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Micromagnetic behavior of electrodeposited cylinder arrays

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Arrays of cylindrical magnetic particles have been made using interference lithography combined with electrodeposition. The cylinders are made from Ni, Co, CoP, or CoNi, with diameters of 57–180 nm, aspect ratios of 0.4–3, and array periods of 100–200 nm. The remanent states of the cylinders correspond to single-domain “flower” states or to magnetization vortices depending on the particle size and aspect ratio. Experimental data are in good agreement with a magnetic-state map calculated using a three-dimensional micromagnetic model, which shows the remanent state as a function of particle size and aspect ratio. The interactions between the particles, and their switching-field distribution, have been quantified.

Micromagnetic behavior of electrodeposited cylinder arrays

- Arrays of cylindrical magnetic particles
- Interference lithography combined with electrodeposition
- The cylinders are made from Ni, Co, CoP, or CoNi
- Particle size and aspect ratio.
- Magnetic domains “flower” or vortices
- Experimental data are in good agreement with three-dimensional micromagnetic model
- Interactions between the particles
- Switching-field distributions

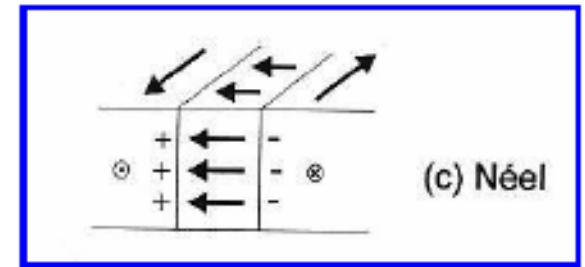
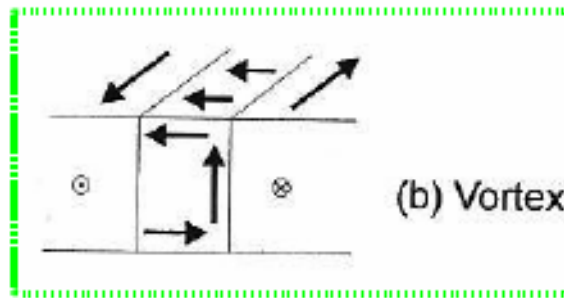
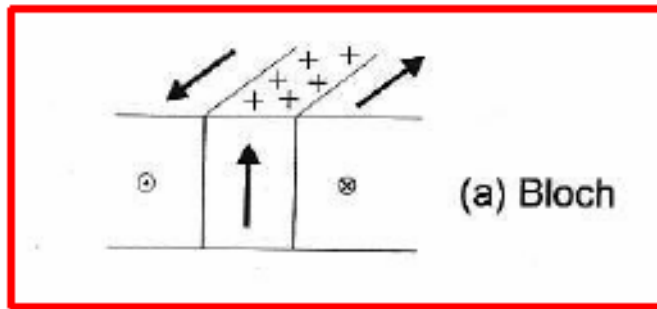
INTRODUCTION.

- **Small** (sub-100 nm) ferromagnetic particles or elements
 - Patterned magnetic recording media.
 - Magnetoelectronic devices.
- **Magnetic behavior** (small particles)
 - Size relative to the magnetic exchange length λ_{ex}
 - 6-20 nm for ferromagnetic metals
 - Too small to support well-developed multidomain structures at remanence
 - Too large to be uniformly magnetized
 - Nonuniform magnetization (vortices, etc)
 - Complex magnetic switching behavior
 - Complex magnetization reversal process

INTRODUCTION.

- **Domain walls**

- Bloch wall.
- Néel wall.



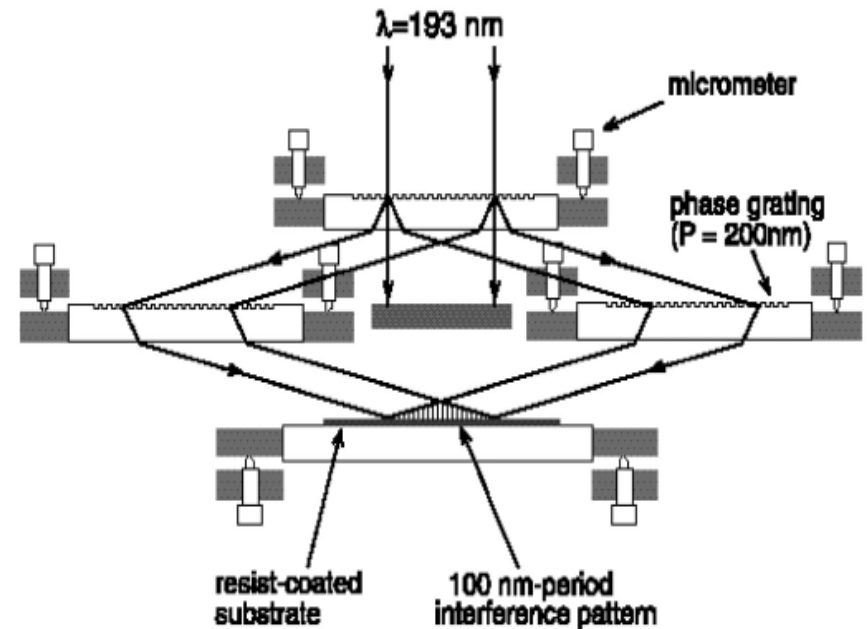
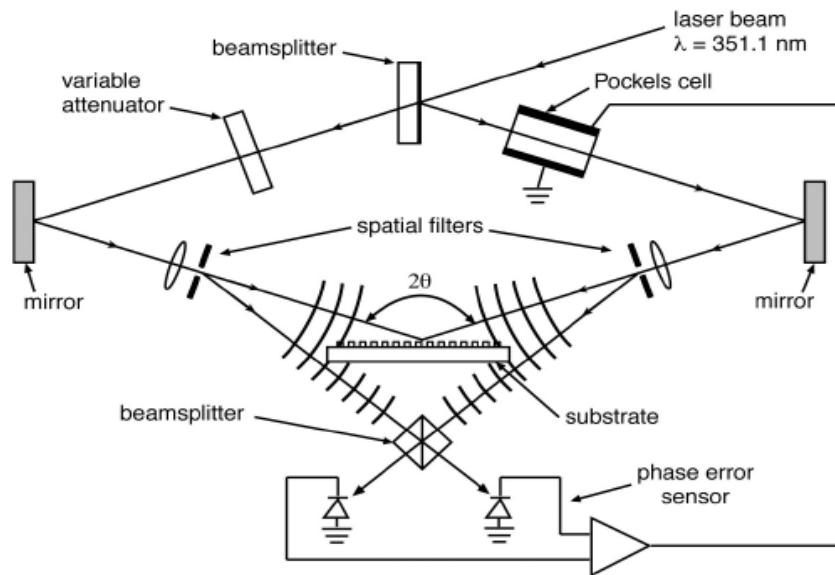
- **Computational micromagnetic models:**

- Remanent states.
- Switching behavior.

- It is now possible to compare three dimensional model predictions directly to experimental data.

SAMPLE FABRICATION.

- **Templates** made by:
 - Interference lithography (200 nm)
 - Achromatic interference lithography (100 nm)



- Large area exposed (cm^2)
- Much faster than electron-beam lithography.
- Two perpendicular exposures are used to define a square array of holes
- The diameter of the holes is controlled through the exposure dose
- A negative resist is used.

