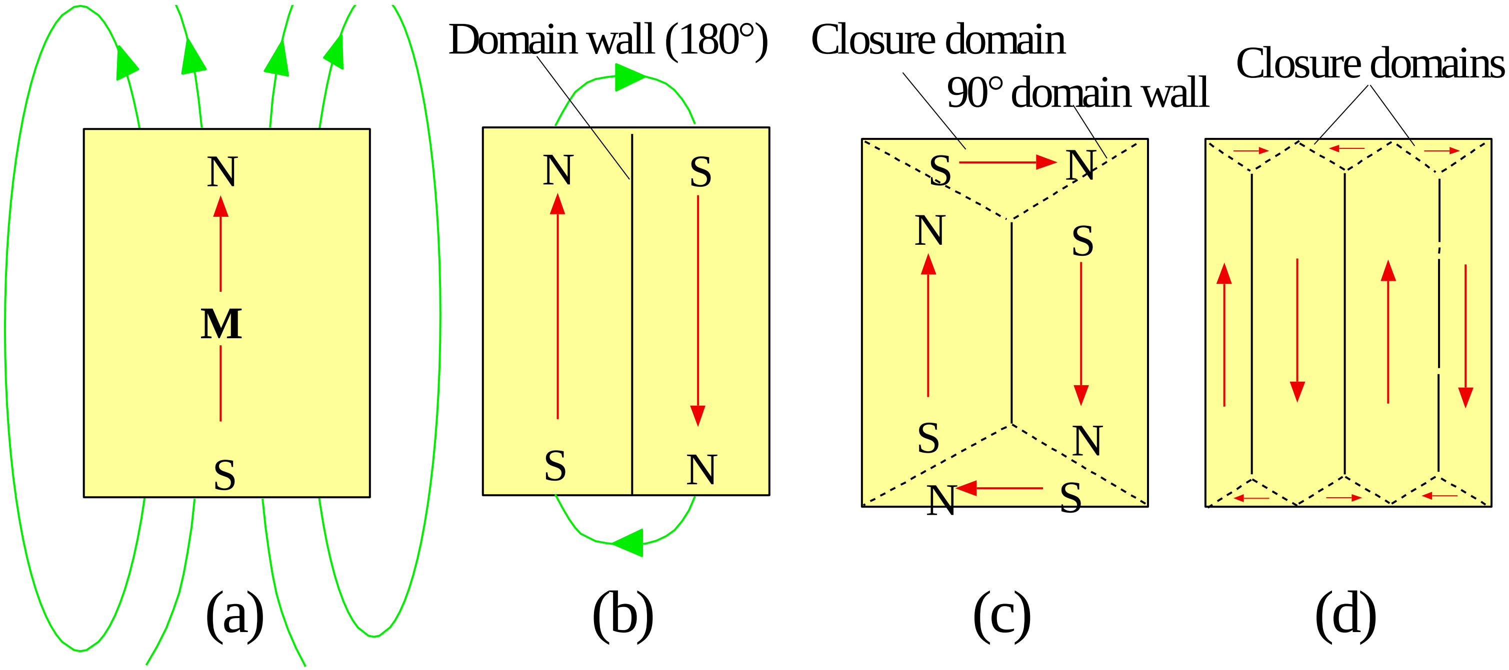
Chapter 7 Magnetic properties

1. Magnetization
2. Classification of magnetic materials
3. Ferromagnetism origin and exchange coupling
4. **Saturation magnetization and Curie temperature**
5. **Magnetic domains**
6. **Hysteresis**
7. **Simulation of hysteresis curve**

Tutorial

Superconductivity

Magnetic domains（磁畴）



(a) Magnetized ferromagnet in which there is only one domain.

(b) Formation of two domains with opposite magnetizations reduces the external field. There are, however, field lines at the ends.

