < f_c$
- Bistability

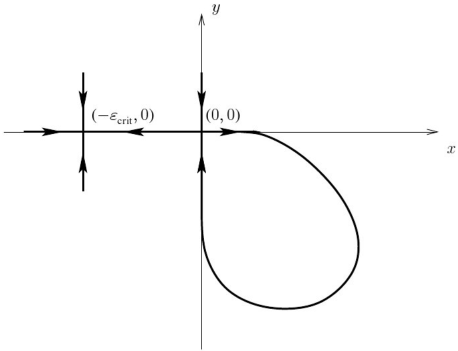
Phase space



In the bistable regime $(f_c^\star < f < f_c)$

Phase space

Homoclinic bifurcation:



$$f = f_c^\star$$

Phase space

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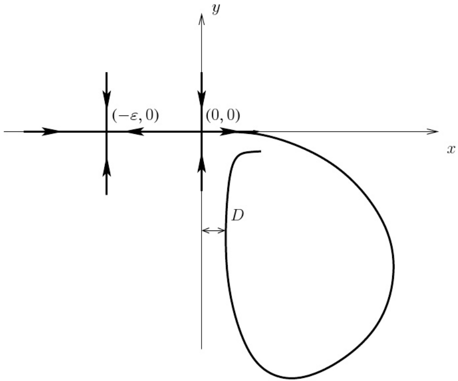
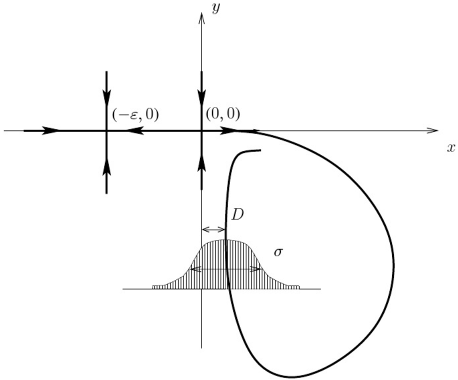


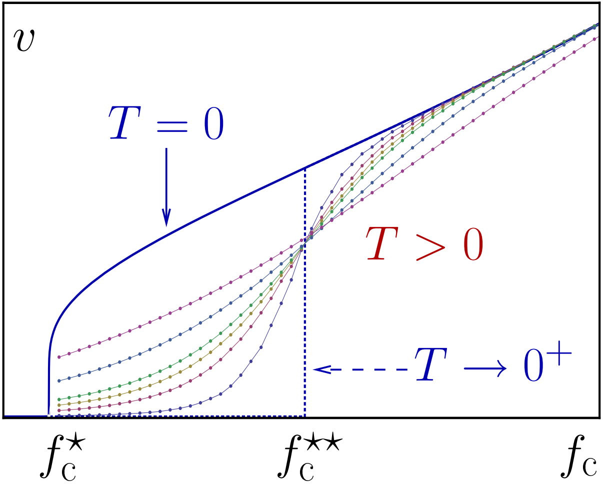
$$f > f_c^\star$$

Finite temperature



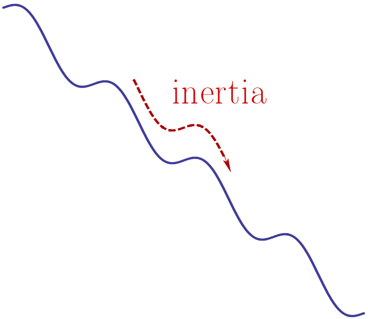
$$\text{escape time} \sim \underbrace{\exp\left(\frac{\epsilon^3}{T}\right)}_{\text{Arrhenius}} \underbrace{\exp\left(-\frac{A}{T}(\epsilon-\epsilon_c)^2\right)}_{\text{Trapping probability}}$$

Finite temperature



Force-velocity characteristics

Analogy

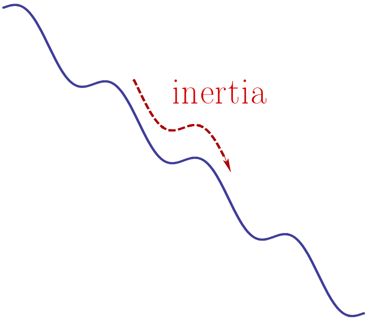


The phase ϕ plays the role of a velocity:

inertia helps to cross barriers

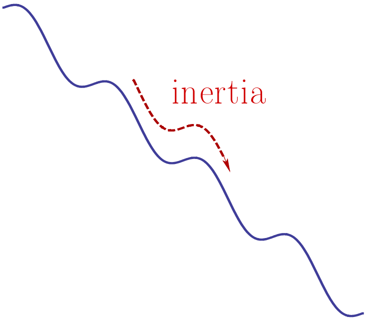
[see also Risken chap.11]

Analogy



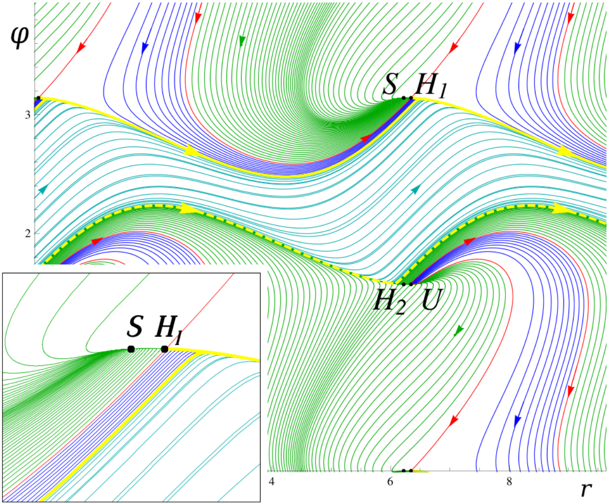
BUT ...

