Lecture 26

Magnetic Domains

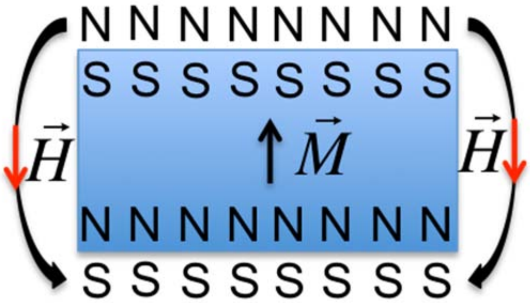
Today

1. Formation of magnetic domains.
2. Domain walls.
3. Domain wall motion: relation to hysteresis.

Questions you should be able to answer by the end of today's lecture

1. What is the reason for formation of magnetic domains?
2. What energies contribute to the domain wall structure?
3. How does domain wall thickness relate to the magnetic anisotropy constant and exchange integral?
4. What is the nature of hysteresis in multi-domain ferromagnetic materials?
5. What is the difference between soft and hard magnetic materials?
   Which material would you use for the hard drive? And for a power generator?

If all ferromagnets consisted of individual magnetic domains magnetized to saturation along one of the easy axes, then any iron rod would act like a permanent magnet. This obviously does not happen in nature. Why not?



Consider a ferromagnet that is magnetized to saturation along one of the easy axis. In this case the edges of the ferromagnet generate a demagnetizing field (the field of the magnetic dipole).

In order to minimize the magnetostatic energy $E_d = \vec{H}_d \cdot \vec{M}$ the material breaks into the "magnetic domains". These domains are not necessarily aligned with grain boundaries: many domains can exist within one large grain, and several small grain can belong to the same magnetic domain.

Illustration bellow shows how formation of domains yields to zero net magnetization (b), (c) in the absence of external magnetic field. In this case each domain is magnetized to saturation in the direction of one of the easy axes, but the sum of the domain magnetization is zero.

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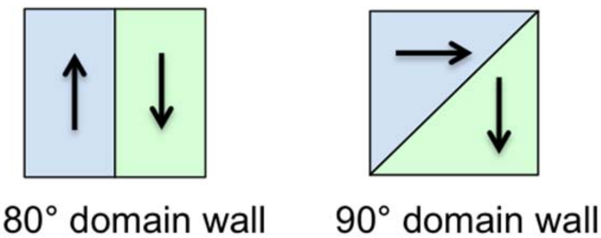
When external field is applied to the multi-domain ferromagnet, saturation magnetization can be achieved through the domain wall motion, which is energetically inexpensive, rather than through magnetization rotation, which carries large anisotropy energy penalty.

So what happens at the boundary between two magnetic domains? What are the domain walls?

Domain walls are the boundaries between the regions (domains) in which all spins (or magnetic dipoles) are aligned in the direction of the easy axis. At the domain wall magnetic dipoles or spins have to reorient themselves.



Does the reorientation of the spins happen instantaneously (within one lattice spacing) or does it take several lattice spacings?

Recall that the energy associated with the positioning of two spins oriented in the opposite direction in each other's proximity results in a large exchange energy penalty:

$$E_{ex} = -2J_{12}\vec{S}_1 \cdot \vec{S}_2 = -2JS^2 \cos\theta,\ \ \theta\uparrow \Rightarrow E_{ex}\uparrow,\ \ \theta = \pi \Rightarrow E_{\max} = 2JS^2$$

Consequently, it turns out to be advantageous to reorient the spins across multiple spacings.

The walls can be classified as (a) Bloch walls – in these walls spins rotate within the plane of the wall, and (b) Neel walls – in these walls spins rotate in the plane perpendicular to the plane of the wall.

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Wall width

Let's consider a simplest Bloch 180º domain wall (a), as we have mentioned above it is energetically cheaper to reorient spins over several lattice spacings.

If we have a wall that is ***N*** lattice spacings wide, then the angle between the neighboring spins is: $\theta = \dfrac{\pi}{N}$.