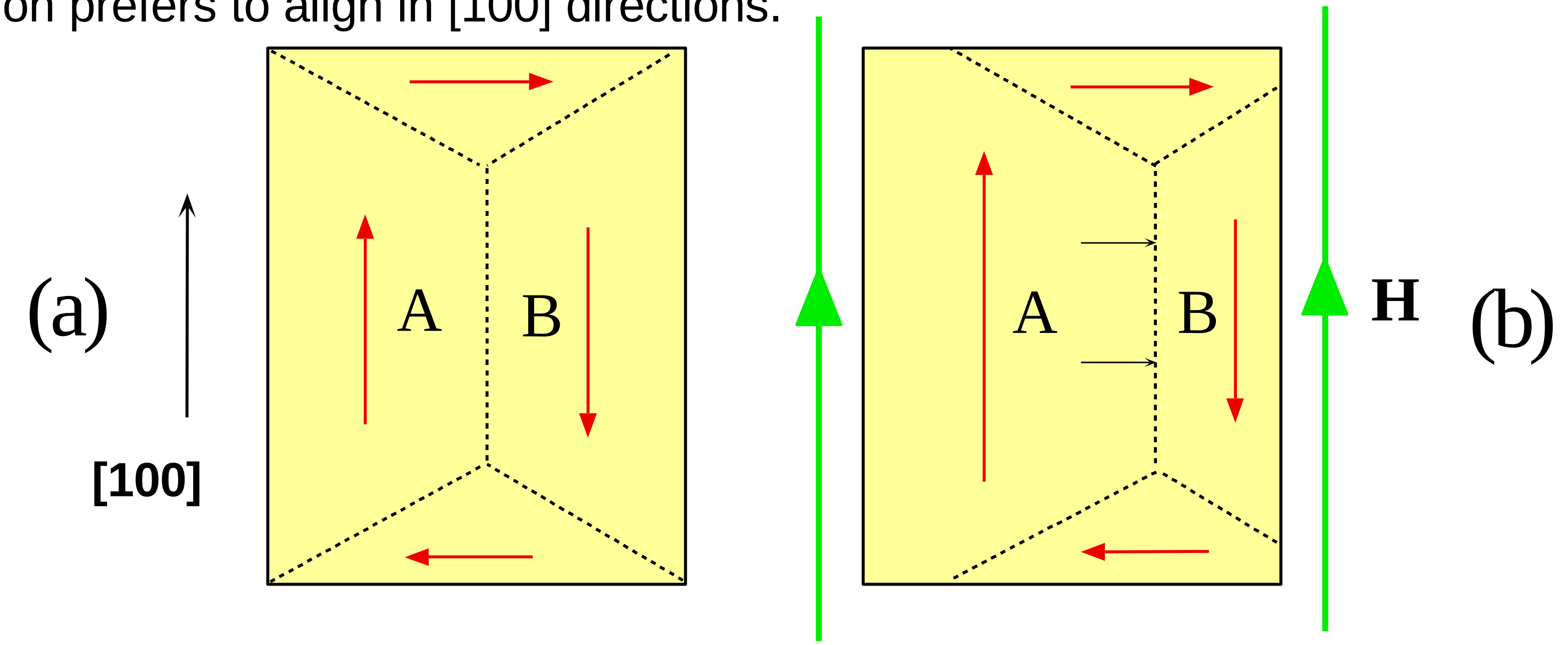
(c) Closure domain at the ends eliminates the external fields.

(d) A ferromagnet with several domains and closure domains. There is no external magnetic field and the specimen appears un-magnetized.

Magnetic domains（磁畴）

Anisotropy is defined by the directional dependence of physical properties. There are two major mechanism of **magnetic anisotropy: shape** and **magnetocyratalline**.

