Population dynamics of topological defects (dislocations) in a 2D magnetic stripe domain pattern

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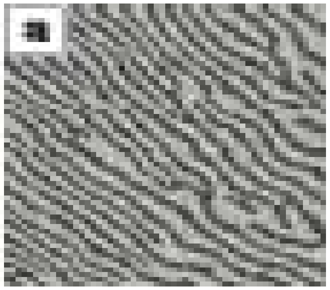
Physical Review B **84**, 094428 (2011); **80**, 184412 (2009)

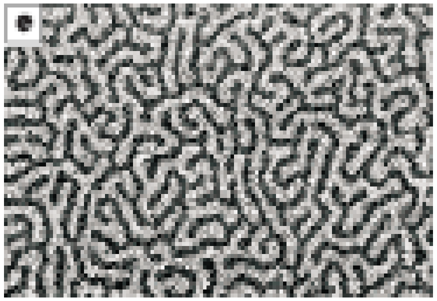
Outline:

1. Domain patterns in perpendicularly-magnetized films
2. Role of topological defects (dislocations)
3. ac magnetic susceptibility measurements, $\chi(T)$
4. Measurements of defect population dynamics

2D magnetic pattern forming systems

Stripe magnetic domains near equilibrium in ultrathin films





O. Portmann et al. Nature **422**, 701 (2003)

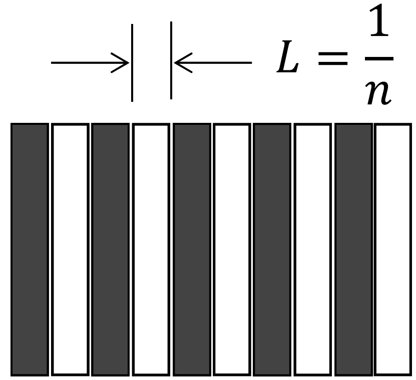
C. Won et al. PRB **71**, 224429 (2005)

Static images for microscopy.
What about dynamics?
How do the patterns evolve near equilibrium?

Other 2D systems:

- surface adsorbates
- Langmuir films
- polymer films
- High-T_c superconductors

Perpendicularly-magnetized ultrathin films



Energy increases from inserting domain walls

Dipole energy decreases from forming antiparallel domain stripes

$$E_0 = E_W(T)Nn - 4\Omega N^2 n \, \ln\left(\frac{2}{\pi \ell n}\right)$$

Depends upon layer thickness N

The two contributions balance at the equilibrium stripe density

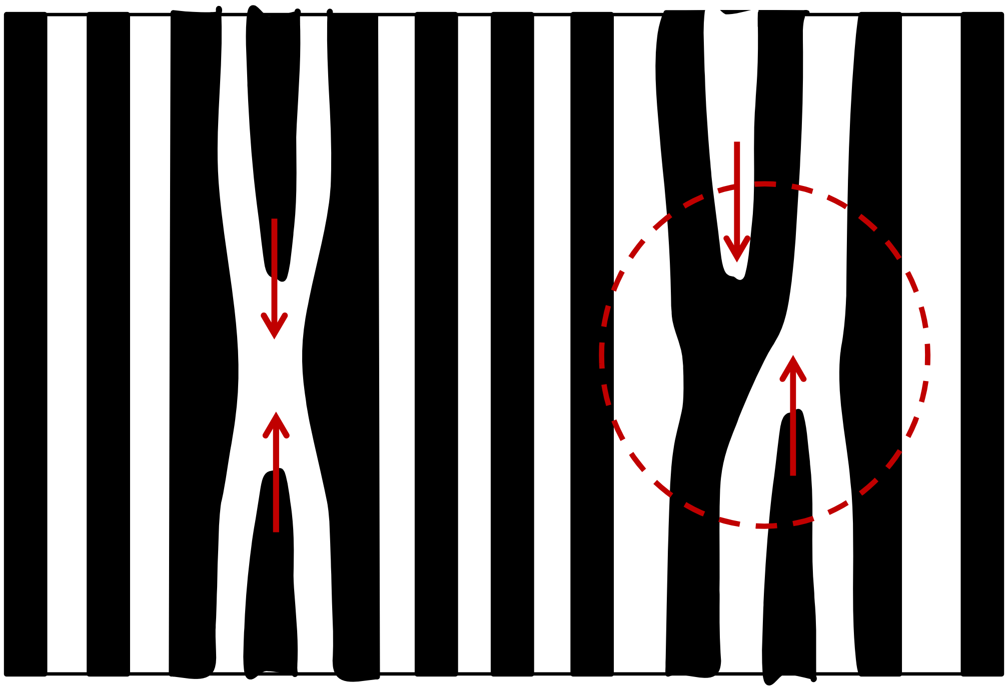
$$n_{eq}(T) = n_0 \exp\left(\frac{E_W(T)}{4\Omega}\right) \qquad \chi_{eq}(\mathrm{T}) \sim \frac{1}{n_{eq}} \approx A_0 \exp(-\kappa_0 T)$$