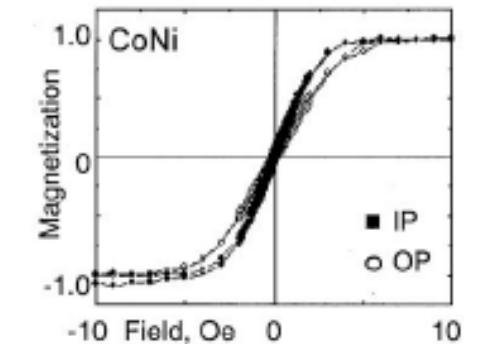
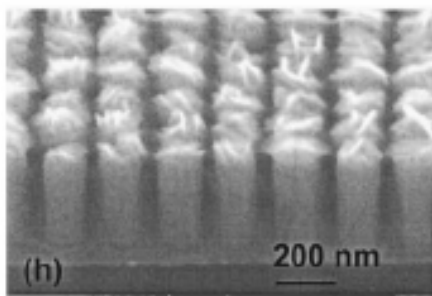
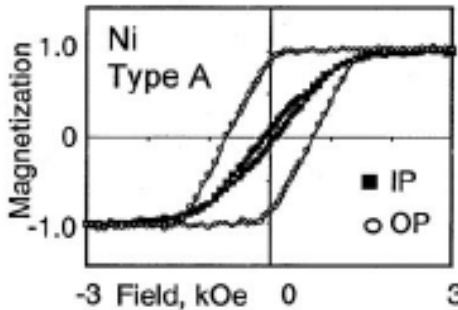
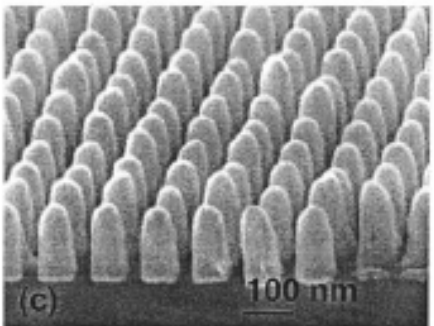
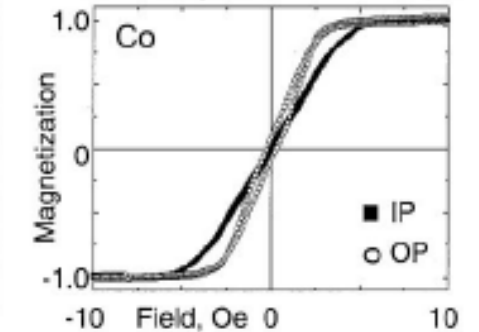
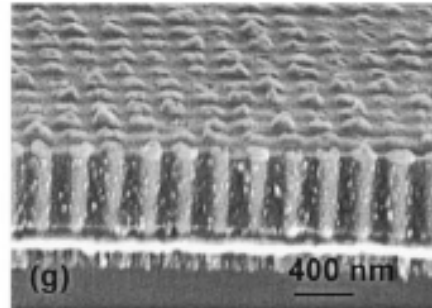
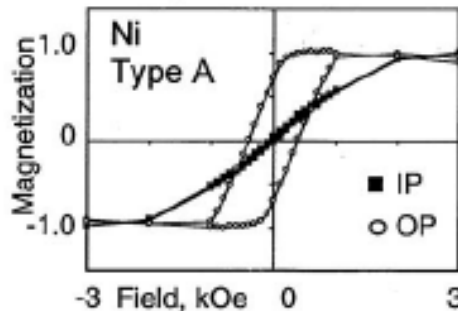
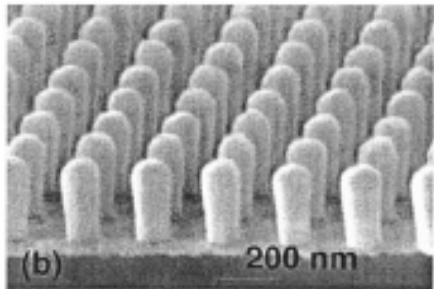
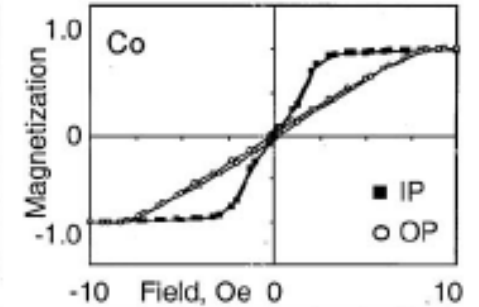
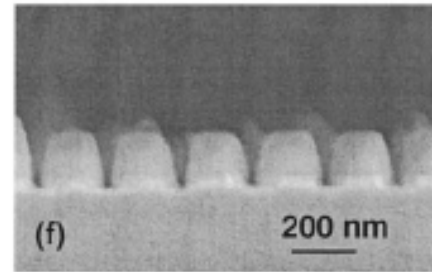
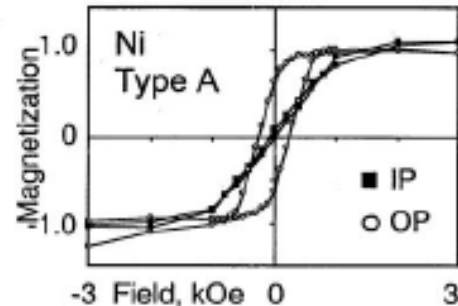
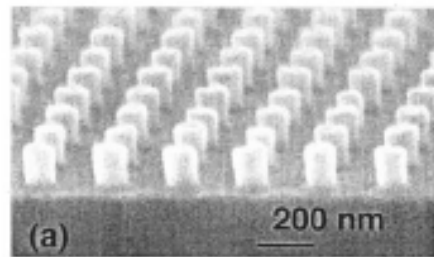
SAMPLE FABRICATION.

- The templates are made on silicon wafers coated with a thin evaporated conductive layer consisting of 5 nm Ti or Cr followed by 5–20 nm Au.
- The cylinder arrays are fabricated by electrodeposition from aqueous electrolytes:
 - Co and Ni are deposited from sulfamate electrolytes
 - CoNi pyrophosphate and CoP phosphate electrolytes were mixed from salts
- Depositions are carried out galvanostatically.
- Except for CoNi alloys that are deposited potentiostatically

STRUCTURAL CHARACTERIZATION.

- Microstructure
 - X-ray diffraction
 - Transmission electron microscopy
 - Scanning electron microscopy
- Compositions of alloys
 - Energy dispersive x-ray analysis
 - X-ray photoelectron spectroscopy
- Magnetic characterization
 - Vibrating sample magnetometer
 - Gradient magnetometer
 - Magnetic force microscope

SAMPLE FABRICATION, STRUCTURAL CHARACTERIZATION.