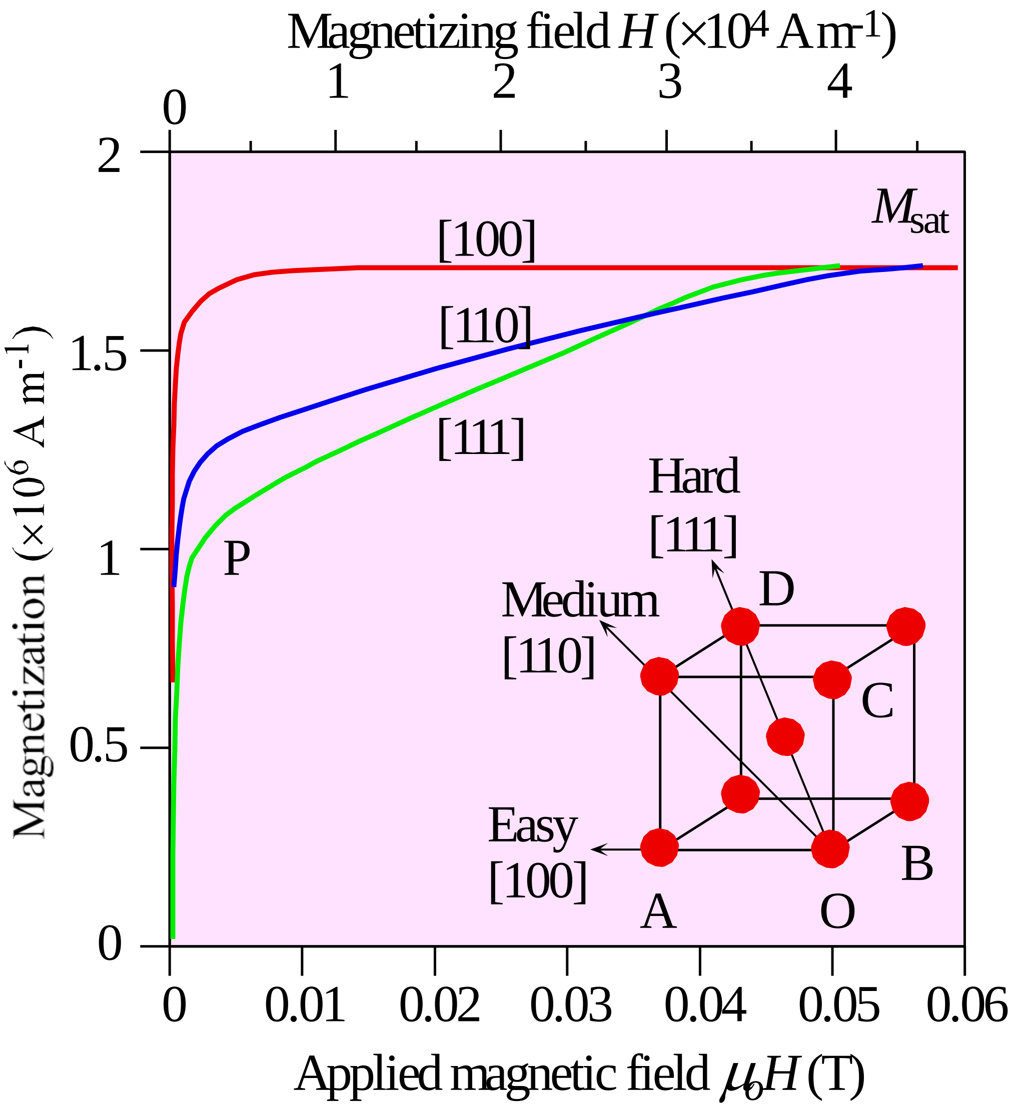
Magnetocrystalline anisotropy （磁晶各向异性）refers to the difference in magnetic properties along different crystal directions. For example, magnetization in bcc-iron prefers to align in [100] directions.



(a)An unmagnetized crystal of iron in the absence of an applied magnetic field. Domains A and B are the same size and have opposite magnetizations.

(b)When an external magnetic field is applied the domain wall migrates into domain B which enlarges A and B. The result is that the specimen now acquires net magnetization.

Magnetocrystalline anisotropy（磁晶各向异性）



Magnetocrystalline anisotrpy in a single iron crystal. *M* vs. *H* depends on the crystal direction and is easiest along [100] and hardest along [111]

Different applied magnetic fields are required to align spin along different crystal directions.

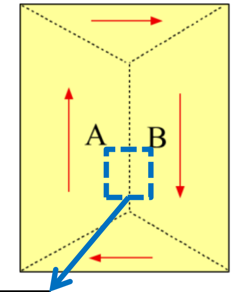
For bcc-Fe, [100] are the **easy axes**（易磁化轴）, while [111] the **hard axes**（难磁化轴）.

The alignment along [111] causes an increase of the potential energy (magnetocrystalline anisotropy energy, **K**) of 48 mJ/cm^3 or 3.5x10^{-6} eV per atom compared to the [100] direction.