Phenomenological parameters, expressed by Taylor expansion

$$\ln A_0 = \frac{1}{4\pi N} E_W[K_{eff}(T_0)]$$

$$\kappa_0 = \frac{1}{4\pi N} \frac{\partial E_W[K_{eff}(T)]}{\partial T} \Big|_{T=T_0}$$

Defects accompany domain creation



Simple stripe completion.

Quick.

Topological defect. (Bound dislocation pair)

Requires geometric rearrangement. Slow.

Microscopy image

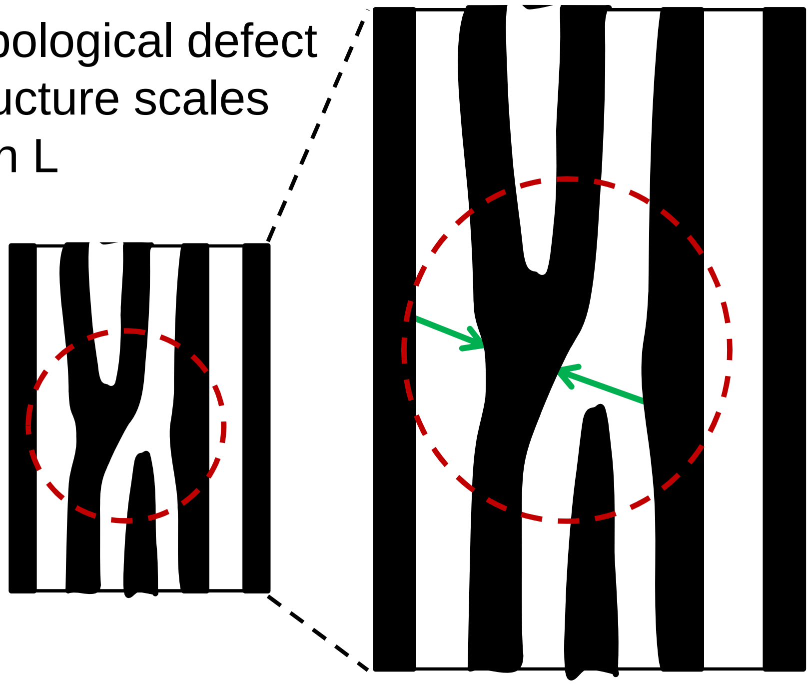
C. Won et al. PRB **71**, 224429 (2005)

Additional energy of the topological defect

Kashuba and Pokrovsky, Phys. Rev. B **48**, 10335 (1993)

Without knowing the precise position of domain walls u(x,y) that make up the metastable topological defect, in general:

Topological defect structure scales with L



Defect energy scales with a dimensionless local integral

$$E_{Defect} = (\frac{Q}{A}) N \Omega L \, f[\frac{u(x,y)}{L}]$$

Number of defects/area

1. Compressional energy $\sim \frac{\partial u}{\partial x}$
2. Extra wall energy $\sim \frac{1}{2}\left(\frac{\partial u}{\partial y}\right)^2$
3. Curvature energy $\sim \frac{1}{2}\left(\frac{\partial^2 u}{\partial y^2}\right)^2$

Optimum wall arrangement $\frac{\delta f}{\delta u} = 0$ gives $f = \gamma \frac{E_W}{\Omega}$