Three-dimensional micromagnetic model

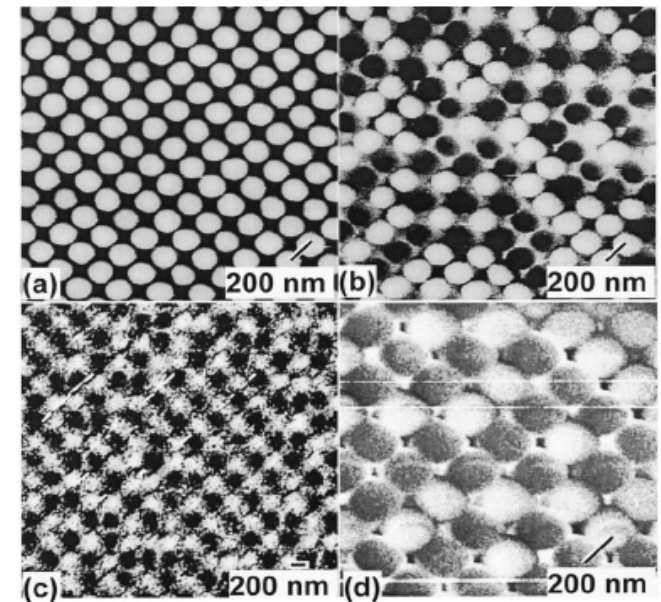
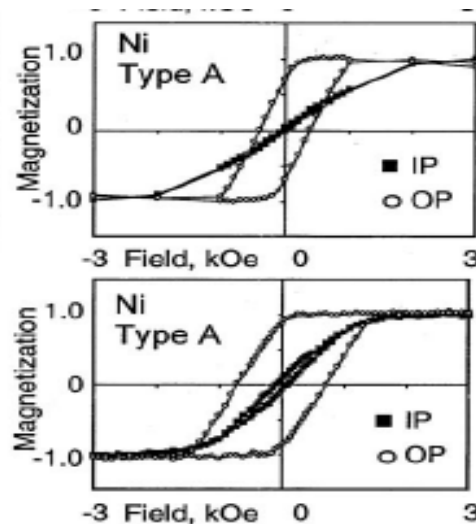
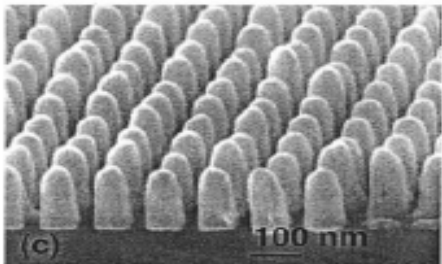
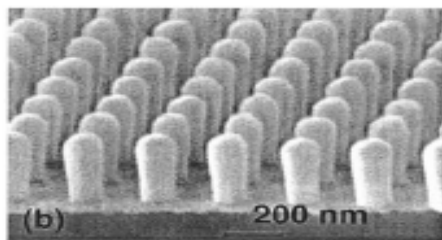
- **Landau-Lifschitz-Gilbert equations**
- The particle was discretized into cubic cells
- The cell size was always kept below $0.5 \lambda_{ex}$
- Magnetostatic interactions, nearest-neighbor exchange interactions, and any external fields or local anisotropies
- The remanent states of isolated cylindrical particles were calculated.

Hysteresis loops

- Three types of hysteresis loops were identified

Type A

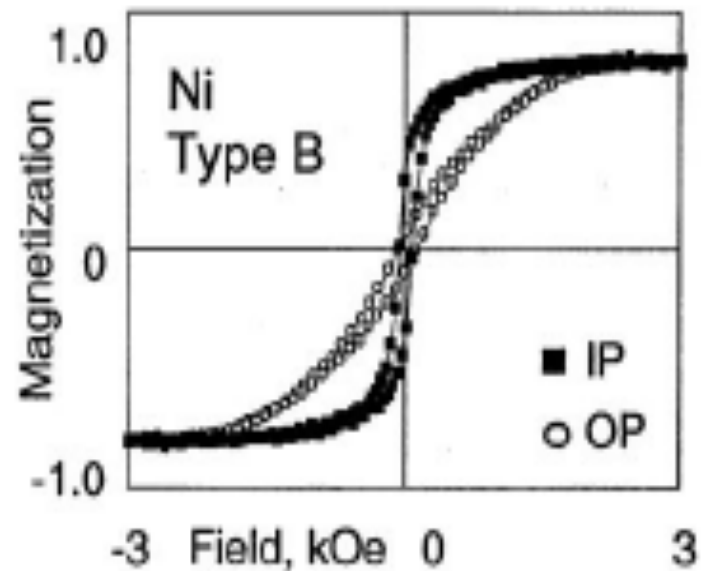
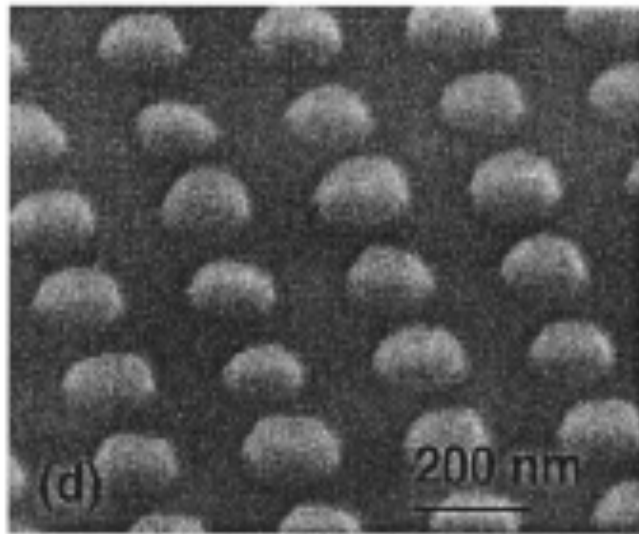
- High aspect ratio, low diameter Ni samples
- High coercivity, trapezoidal hysteresis loop (out-of-plane)
- Low coercivity and remanence characteristic of a hard axis (in-plane)
- Each cylinder behaves like a magnetic dipole oriented perpendicular to the plane



Hysteresis loops

Type B

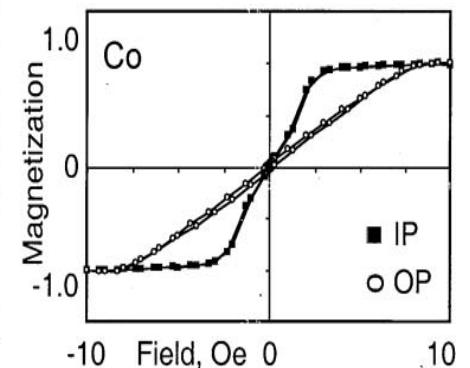
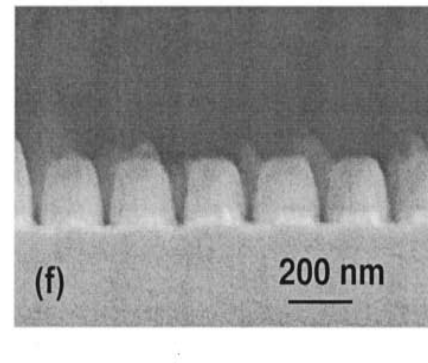
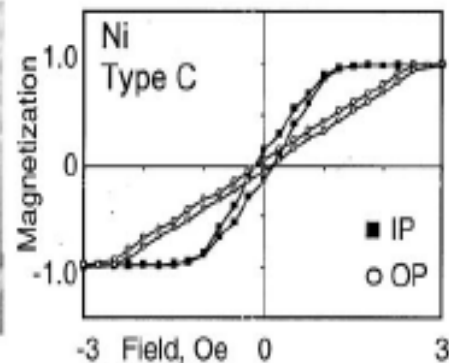
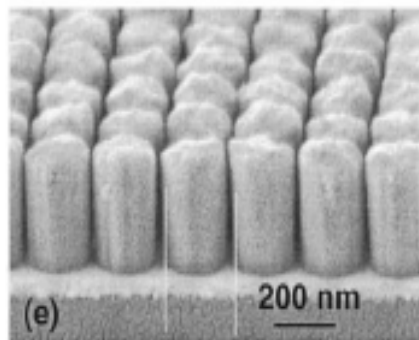
- Low-aspect-ratio Ni samples ($R = 0.41$ and 0.74)
- In plane easy axis
- Hard axis parallel to the cylinder height