Table 8.4 Exchange interaction, magnetocrystalline anisotropy energy K, and saturation magnetostriction coefficient λ_{sat}

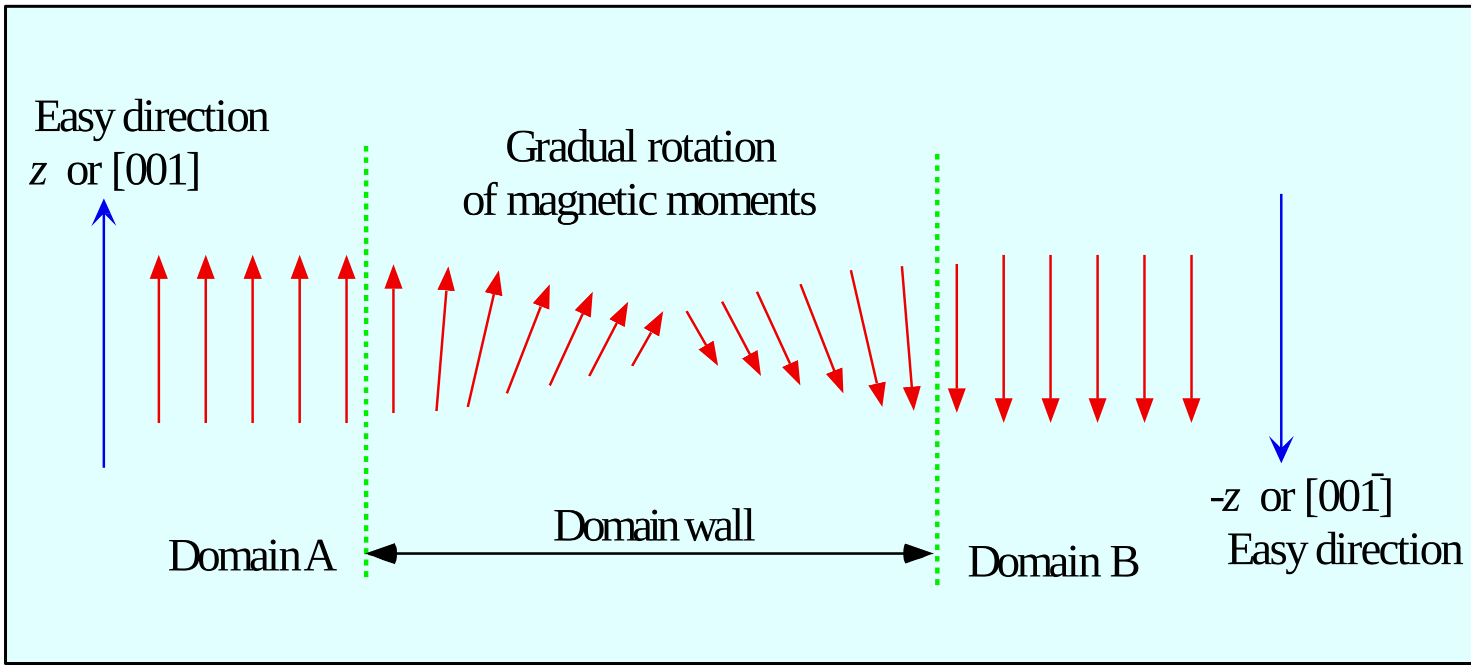
Material	Crystal	$E_{ex} \approx kT_C$ (meV)	Easy	Hard	K (mJ cm^{-3})	λ_{sat} ($\times 10^{-6}$)
Fe	BCC	90	<100>; cube edge	<111>; cube diagonal	48	20 [100]
						−20 [111]
Co	HCP	120	// to c axis	⊥ to c axis	450	
Ni	FCC	50	<111>; cube diagonal	<100>; cube edge	5	−46 [100]
						−24 [111]

Magnetic domain wall （磁疇壁）



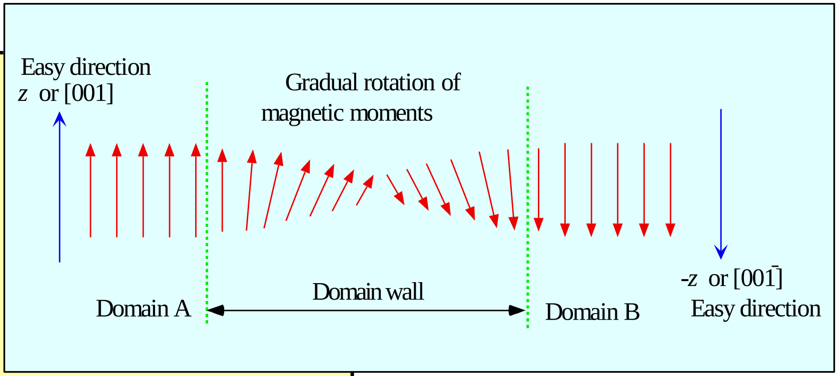
Two neighbored domains are separated by a domain wall.

