SUMMER INTERNSHIP PROJECT
DOMAIN DYNAMICS UNDER STRAIN

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Abstract

Magnetic storage media are widely used in computers to store data and record audio and video signals. One of the ways to store the data is to change the magnetization states in a magnetic layer using an electric current or applying a magnetic field. The aim of this study is to understand the structure and dynamics of domain walls and the effect of stress on the magnetic properties of ferromagnets.

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CERTIFICATE

This is to certify that the project report "Domain dynamics under Strain", is being submitted by Bhavani Prasad Behera under the supervision of Dr. Subhankar Bedanta to the School of Physical Sciences as a summer project report.

Date: (Dr. Subhankar Bedanta)

INTRODUCTION

Domain theory has become central to any discussions regarding magnetization processes in materials. In the initial years of the development of theories of magnetization, not much importance was given to domain theory for explaining the magnetization curves or the mechanism of magnetic hysteresis. Magnetic domains are the regions of uniform magnetization in ferromagnets. The interface between two domains having magnetizations in different directions is known as a domain wall. In storage devices like MRAMS where data is stored using the magnetization of layers, the efficiency of writing in the device depends on how efficiently we can control the domain sizes and their magnetization. Hence, knowledge of the properties of domain walls and domain wall dynamics is necessary.

DOMAIN WALLS

Domain walls are the interfaces between two domains of different directions of magnetization. There are two types of walls based on how the spins of the constituent atoms are arranged inside the wall – Bloch walls and Neel walls.in Bloch walls, the spins rotate in the plane of the wall, and in Neel walls, in the plane perpendicular to the wall.

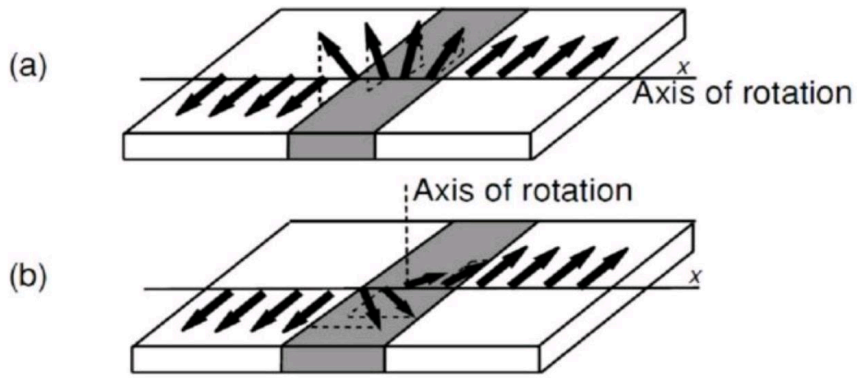

Fig 1: Two types of domain walls[3]

The structure of domain walls is determined by the magnetic anisotropy of the material and the exchange interaction. In the domain wall, the direction of the spin of any particular atom is determined by the torques generated by these two interactions. They are discussed briefly below.

Exchange interactions

The exchange forces between two particles depend entirely on the relative spin orientations. When two atoms have spins S_i and S_j, the energy of the system of the two atoms has exchange energy which is given as:

$$E_{ex} = -2J_{ex}S_i.S_j = -2J_{ex}S_iS_j\cos\phi_{ij} \quad (1)$$

J_{ex} is the exchange integral and ϕ is the angle between the spins of the two atoms. When E_{ex} is positive, the exchange energy is minimum for parallel spins and maximum for antiparallel spins. This is the case with atoms as they have a positive exchange integral.

Magnetic anisotropy

The term "magnetic anisotropy" simply refers to the difference in magnetic properties when measured in different directions in a material. Generally, in a ferromagnet, axes exist along which magnetization requires less applied field and other axes along which magnetization requires more applied field. The axes are known as easy and hard axes of magnetization respectively. There are several kinds of anisotropies – crystal anisotropies, shape anisotropy, stress anisotropy, induced anisotropy, exchange anisotropy. Out of these, only crystal anisotropy is intrinsic to the material.