Hysteresis loops

Type C

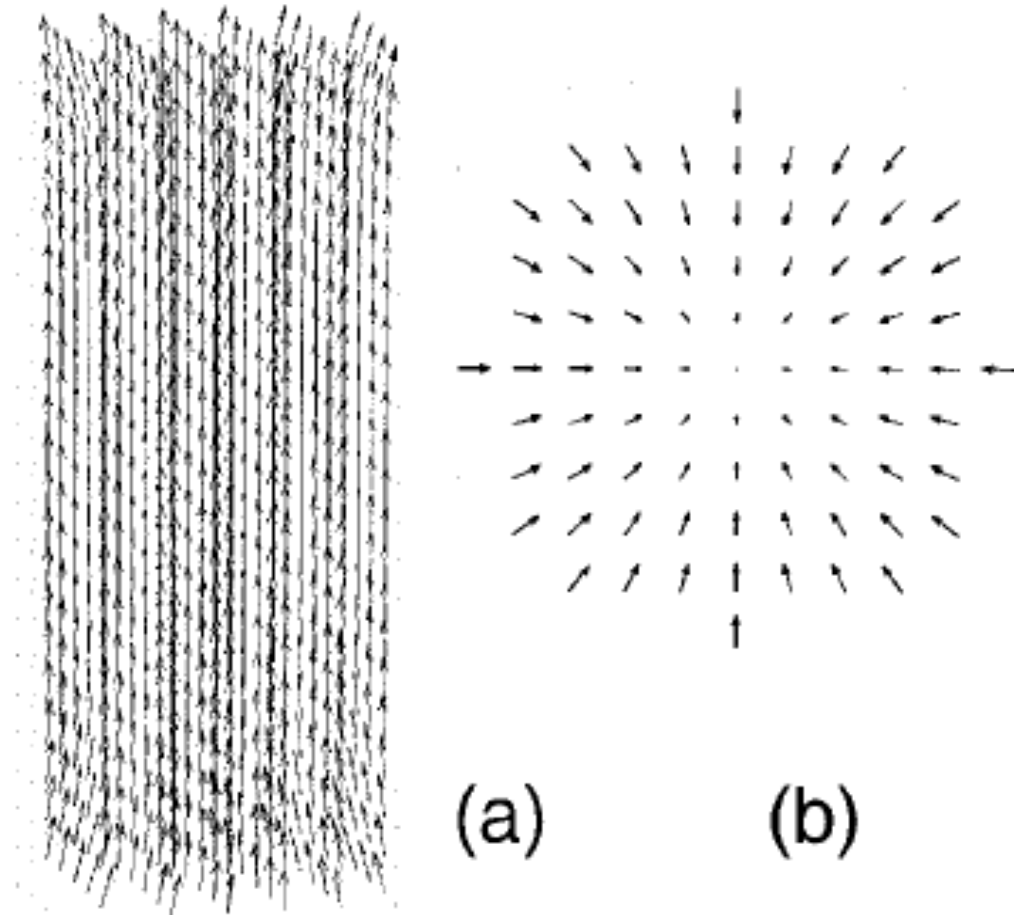
- Larger diameter Ni samples and all the Co and CoNi samples
- Hysteresis loops in which both in-plane and out-of-plane magnetization directions have low coercivity and remanence
- The field required to saturate the magnetization in either direction depends on the aspect ratio and spacing of the cylinders
- Higher aspect ratio or more widely separated cylinders have lower out-of-plane saturation fields.



Remanent states

High-aspect-ratio particles ($R > 0.9$)

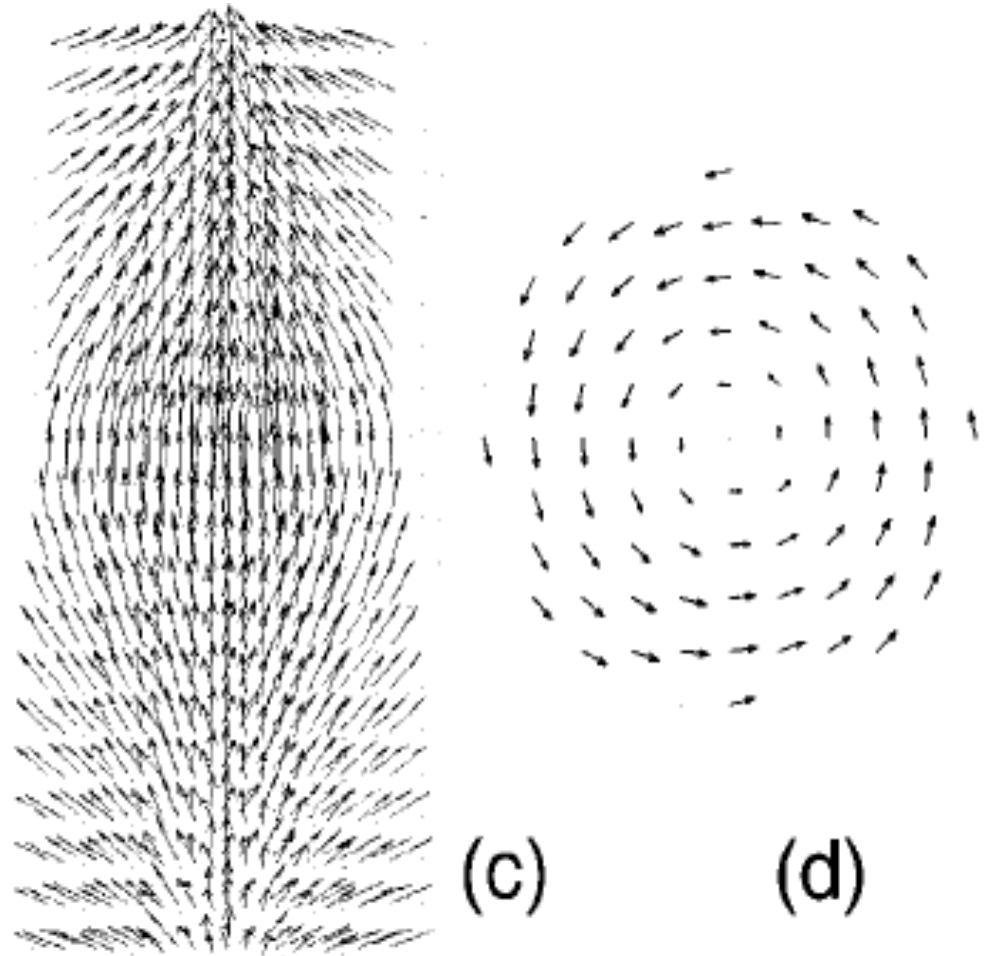
- Micromagnetic simulations of the remanent state of an isolated cylindrical particle
- **Small diameters**
 - “Flower-state” magnetization
 - The magnetization is parallel to the axis of the particle except near the top and bottom surfaces where it spreads radially, and the axial remanence is close to 1



Remanent states

High-aspect-ratio particles ($R > 0.9$)