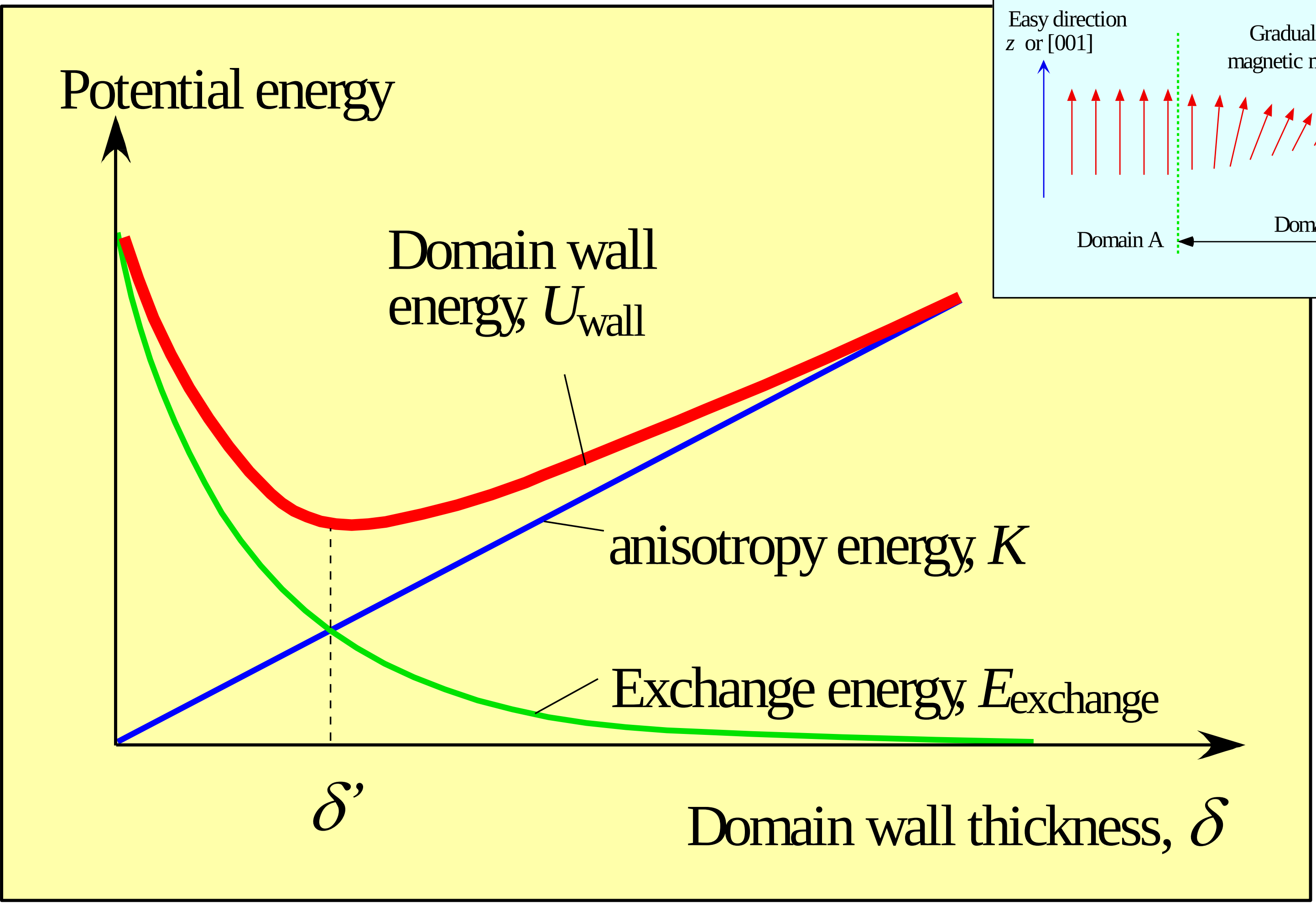
Magnetic moments rotate across a domain wall.



In a domain wall the neighboring spin magnetic moments rotate gradually and it takes several hunbdred atomic spacings to rotate the magnetic moment by 180°.