Scale defect density to *L* as well $\frac{Q}{A} \rightarrow \frac{Q}{N_x N_y} \frac{1}{L^2} \rightarrow \frac{1}{L^2} q$

$$E_{Defect} \rightarrow q\gamma \cdot E_W N n$$

Metastable domain density and susceptibility

$$E_0 + E_{Defects} = E_W(T)Nn(1+\gamma q) - 4\Omega N^2 n \ \ln\left(\frac{2}{\pi \ell n}\right)$$

$$n_{ms}(T) = n_0 \exp\left(\frac{E_W(T)}{4\Omega}(1+\gamma q)\right)$$

$$\chi_{ms}\,(\mathrm{T}) \sim \frac{1}{n_{ms}} \approx \mathrm{A}\exp(-\kappa T)$$

$$\ln A = (1+\gamma q)\ln A_0 \qquad \kappa = (1+\gamma q)\kappa_0$$

Including the defect energy changes the susceptibility by varying the fitting parameters linearly with the defect density. The relaxation of q(T) can be extracted from the relaxation of $\chi(\mathrm{T})$.

Magnetic susceptibility measurements

PRB **80**, 184412 (2009)

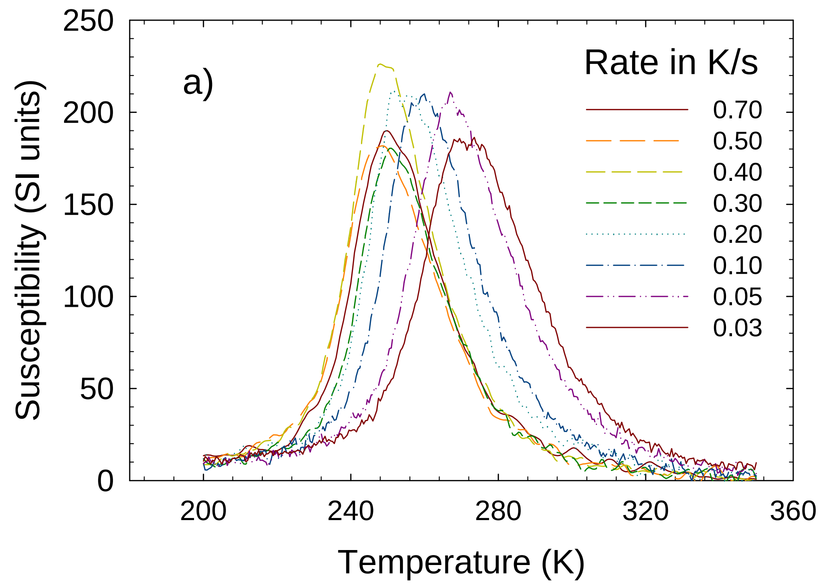
Experiments with different heating rates

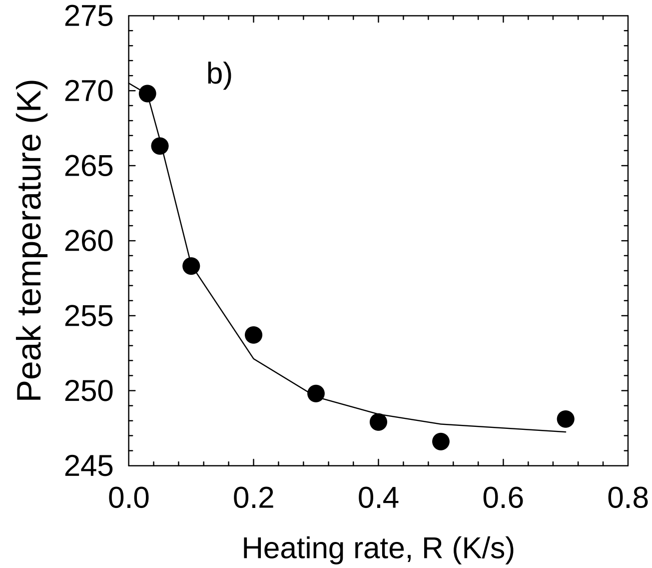
- perpendicularly-magnetized Fe/2 ML Ni/W(110) films
- ac field of 2 Oe at 210 Hz