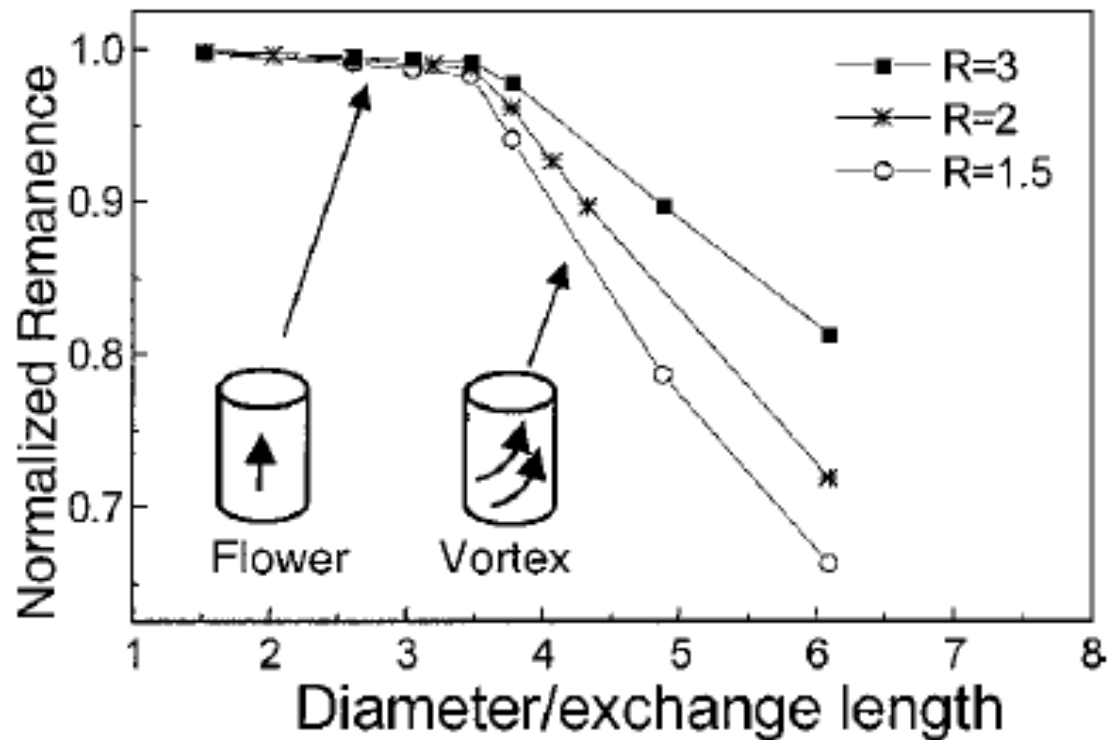
- **As the diameter increases**
 - Transition to a “vortex” state occurs.
 - The magnetization adopts a helical structure, starting at the ends of the particle.
 - Magnetization at the center of the particle remains oriented primarily along the axis



Remanent states

High-aspect-ratio particles ($R > 0.9$)

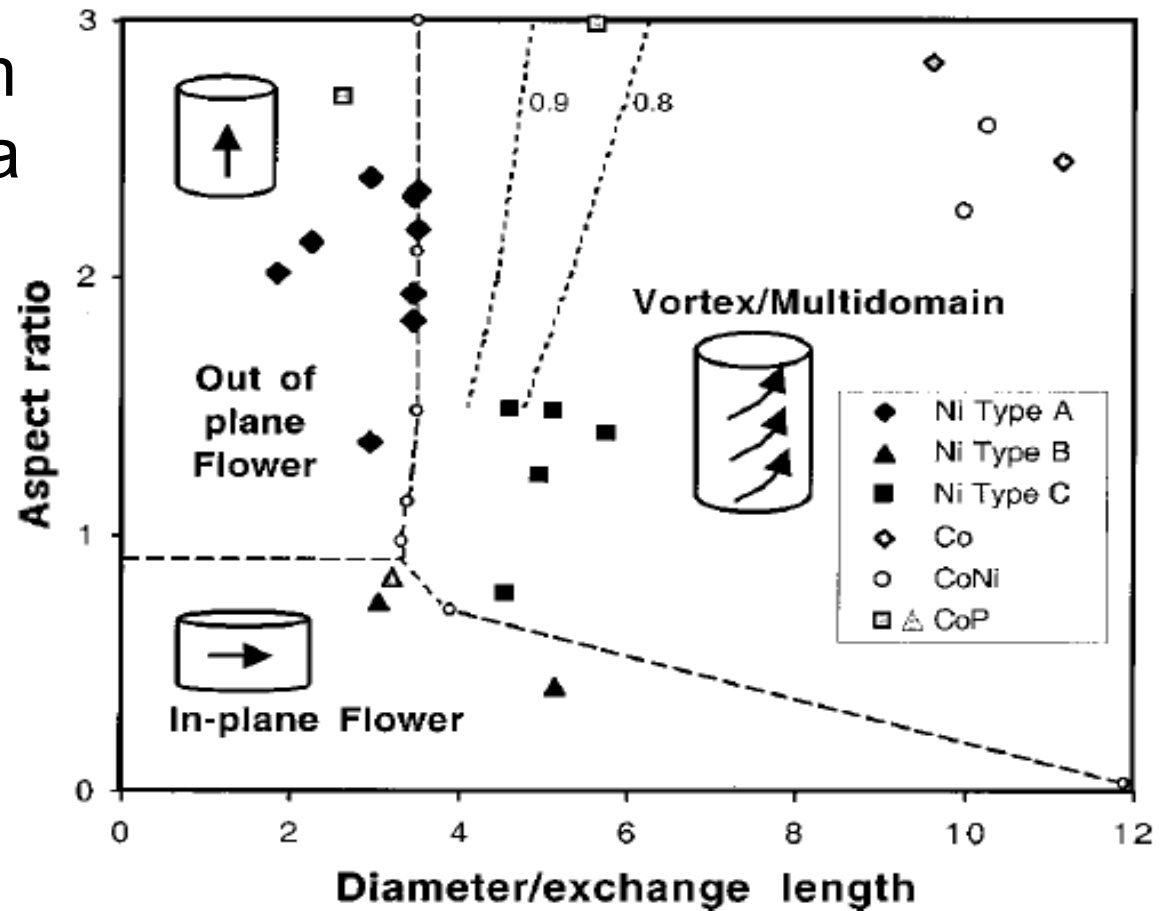
- The remanence drops with increasing diameter as the magnetization tilts away from the axis
- Remanence decreases more slowly with diameter for higher aspect ratio cylinders because the region of tilted magnetization is confined to a smaller volume fraction of the particles.



Remanent states

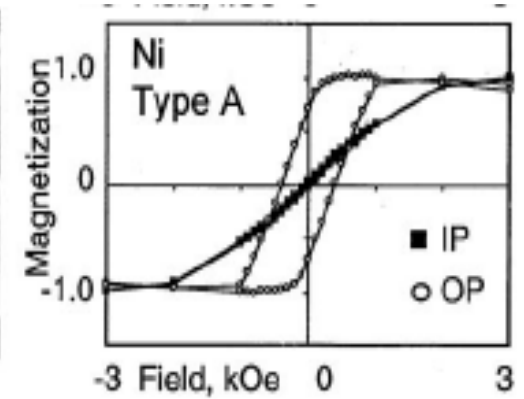
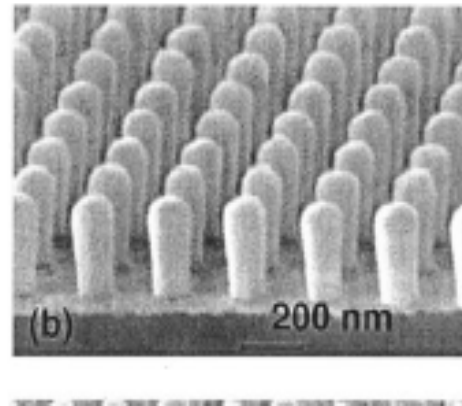
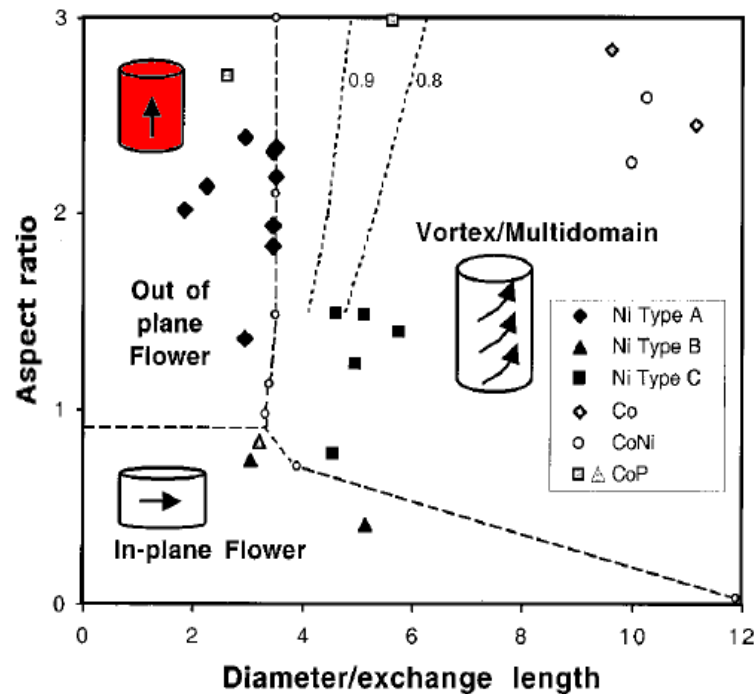
Low-aspect-ratio particles ($R < 0.9$)

- As the aspect ratio decreases, there is a transition from the out-of-plane flower state to an in-plane flower state
- Particles with $R < 0.9$ show a transition from an in-plane flower to a vortex state with increasing diameter
- As the cylinder diameter increases, more complex states were obtained containing domain walls.