The domain wall thickness can be determined by the minimization of the total energy (anisotropy energy and exchange energy)





Potential energy of a domain wall depends on the exchange and anisotropy energies

If the interatomic spacing is a, the potential energy U_{wall} of a 180° wall is given as:

$$U_{wall} = \frac{\pi^2 E_{ex}}{2a\delta} + K\delta$$

The minimization of $dU_{wall}/d\delta = 0$ gives:

$$\delta = \left(\frac{\pi^2 E_{ex}}{2aK} \right)^{1/2}$$

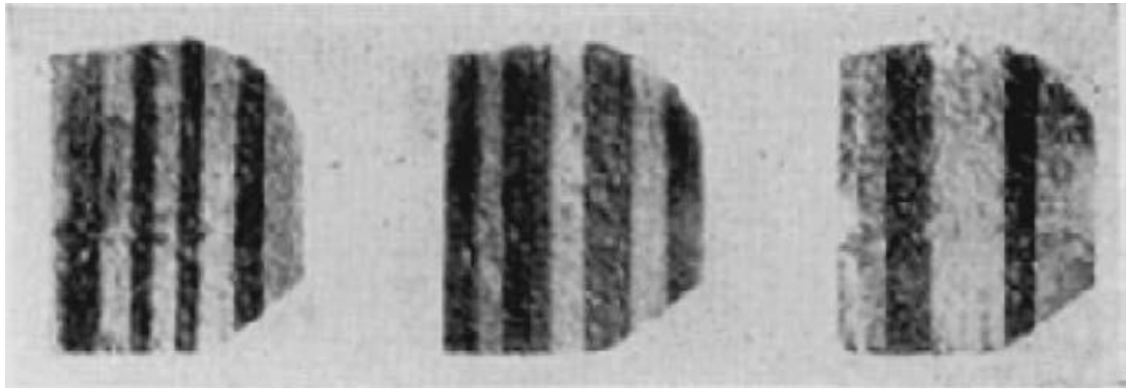
Example (domain wall): *Estimate the domain wall thickness of a 180° wall in bcc-Fe.*

From $E_{ex} = kT_c = 1.38x10^{-23}$ x $1043 = 1.4x10^{-20}$ J, a = 0.3 nm and K = 50 kJm^{-3}:

$$\delta = \left(\frac{\pi^2 \cdot 1.4x10^{-20}}{2 \cdot 0.3x10^{-9} \cdot 50x10^3} \right)^{1/2} = 6.8x10^{-8} m = 68 nm$$

