Characterization of the 2D percolation transition in ultrathin Fe/W(110) films using the magnetic susceptibility

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What is Percolation?

- $p_c$ is the threshold concentration: the point at which a percolating cluster extends the length of the lattice
- $p_c = 0.5928 \ldots$ for an infinite 2D square lattice (theoretical)
Percolation in Ultrathin Films

Top View

Side View

Increased Deposition

W(110) Substrate
Fe atoms

Very difficult to study as the transition is occurring

Note: Deposition ($t$) $\neq$ Coverage ($p$)

Percolation in Ultrathin Films

Why is this interesting?

- Radical change in film properties at percolation
- Interesting example of a non-thermal phase transition

Note: Deposition ($t$) ≠ Coverage ($p$)
Measuring Percolation with Magnetic Susceptibility, $\chi$

$$\chi = \frac{dM}{dH}$$
Measuring Percolation with Magnetic Susceptibility, $\chi$

\[ \chi = \frac{dM}{dH} \]

Islands: $\chi$ vs $T$

Temperature, $T$ (K)

Top View

Side View

Increased Deposition

W(110) Substrate

Fe atoms
Measuring Percolation with Magnetic Susceptibility, $\chi$

\[ \chi = \frac{dM}{dH} \]

Top View

Side View

Increased Deposition

Islands: $\chi$ vs $T$

Percolated Film: $\chi$ vs $T$
Measuring Percolation with Magnetic Susceptibility, $\chi$

$\chi = \frac{dM}{dH}$

Susceptibility, $\chi$ (nrad/Oe)

Temperature, $T$ (K)

Islands: $\chi$ vs $T$

As transition is occurring: $\chi$ vs $t$

Susceptibility, $\chi$ (nrad/Oe)

Deposition, $t$ (ML)

Percolated Film: $\chi$ vs $T$

Temperature, $T$ (K)

Increased Deposition

Top View

Side View

W(110) Substrate

Fe atoms
Surface Magneto-optic Kerr Effect

\[ \chi = \frac{dM}{dH} \approx \frac{\Phi_k}{H} \]
Results: Susceptibility versus deposition
Results: Susceptibility versus deposition

\[ \chi (\text{nrad/Oe}) \]

260 K

400 K
Results: Susceptibility versus deposition

Wider peaks at higher temperature: suggests different mechanisms
Thermal vs. geometric transitions

- Evidence of different transition types: thermal above ~350 K, percolation below

Scaled shapes of $\chi$ at various temperatures
Thermal vs. geometric transitions

- Evidence of different transition types: thermal above ~350 K, percolation below
Thermal vs. geometric transitions

- Sharp vertical section agrees qualitatively with theoretically predicted crossover from percolation to thermal behaviour of the transition:

\[ T_c \sim \frac{1}{\ln|p - p_c|} \]

Peak of $\chi$ at various temperatures

Magnetic susceptibility in terms of percolation

\[ M \propto SH \]

Mean Cluster Size

Applied Field

Magnetization

Susceptibility

\[ \chi = \frac{dM}{dH} \propto S \]

Susceptibility

\[ \chi \text{ diverges as } S \text{ diverges} \]

\[ S \text{ diverges at } p_c \]

\[ p_c \]
Scaling with Critical Exponents

\[ \chi \propto |p - p_c|^{-\gamma} \approx |t - t_c|^{-\gamma} \]

Coverage

Percolation Critical Exponent

Deposition
Scaling with Critical Exponents

$$\chi \propto |p - p_c|^{-\gamma} \approx |t - t_c|^{-\gamma}$$

Coverage

Deposition

Percolation Critical Exponent

$$\gamma = \frac{43}{18} \approx 2.39$$

From theory (for percolation in 2d)
Fitting to critical exponent

\[ \chi = A |t - t_c|^{-\gamma} \quad \rightarrow \quad \log(\chi) = \log(A) - \gamma \log |t - t_c| \]

\( 240 \text{ K} \)

\( \gamma = -\text{slope} \)

Deposition, \( t \) (ML)

Susceptibility, \( \chi \) (nrad/Oe)
Minimizing variance

- No minimum in the variance
- Variance begins to level out when $p_c$ is chosen close to the peak in the susceptibility

\[ \gamma_{\text{mean}} = 2.6 \pm 0.2 \]
Minimizing variance

- No minimum in the variance
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$\gamma_{mean} = 2.6 \pm 0.2$
Minimizing variance

- No minimum in the variance
- Variance begins to level out when $p_c$ is chosen close to the peak in the susceptibility

$$\gamma_{theory} = \frac{43}{18} \approx 2.39$$

$$\gamma_{peak} = 2.46$$

$$\gamma_{mean} = 2.6 \pm 0.2$$

$$\gamma_{limit} = 2.82$$
Conclusions

- Measured and characterized 2D percolation *as it occurs* by using changing magnetic properties as probe

- Observed crossover from percolation to thermal transitions

- Agreement with theory
  - Very sharp (essentially vertical) transition line for percolation
  - Critical exponent:
    - Theory: $\gamma = 43/18 \approx 2.39$
    - Experiment: $\gamma = 2.6 \pm 0.2$
Acknowledgements

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Extra Slides
Apparatus

Fe Evaporator
Helmholtz Coils
W Substrate
Sample Manipulator Arm
Fe Evaporator
AES Apparatus
He-Ne Laser
AES Gun
Sample Manipulator Arm
Quartz Window Birefringence

- Strain induced by UHV on quartz windows worsens birefringence
  - Causes linearly polarized light to become elliptically polarized upon entering the chamber.

- Method developed to counteract effect\(^1\)
  - Initial polarizer rotated slightly such that ellipticity from sample counteracts ellipticity from windows resulting in linearly polarized light at analyzer

Measuring Film Thickness

- Film thickness measured by Auger Electron Spectroscopy (AES)
- Measure W spectrum before and after film growth: attenuation proportional to the deposition up to the first ML

Growth Modes

- At room temperature, growth by isolated islands (quenched magnet)
- At >500K, growth by stripes (annealed magnet)
  - Grows along terrace step edges
    - terraces due to cleaving of mosaic W crystal to reveal (110) surface.
  - Growth is monolayer by monolayer

Indirect Observation of Percolation

Evaporator
Relation between coverage, $p$, and deposition, $t$

- A simple model of particles landing randomly on lattice sites
- Particles are permitted to land on other particles
- Particles more likely to land on other particles at higher coverages $p$

$$p = 1 - e^{-t}$$

For critical deposition, $t_c = 1.2\text{ML} \Rightarrow p \approx 0.7$
Derivation of Susceptibility for Percolation

Magnetization of a single cluster:

\[ m_{\text{cluster}} = s m \tanh \left( \frac{s m H}{k T} \right) \]

Film magnetization:

\[ M = \sum_s m_{\text{cluster}} n_s = \sum_s s m n_s \tanh \left( \frac{s m H}{k T} \right) \approx \sum_s \frac{(s m)^2 n_s H}{k T} \]

Mean cluster size:

\[ S = \frac{\sum_s s^2 n_s}{\sum_s s n_s} \]

Susceptibility:

\[ \chi = \frac{dM}{dH} = \frac{m^2}{k T} \sum_s s^2 n_s \Rightarrow \chi \propto S \]

\( s = \) number of lattice sites in a cluster
\( m = \) magnetic moment of single atom
\( H = \) applied field
\( n_s = \) number of clusters of size \( s \) per lattice site