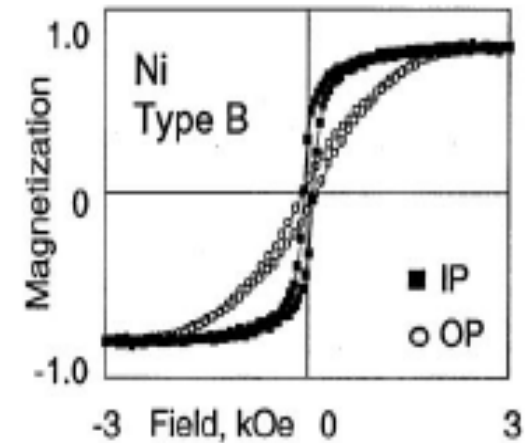
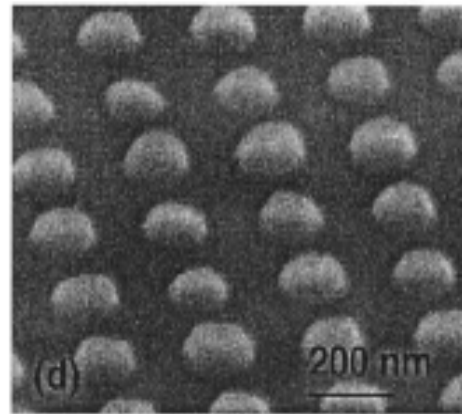
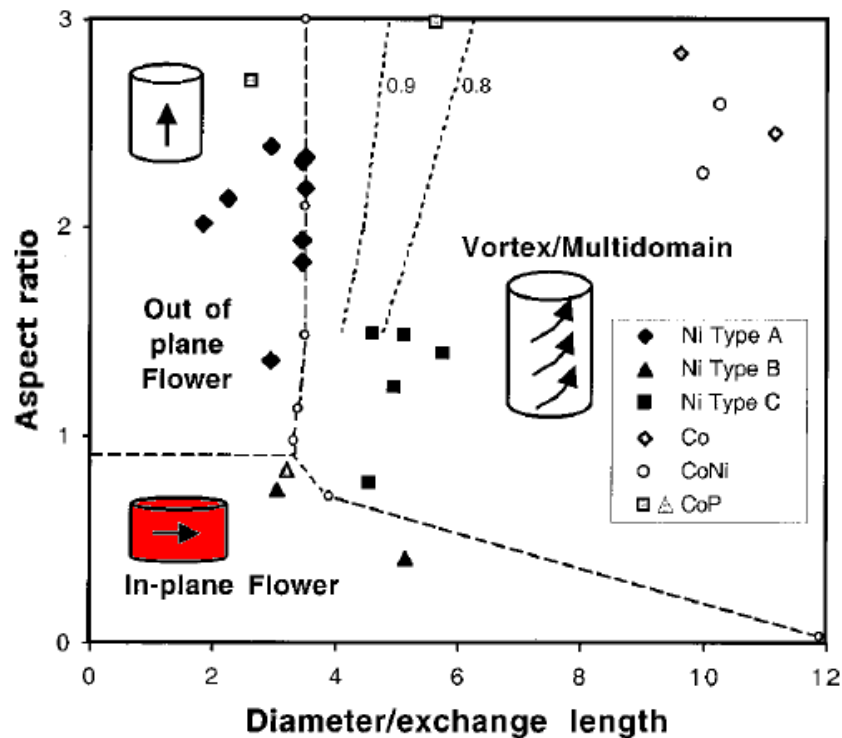
Hysteresis loops and remanent states

- The **type-A** loops represent out-of-plane flower-state particles with high coercivity and remanence
- The shear of the out-of plane hysteresis loop is a result of magnetostatic interactions between the particles



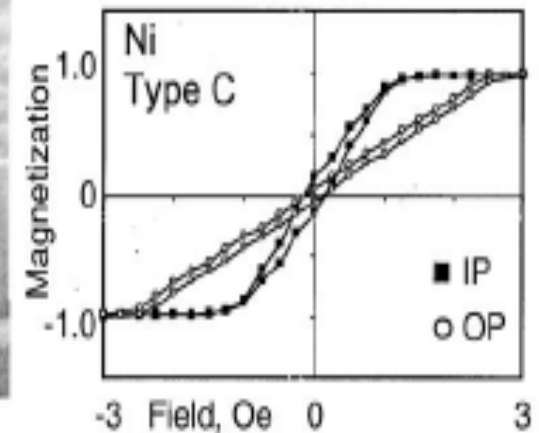
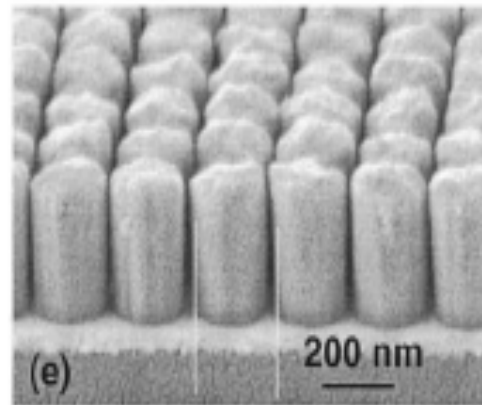
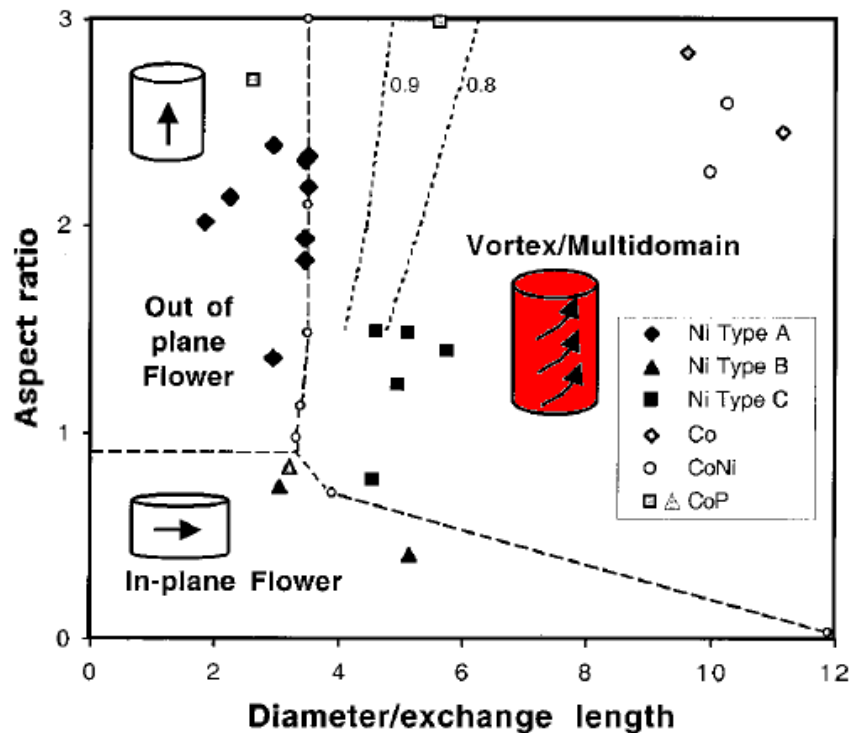
Hysteresis loops and remanent states