Experimental procedure

- anneal film to 400 K
- cool at -0.1 K/s to 200 K
- heat at different constant rates, R, to a maximum of 360 K
- rates chosen in random order

1.5 ML Fe/2ML Ni/W(110)
Measured while heating





Quantifying the changes in the susceptibility

Phenomenological fitting of data to

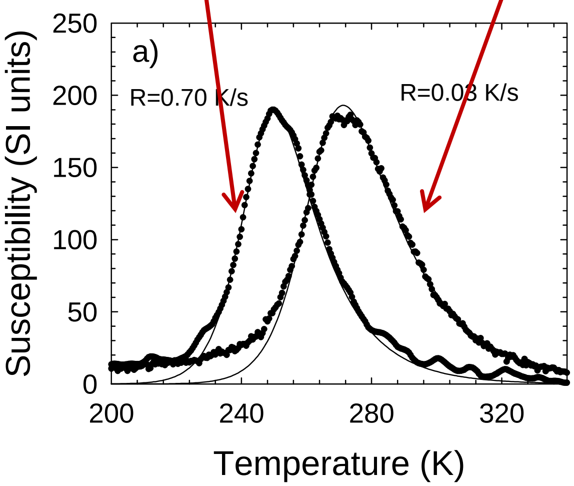
$$\chi(T) = \frac{A\exp(-\kappa T)}{1+\omega^2\tau_{pin}^2}$$

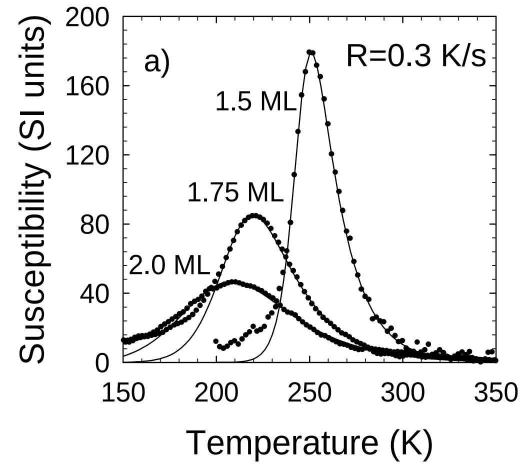
$$\tau_{pin} = \tau_{0p} e^{\frac{E_p}{kT}}$$

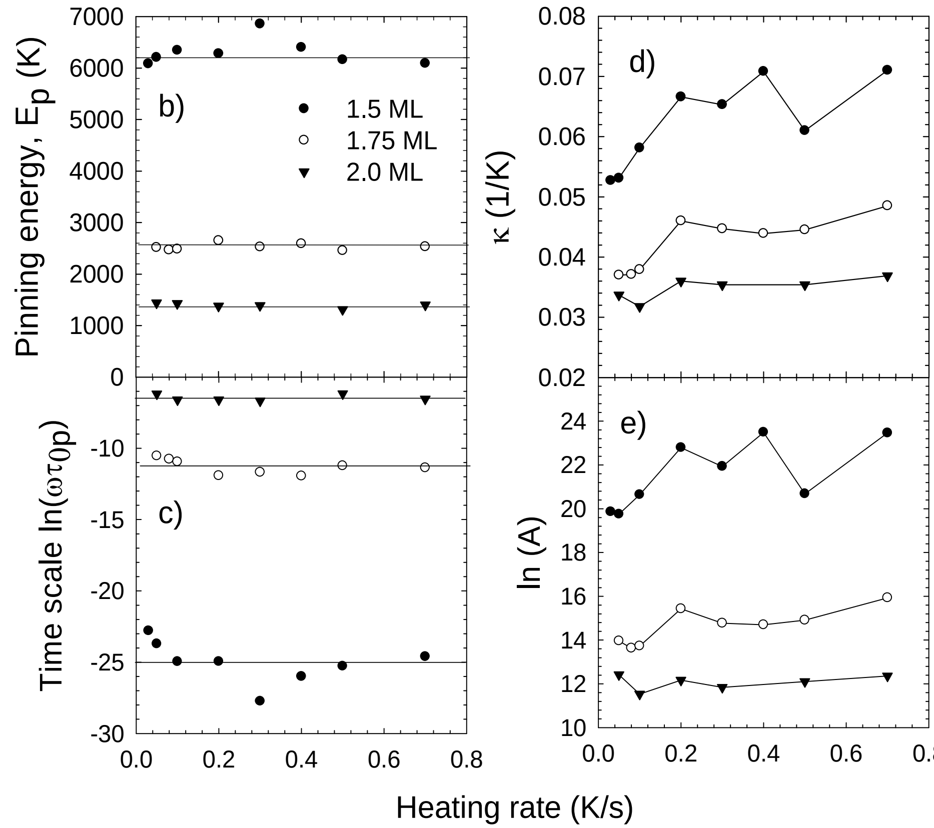
Pinning (τ_{0p}, E_p)