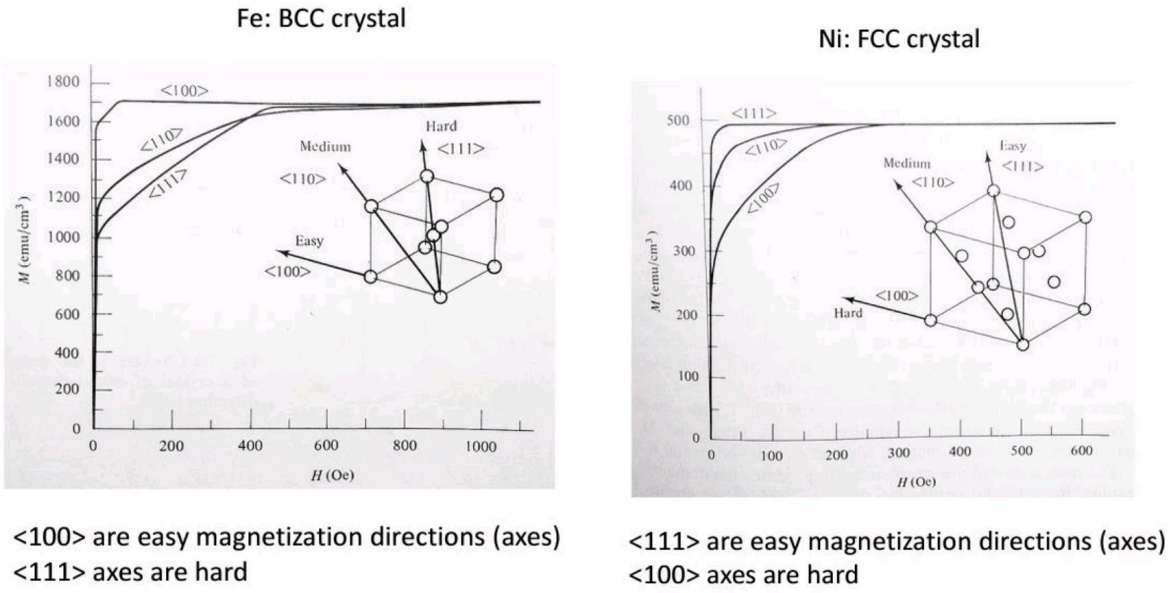

Fig 2: Figure showing magnetocrystalline anisotropy of two crystals.[2]

For cubical anisotropies, the expression of anisotropy energy is given as,

$$E_{cub} = K_O + K_1(\alpha_1\alpha_2 + \alpha_1\alpha_3 + \alpha_3\alpha_2) + K_2\alpha_1\alpha_2\alpha_3 + \cdots (2)$$

Where, K_0, K_1, K_2 are the anisotropy constants for a particular material, α_1, α_2, α_3 are the direction cosines of the saturation magnetization with respect to the axes of the cubic crystals.

For uniaxial anisotropy, the anisotropy energy is given by,

$$E_{uni} = K_0 + K_1 \sin^2\theta + K_2 \sin^4\theta + \cdots (3)$$

Where, K_0, K_1, K_2 are the anisotropy constants and θ is the angle between the saturation magnetization and the easy axis. Since there is only one easy axis of magnetization in uniaxial crystals, there is only one angle.

The origin of crystal anisotropy is attributed to spin-orbit coupling and lattice-orbit coupling. The spin orientations are coupled to the lattice strongly and hence it is very difficult to change

the direction of magnetization. When we try to change the direction of the spin of an atom, the orientation of the orbit tends to get changed due to spin-orbit coupling, but is resisted by orbit-lattice coupling.

To obtain the thickness of a domain wall and domain wall energy in a uniaxial crystal, the torque generated by the exchange interaction and the anisotropy is compared. The torque due to exchange interaction inside a wall isobtained by taking the derivative of energy with resepect to x and is given by,

$$L_{ex} = 2A\left(\frac{d^2\phi}{dx^2}\right) \qquad (4)$$

Similarly, the torque due to anisotropy is given by,

$$L_K = \frac{\partial(K_U \sin^2\phi)}{\partial\phi} \qquad (5)$$

On equating the two torques and integrating with respect to x and ϕ, we get,

$$x = \sqrt{A/K_u} \int (d\phi / \sin\phi) \quad (6)$$

From this expression, the wall thickness is given as,

$$wall\ thickness = \delta = \pi\sqrt{A/K_U} \quad (7)$$

For calculating the wall energy, we take both the exchange and anisotropy energy. Wall energy per unit area is given by,

$$wall\ energy\ per\ unit\ area = \sigma = \sigma_{ex} + \sigma_{ani} = \int \left[A\left(\frac{d\phi}{dx}\right)^2 + K_u \sin^2(\phi)\right] dx \qquad (8)$$

Integrating the above quantity from -∞ to ∞ we get,

$$\sigma = 4\sqrt{AK_U} \qquad (9)$$

MAGNETOSTRICTION

Before talking about the effect of stress on the magnetization of the material, we need to know about the effect of magnetization on the strain of the material. When a sample is magnetized along a particular direction, it tends to elongate or shrink the material in that direction. This phenomenon is called as magnetostriction.