- The **type-B** loops represent particles with an in-plane flower state.
- Individual particles have high remanence but interactions tilt the magnetizations in plane and reduce the net remanence of the array



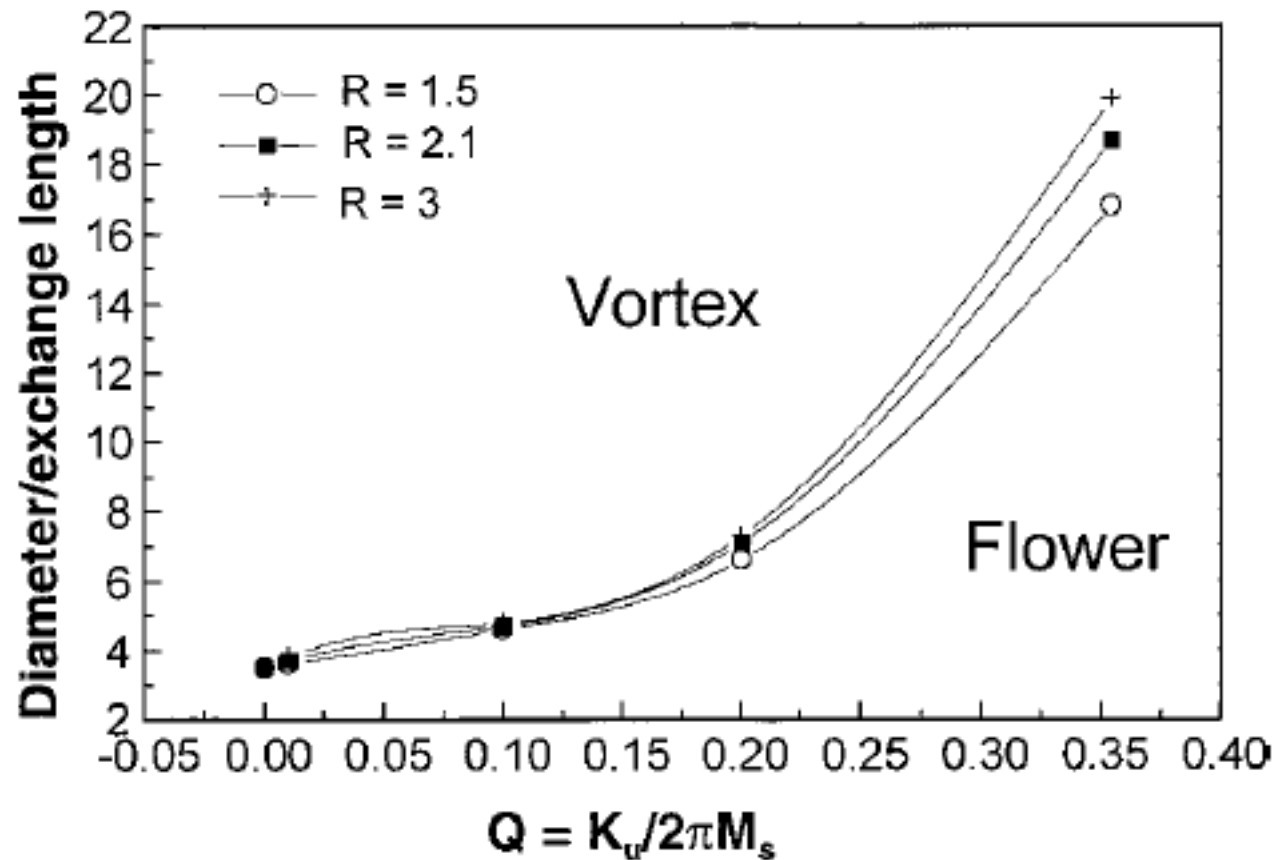
Hysteresis loops and remanent states

- The **type-C** loops represent particles that contain more complex configurations such as vortices causing partial flux closure, which reduces the remanence of individual particles to a greater degree as the particles become larger.
- These particles are expected to have low coercivity because small applied fields can move the vortex through the particle



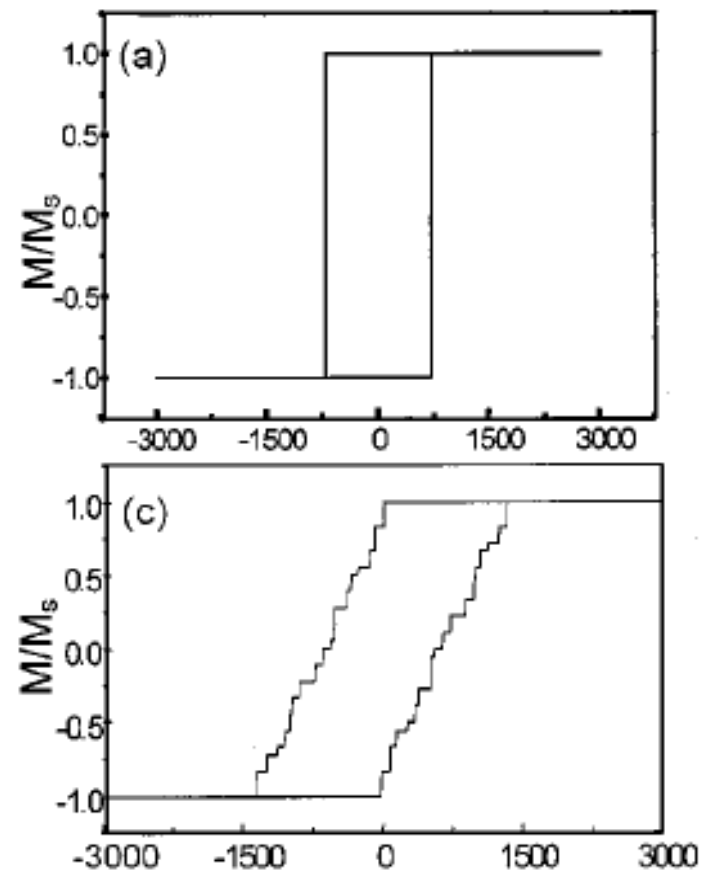
Anisotropy effects

- The presence of uniaxial anisotropy additionally influences the remanent state of small particles