Increasing domain density (A,κ)

1.5 ML Fe/Ni/W(110)







Prediction: Shift is due to defect energy

$$\ln A = (1 + \gamma q) \ln A_0$$

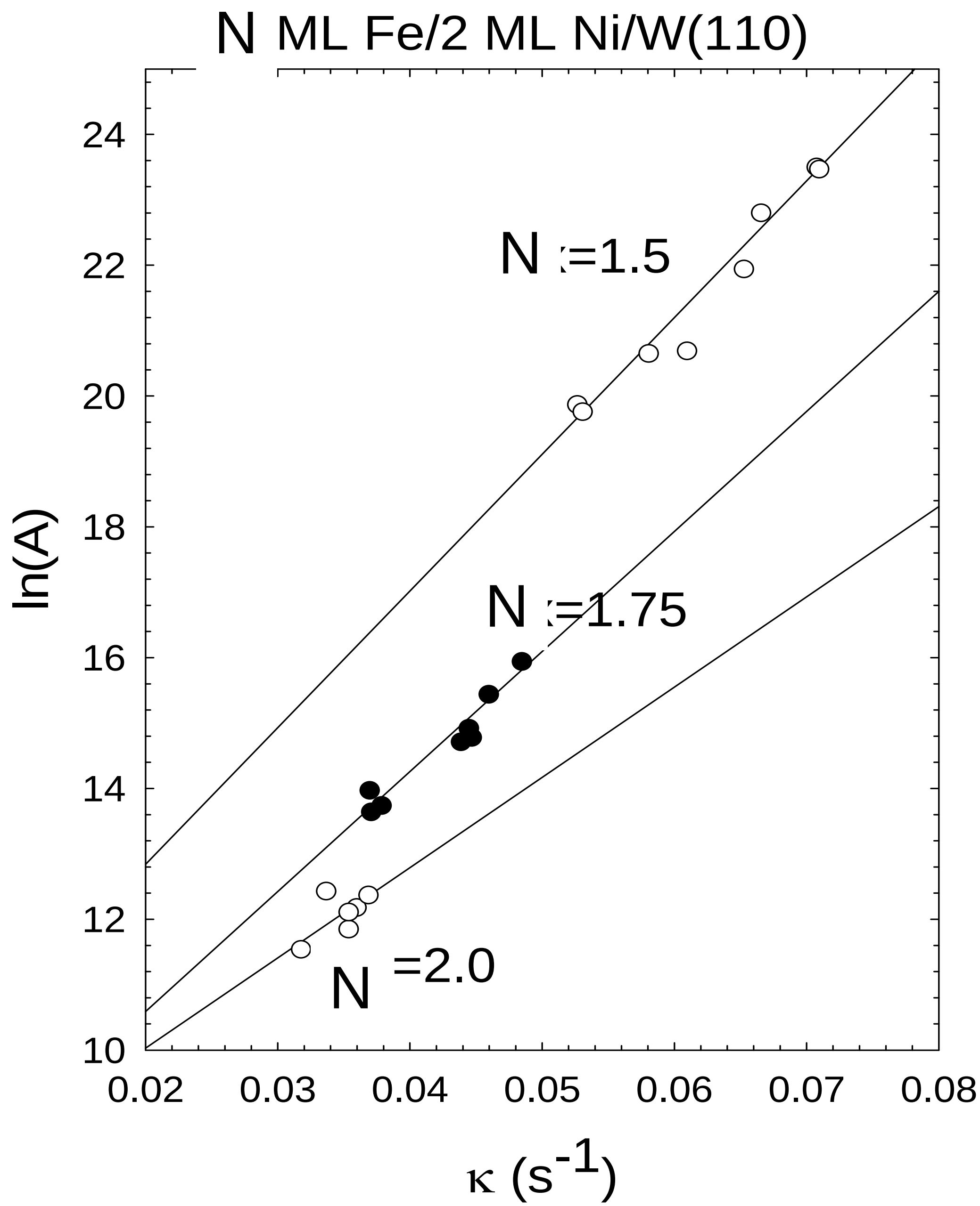
$$\kappa = (1 + \gamma q)\kappa_0$$

Slope of ln A vs. κ plot with

$$K_{eff} = \frac{K_{s,0} - \lambda T}{N} - \frac{\Omega}{b}$$

$$\frac{\ln A_0}{\kappa_0} = \frac{2K_{eff}(T_0, N)}{\frac{\partial K_{eff}(T_0, N)}{\partial T}}$$

$$= 2[\frac{K_{s,0}}{\lambda} - T_0 - N\frac{\Omega}{b\lambda}]$$