Analogy



the velocity is unbounded WHEREAS ϕ is bounded and periodic

Topological transition



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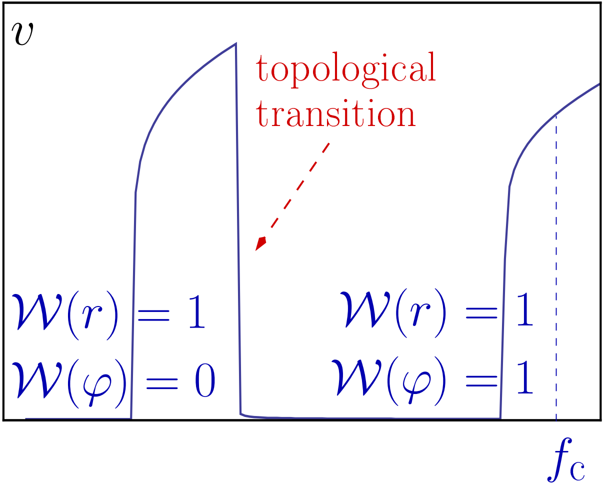
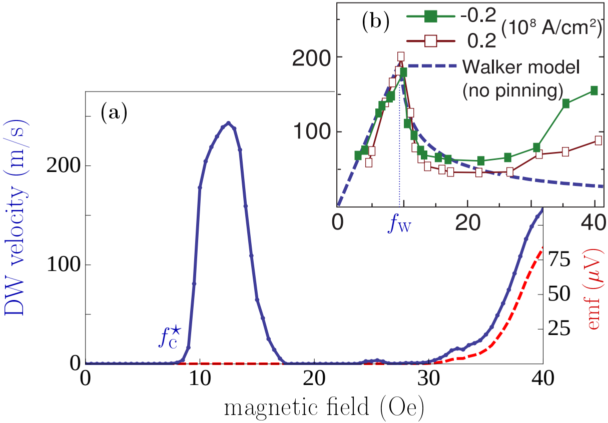


Successive regimes characterized by winding numbers $\mathcal{W}$

Experiment

SPINTRONICS

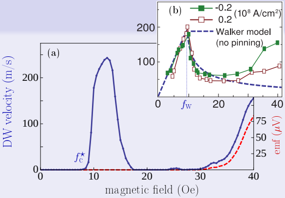
experiment from Parkin *et al.*, Science **320** 190 (2008)



Outlook

Internal degree of freedom

- unusual depinning law
- bistability
- non-monotonous $v(f)$ at finite T
- link with experiments



Perspective

- Current driven wall
- Interface with elasticity

→ modified creep law?

- Experiments

periodic patterning

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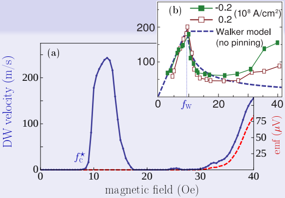

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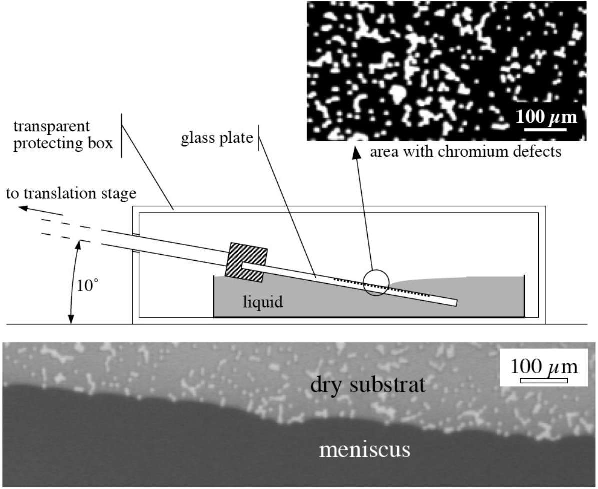
Contact line of a fluid



from Moulinet, Guthmann and Rolley, *Eur. Phys. J. E*, **8** 437 (2002)

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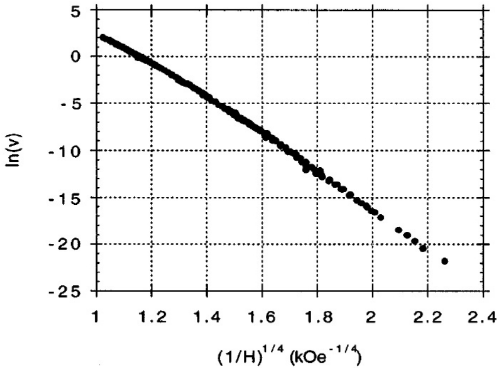

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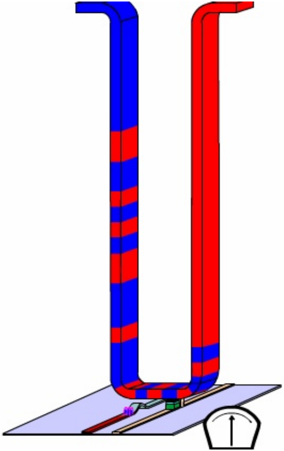
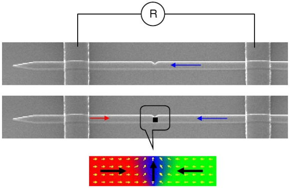


SPINTRONICS



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