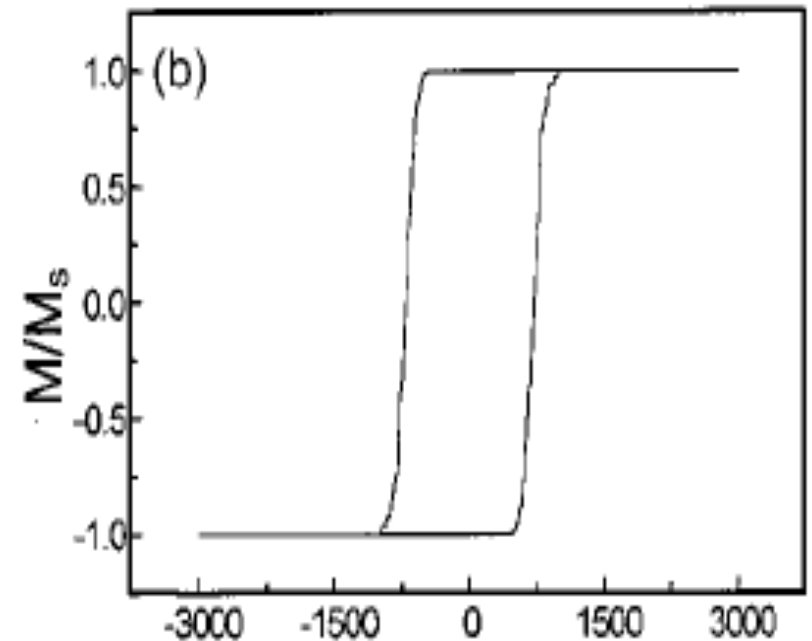
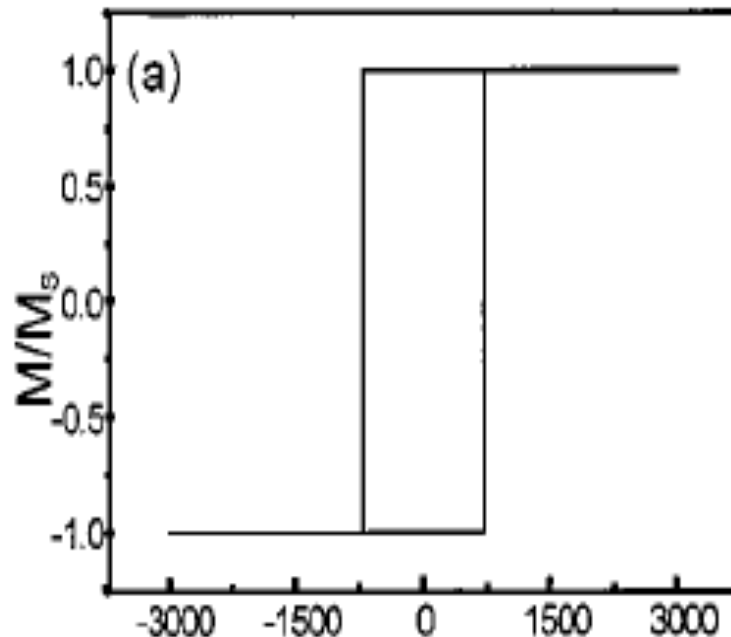
Interactions between particles

- Interparticle magnetostatic interactions can be estimated by comparing the nearest-neighbor interaction field H_i to the switching field of an individual cylinder H_c .
- **Dipolar** field from all other particles in the array, is $9H_i$
- If $9H_i / H_c > 1$, then the fields from neighboring particles can be large enough to reverse the magnetization of a particle in the array leading to a remanence less than 1



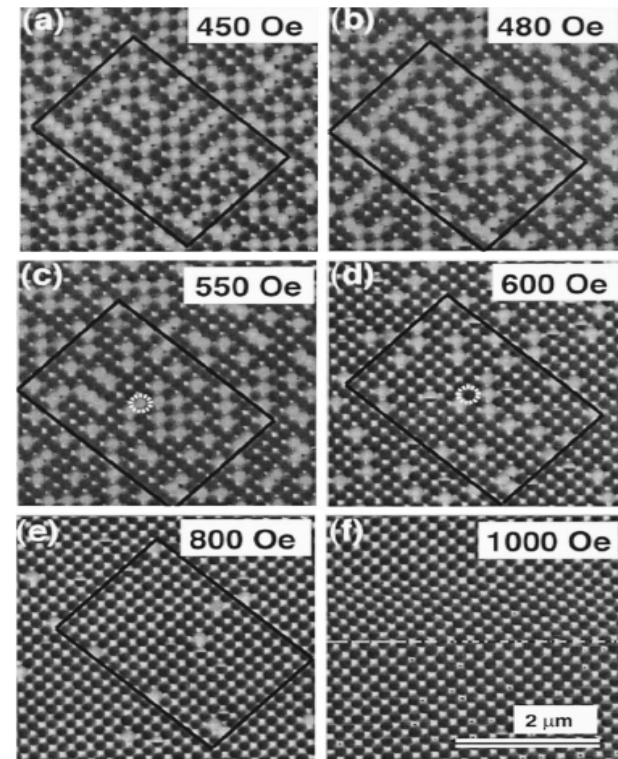
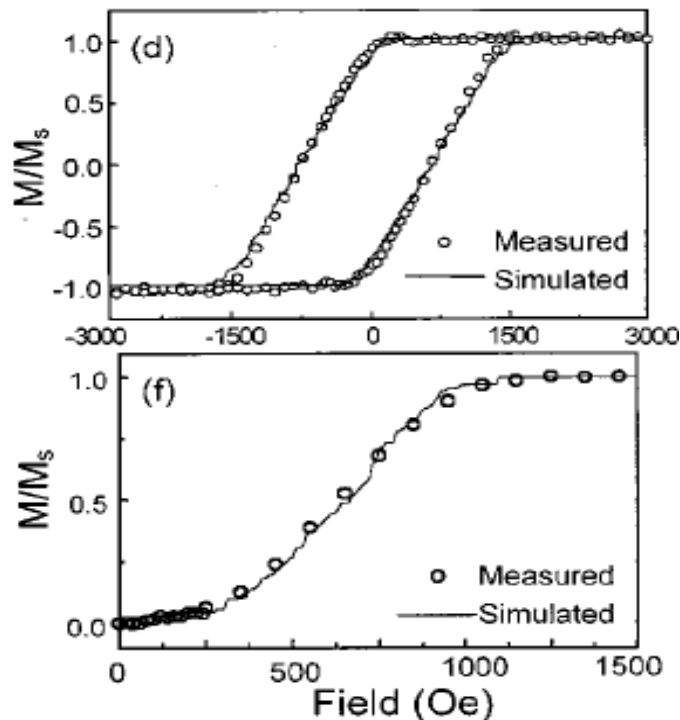
The switching field distribution

- The spread in switching fields of the particles arises from two causes: the effects of magnetostatic interactions, and intrinsic variability between the particles.
- These two factors cause the hysteresis loop of the array to be nonsquare, even though individual particles may have square hysteresis loops.
- Intrinsic variability between particles arises from small variations in size, shape, or the statistical effects of the grains in polycrystalline particles.



The switching field distribution

- The intrinsic variability is expressed by the standard deviation σ of the switching-field distribution
- It can be extracted from the fit to the shape of the hysteresis loops
- A better estimate of σ can be obtained by the process of imaging the array by MFM in a varying applied field



CONCLUSIONS

The magnetic behavior of arrays of electrodeposited cylinders has been investigated.

For aspect ratios greater than 0.9, small diameter

- The particles show high remanence parallel to the cylinder axis
- Hysteresis loops characteristic of an array of “single-domain” particles that interact magnetostatically

As the particle size increases

- The remanence and coercivity decrease
- The existence of vortex or multidomain states is inferred

Excellent agreement with the results of a micromagnetic model, which predicts a gradual transition from a flower to a vortex

CONCLUSIONS

Low-aspect-ratio particles

- Easy magnetization plane parallel to their base
- The flower-vortex transition occurs at larger diameters as the aspect ratio decreases.

Applications in patterned magnetic recording media

- Requires the particles to be single domain with significant axial remanence.
 - This can be achieved in small particles even at modest aspect ratios, and is promoted by the presence of axial anisotropy
- Magnetostatic interactions must be sufficiently small to avoid array self-demagnetization
- Intrinsic switching-field distribution must be minimized by control of lithography and microstructure