$\Rightarrow$

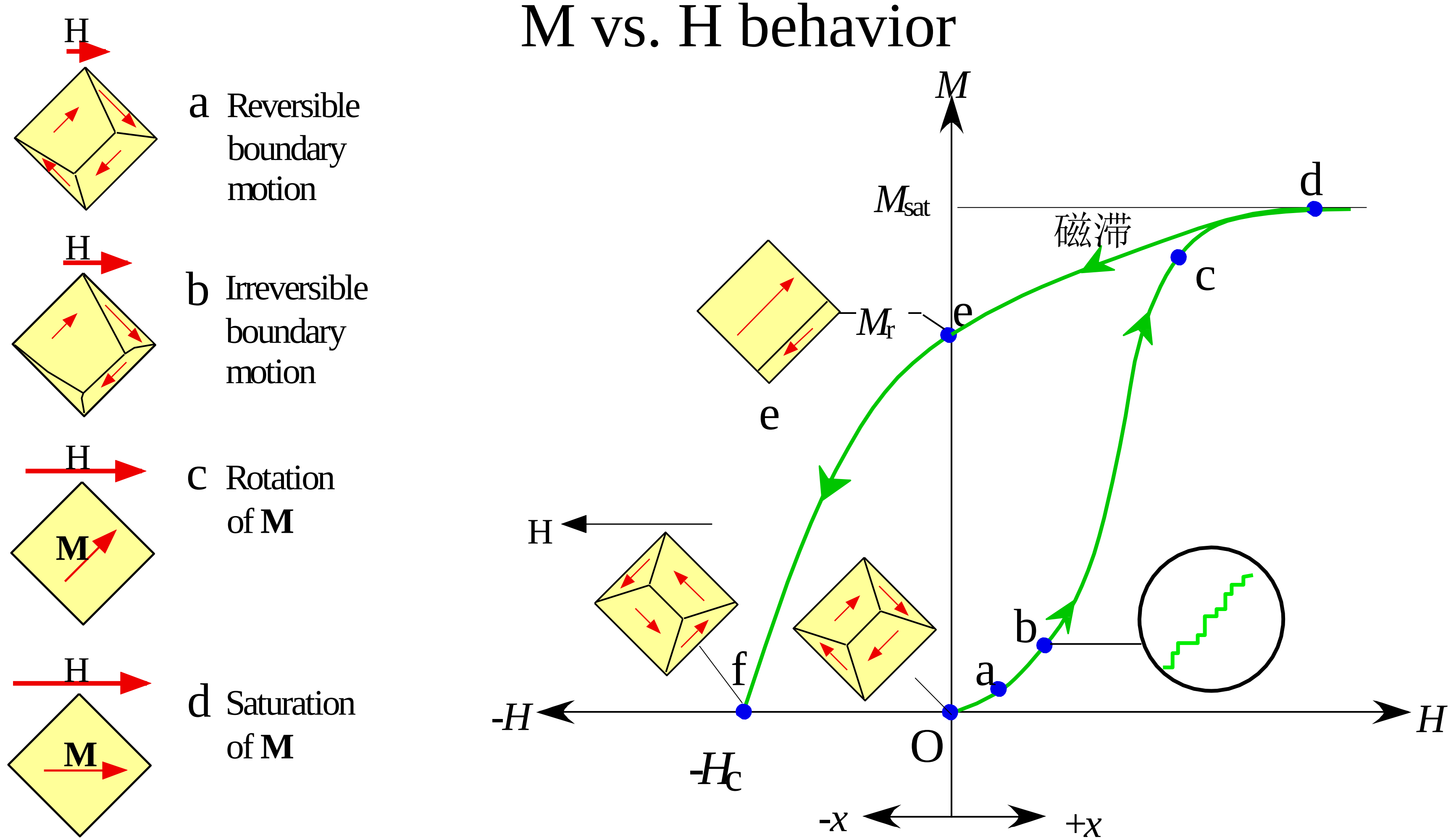
$$U_{wall} = \frac{\pi^2 E_{ex}}{2a\delta} + K\delta = 0.007 Jm^{-2}$$



Three different **domain configurations** in a demagnetized sample of silicon iron.

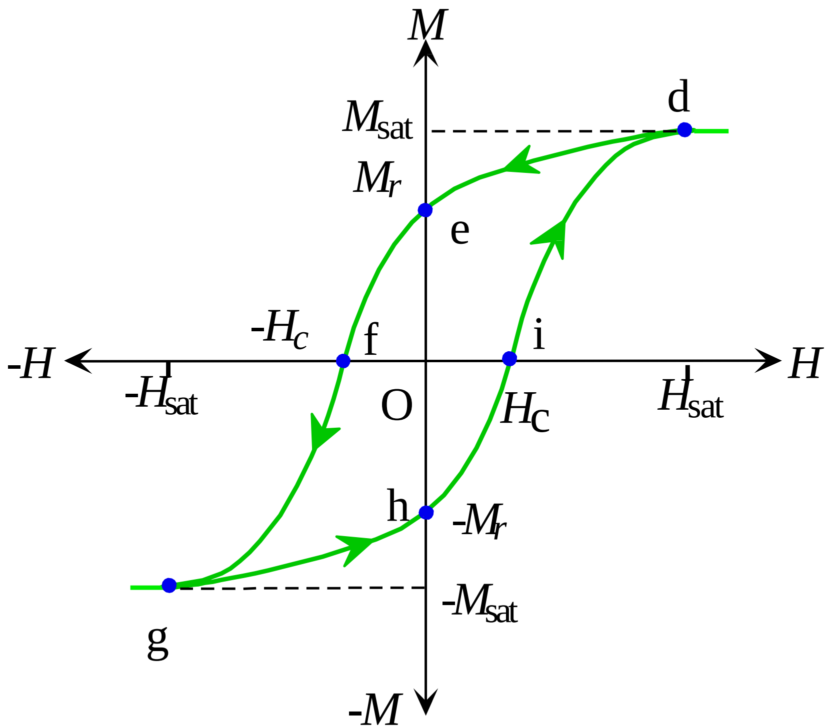
Pattern of domains on single crystals of silicon iron. The lighter-colored regions are the **domain boundaries**.