Prediction:
Shift in χ relaxes linearly with q

$$\frac{\partial \chi}{\partial T}\Big|_{T=T_p} = 0 \qquad \Delta T_p \propto \Delta\kappa \propto q$$

Assume an activated relaxation

$$\tau_r(T) = \tau_{0r}\exp\left(\frac{E_r}{kT}\right)$$

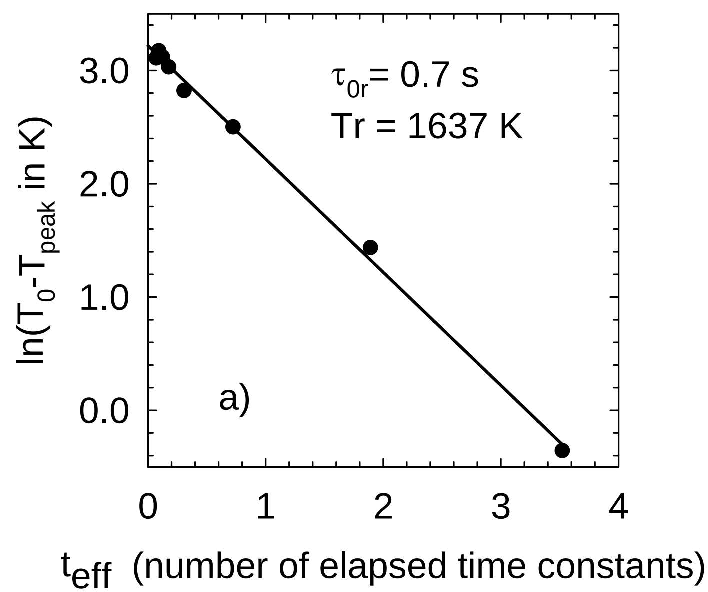
Number of time constants that have elapsed

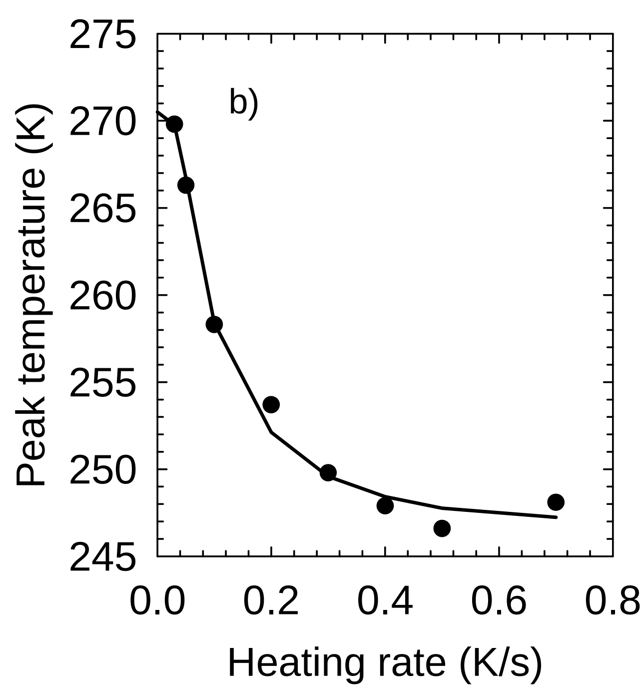
$$t_{eff}(R) = \int_{T_i}^{T_{pk}(R)} \frac{dT}{R\,\tau_r(T)}$$