Then the corresponding exchange energy penalty is:

$$\Delta E_{ex} = E_{ex} - E_{ex}^{\theta=0} = -2JS^2\cos\theta + 2JS^2 \approx 2JS^2\frac{\theta^2}{2} = JS^2\frac{\pi^2}{N^2}.$$

Then the total exchange energy penalty is a sum of the penalties between each pair of spins over ***N*** lattice spacings: $\Delta E_{ex}^{total} = N \cdot JS^2\dfrac{\pi^2}{N^2} = JS^2\dfrac{\pi^2}{N}$.

If ***a*** is the lattice constant, then the exchange energy penalty per unit area of the 180º Bloch wall is:

$$\sigma_{BW}^{ex} = \frac{\Delta E_{ex}^{total}}{a^2} = JS^2 \frac{\pi^2}{a^2 N}$$

From this expression it looks like: $N \to \infty \Rightarrow \sigma_{BW}^{ex} \to 0$, i.e. it is energetically advantageous to have infinitely thick domain walls, which means that there will be no domains but just randomly oriented spins. This is obviously not the case in ferromagnets, and the reason for this is the magnetic anisotropy energy increases when spins are not oriented in the direction of the easy axis. **This means that the domain w all width is determined by the balance betw een the exchange energy and the magnetic anisotropy.**

Recall that the magnetic anisotropy energy is: $E_a \approx K_u \sin^2\theta$, where θ is the angle between the magnetic dipole and the easy axis.

Assuming that within the domains the spins are oriented along the easy axis and the neighboring domains are magnetized in opposite directions (180º wall) we can calculate the total anisotropy energy associated with the spins in the wall that is N lattice spacing wide. Replacing the sum by the integral and taking into account that $\theta = \frac{\pi}{N}$, we find:

$$E_a^{total} = \sum_{i=1}^{N} K_u \sin^2\theta_i \approx \frac{1}{d\theta} K_u \int_0^{\pi} \sin^2\theta \, d\theta = \frac{1}{\pi/N} K_u \frac{1}{2}\pi = \frac{NK_u}{2}.$$

As anisotropy constant is per unit volume the total anisotropy energy density per unit area of the Bloch wall is:

$$\sigma_a^{total} = \frac{NK_u}{2}\frac{a^3}{a^2} = \frac{NK_u a}{2}$$

Bringing together the contributions of the exchange energy and the magnetic anisotropy energy, we find the energy density associated with a unit area of the Bloch wall is:

$$\sigma_{BW} = \sigma_{BW}^{ex} + \sigma_{BW}^{a} = JS^2 \frac{\pi^2}{a^2 N} + \frac{NK_u a}{2}$$

Now all we need to do in order to find the wall width is to find the number of lattice spacings ***N*** that minimizes the energy density of the wall:

$$\frac{d\sigma_{BW}}{dN} = -\frac{JS^2\pi^2}{N^2 a^2} + \frac{K_u a}{2} \Rightarrow N = \pi S\sqrt{\frac{2J}{K_u a^3}}$$

Then the wall width is: $\delta = Na = \pi S\sqrt{\frac{2J}{K_u a}} \Rightarrow \begin{cases} J\uparrow \Rightarrow \delta\uparrow \\ K_u\uparrow \Rightarrow \delta\downarrow \end{cases}$

Larger exchange integral yields wider walls and higher anisotropy yields thinner walls.

If the piece of the ma terial were smaller than the size of the domain wall, then this piece would consist of one single domain. It is true, for example, for some nanoparticles.

The total energy per unit area of the wall is:

$$\sigma_{BW} = \pi S \sqrt{\frac{2JK_u}{a}}$$

Both exchange and anisotropy contribute to the energy penalty of a wall formation.

Magnetization curve of the multi-domain ferromagnet.

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)LJ 2'+DQGOH\ 5REHUW & *Modern Magnetic Materials*. Wiley, 1999.

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Increasing magnetic field: O'Handley, Robert C. *Modern Magnetic Materials*. Wiley, 1999.

In the previous lecture we have derived the hysteresis loop for the single-domain ferromagnet. We have found that in the direction of the easy axis the hysteresis loop has a perfect rectangular shape and the coercive field is determined by the anisotropy and the saturation magnetization.