M vs. H behavior



M vs. H behavior of a previously unmagnetized polycrystalline iron specimen. An example grain in the unmagnetized specimen is that at O. (a) Under very small fields the domain boundary motion is reversible. (b) The boundary motions are irreversible and occur in sudden jerks. (c) Nearly all the grains are single domains with saturation magnetizations in the easy directions. (d) Magnetizations in individual grains have to be rotated to align with the field, H. (e) When the field is removed the specimen returns along d to e. (f) To demagnetize the specimen we have to apply a magnetizing field of Hc in the reverse direction.

M vs. *H* hysterisis curve（磁滞回线）



Several important parameters from the magnetic hysteresis loop (when H is sufficiently high):

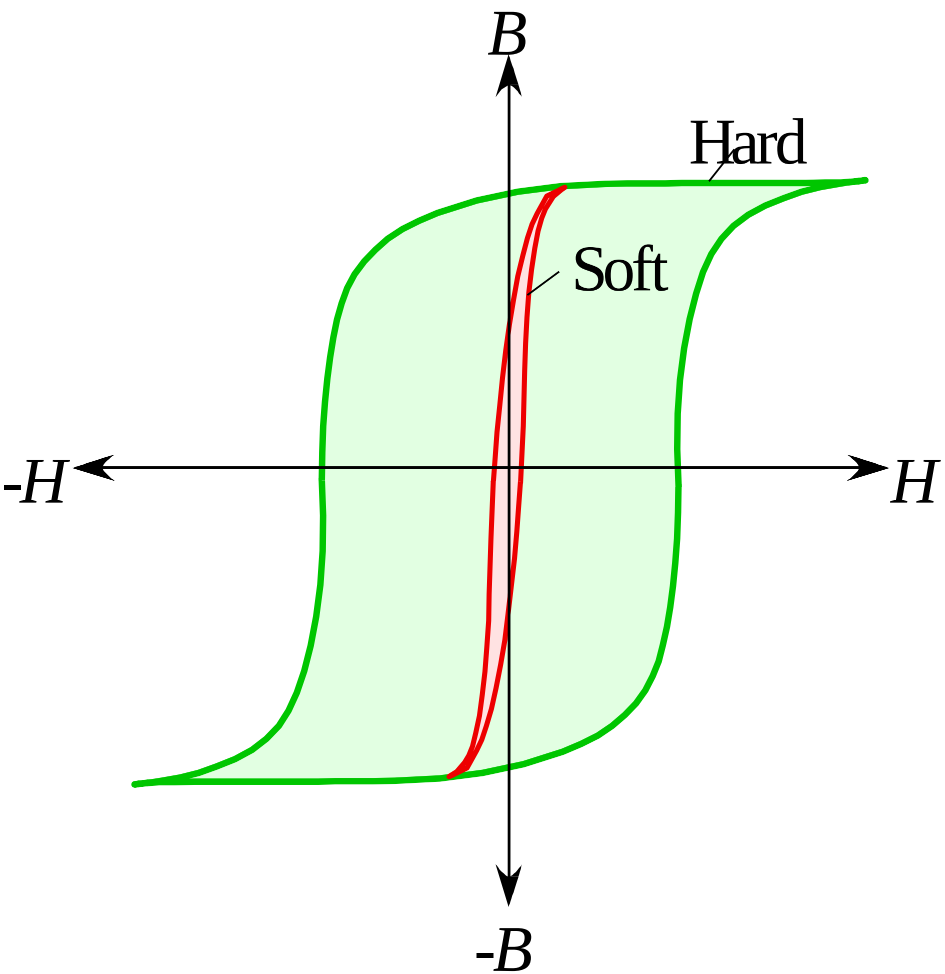
M_{sat}: saturation magnetization

M_r: remanence or remanent magnetization （剩磁）

H_c: coercivity（ 矫顽力）

Soft and hard magnets

Soft-magnets can be easily magnetized and demagnetized.
Hard-magnets are characterized by large values of coercivity and remanence.



In general, hard magnets require a large value of magnetic anisotropy.

Magnetic anisotropy values of soft magnets are usually very small.

完成 **Assignment 7.1、7.2**，提交**Assignment 7.1**

提交时间：**5月22日**（周四）中午前

提交方式：电子版（写明姓名、学号），通过本班课代表统一提交