Relaxation of susceptibility peak

$$T_{pk}(R) = T_0 - \Delta\exp(-t_{eff}(R))$$

1.5 ML Fe/2 ML Ni/W(110)



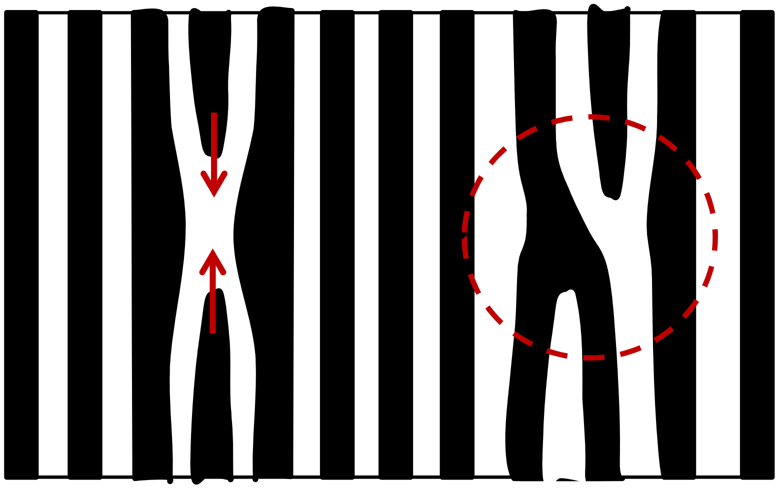


Prediction: Population dynamics of defects reflected in χ

$$\frac{\partial Q}{\partial t} = -\frac{Q}{\tau_r} + \varepsilon \frac{\partial}{\partial t} N_x N_y$$

Decay of metastable defects

Fraction ε of new stripes create a defect



Substitute: $$\frac{Q}{A} = \frac{1}{L^2} q$$

$n_{ms} \sim \frac{1}{A} e^{\kappa T}$ and $\frac{\partial}{\partial t} = R \frac{\partial}{\partial T}$ and $\gamma q = \frac{\kappa - \kappa_0}{\kappa_0} = \frac{\Delta\kappa}{\kappa_0}$

$$\frac{1}{2\kappa_0} \frac{\partial}{\partial T}\left(\frac{\Delta\kappa}{\kappa_0}\right) = -\left[(1-\varepsilon\gamma) + \frac{1}{2\kappa_0 R \tau_r}\right]\left(\frac{\Delta\kappa}{\kappa_0}\right) - \left(\frac{\Delta\kappa}{\kappa_0}\right)^2 + \varepsilon\gamma$$