The magnetic fields required to magnetize the individual domains to saturation are small in ferromagnets and consequently it is reasonable to assume that in zero applied field individual domains are fully magnetized but the net magnetization of the entire specimen is zero.

When external magnetic field is applied the domains that are oriented in the direction of the field start to grow at the expense of the other domains. This is achieved by the ***domain wall motion***, which is energetically cheap process (bottom illustration).

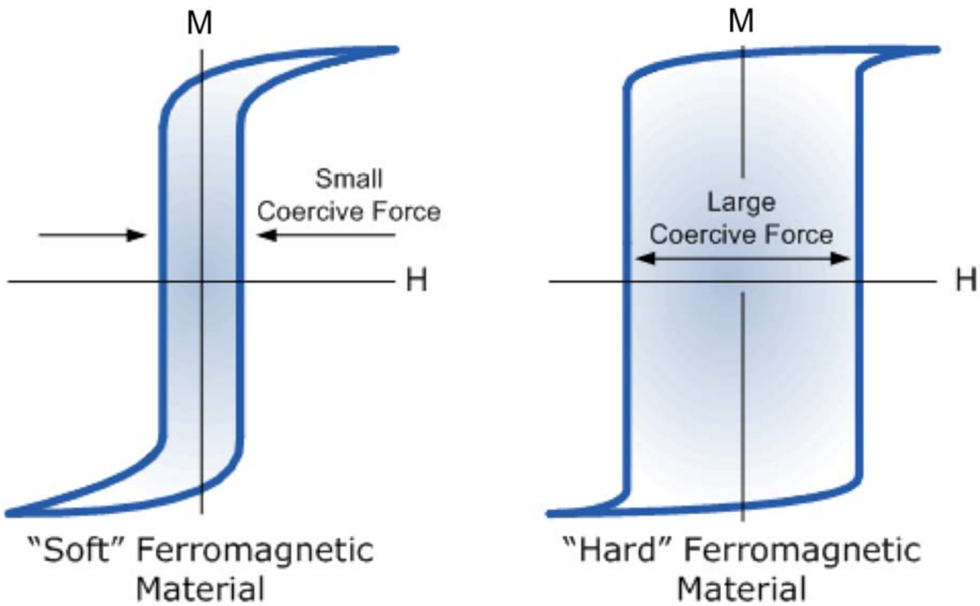
If applied magnetic field is sufficiently large it will eventually overcome the anisotropy energy and domain magnetization will be reoriented in the direction of the easy axis closest to the direction of the applied field.

If the anisotropy energy is high, which yields high coercive field, then it will be difficult to move the domain walls as well as change the direction of the domain magnetization. Consequently it will be difficult to magnetize material to saturation and it will also be difficult to demagnetize it back to zero magnetization.

In addition coercive field can be increased by pinning of the domain walls. Defects, built-in strains, impurities impede the domain wall motion and hence contribute to coercivity.

High coercivity yields large area of the hysteresis loop. The area of the hysteresis loop is the energy dissipated during magnetization – demagnetization - reverse magnetization cycle.

***Soft* and *hard* magnetic materials:**



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1. **Magnetically soft materials:**
   - Low anisotropy => wide domain walls
   - Low coercivity (e.g. permalloy Ni/Fe $B_c \sim 2 \cdot 10^{-7}$T)
   - Small area hysteresis loop
   - Large saturation magnetization

These materials are easy to magnetize and demagnetize. They are used in applications where magnetization direction has to be frequently flipped, i.e. devices that run in AC mode. For example transformers, generators and motors have soft magnetic cores.

2. **Magnetically hard materials**
   - High anisotropy => narrow domain walls
   - High coercivity (e.g. $Nd_2Fe_{14}B$ $B_c \sim 1.2$T)
   - Large area hysteresis loop
   - Large saturation magnetization

These materials are very difficult to magnetize and demagnetize, hence they can be used for information storage since they won't demagnetize spontaneously. Hard magnetic materials are use in hard drives, where 1 bit of information is actually 1 domain magnetized to saturation or demagnetized to zero, the bits are generally referred to as per square inch. Modern hard drives are within Tbit/in^2.