Prediction: Population dynamics of defects reflected in χ

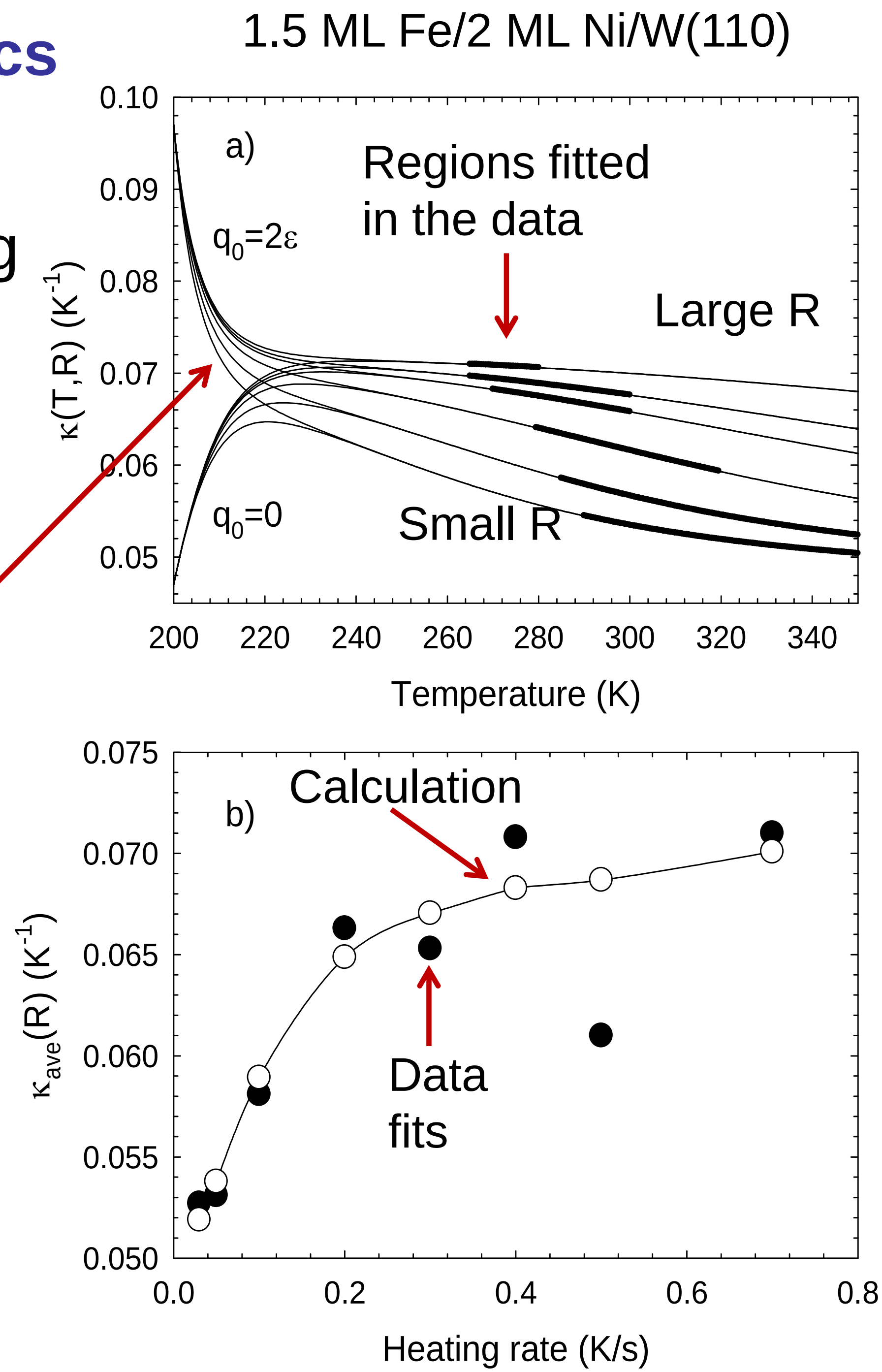
Solve differential equation, using

$$\tau_r, \kappa_0\ , \frac{\Delta\kappa_{max}}{\kappa_0} = \gamma\varepsilon$$

from the experimental traces, using different heating rates R.

Exponential growth erases memory quickly.

Fitted $\gamma\varepsilon = 0.45$ gives 30% of the domain energy is due to defects at large heating rates.



Conclusions

- Magnetic domain patterns in ultrathin films can be studied in detail using the magnetic susceptibility
- Domain growth process leaves topological defects that decay very slowly and alter the magnetic compressibility
- Resulting shift and shape change in the magnetic susceptibility peak can be used to follow the population dynamics of the topological defects
- Quantitative modeling gives:
  Internally consistent model of defect energy on $K_{eff}(T)$
  Fundamental relaxation time 0.7 s
  Activation energy 1600 K
  Up to 30% of domain energy due to topological defects