$$\lambda = \frac{\Delta l}{l} \qquad (10)$$

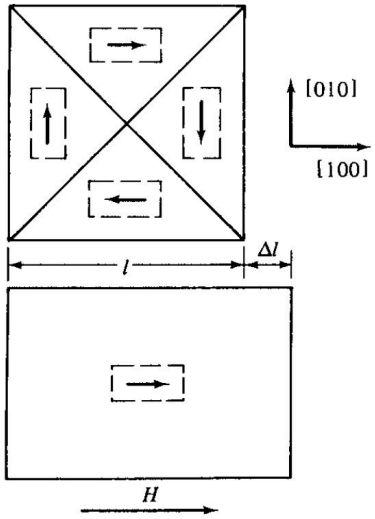

Fig 3: Effect of magnetostriction on iron crystal[7]

Where λ is the strain of the material at saturation magnetization. Depending on whether the value of λ is positive or negative, the material will elongate or get shrunk in the direction of magnetization.

Magnetostriction arises from spin-orbit coupling. For very strong spin-orbit coupling, applied magnetic field tries to change the orientation of the spin as well as the electron cloud. For a particular orientation, the electron cloud repulsions between two adjacent atoms becomes high. Hence, a strain is observed in the material.

EFFECT OF STRESS ON MAGNETIC PROPERTIES

From magnetostriction, we can infer that applied stress on materials can alter the magnetic properties and can hence have a new form of anisotropy. From experimental data, it has been observed that there is close connection between magnetostriction of a material and its magnetic properties. The effect of stress is called the magneto-mechanical effect. As additional stress tends to change the direction of magnetization in a material. Since the direction of magnetization is controlled by both anisotropy and stress, the energy associated with the saturation magnetization is given by,

$$E = K_1(\alpha_1^2\alpha_2^2 + \alpha_1^2\alpha_3^2 + \alpha_3^2\alpha_2^2) - \frac{3}{2}\lambda_{100}\sigma(\alpha_1^2\gamma_1^2 + \alpha_2^2\gamma_2^2 + \alpha_3^2\alpha_3^2) - 3\lambda_{111}\sigma(\alpha_1\alpha_2\gamma_1\gamma_2 + \alpha_2\alpha_3\gamma_2\gamma_3 + \alpha_1\alpha_3\gamma_1\gamma_3) \quad (11)$$

Where $\alpha_i's$ are the direction cosines of M_s and γ_i's are the direction cosines of applied stress σ. The stress is below the elastic limit. The last two terms of the expression of energy comprise the magnetoelastic energy. When the magnetostriction is isotropic i.e., $\lambda_{100} = \lambda_{111}$, then the magnetoelastic energy is simplified to

$$E_{me} = \frac{3}{2}\lambda_{si}\sigma \sin^2\theta \quad (12)$$

This suggests that the magnetoelastic energy is zero when M_s and σ are parallel and maximum when they are perpendicular. This suggests that when λ_{si} is negative, the stress axis becomes the hard axis because extra energy is required to rotate the spin to make it perpendicular to the hard axis.

DOMAIN WALL DYNAMICS

To study the dynamics of domain walls, they have been considered as 1-D elastic interface in a 2-D medium. In earlier sections we saw how exchange energies and anisotropy contribute to the formation of domain walls. Due to this, the wall has some energy per unit area and deforming the wall requires energy, thus making it an elastic system. In such a system, the dynamics can be divided into three regions – high force flow region, depinning region and flow region. These are discussed in brief below,

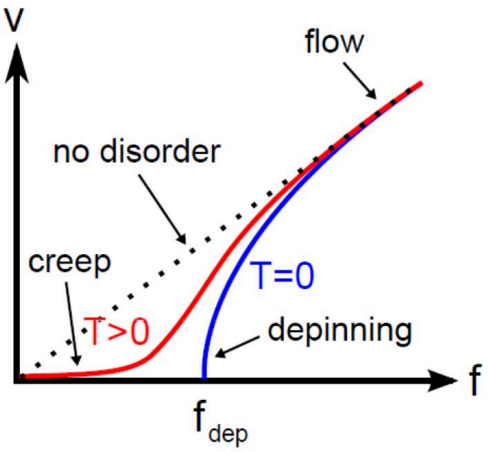

Fig 4: Different regimes of doman wall motion.[4]

High force flow

In this flow regime, the velocity is proportional to the applied driving force and limited only by intrinsic dissipation or friction-like forces. This occurs at fields high enough so that the domain walls overcome any pinning barriers.

Depinning region

At low fields the velocity of the domain wall is not proportional to the field. At zero temperature, there will not be any motion of the domain wall below a critical depinning field. At finite non-zero temperatures, thermal energy might help the domain wall to overcome the pinning barriers to have some motion. For fields above the depinning field, the velocity is proportional to some power of the field, i.e.,

$$v \propto (f - f_{dep})^{\vartheta} \qquad (13)$$

Low force creep region

In the thermally activated creep region, the expression of velocity is given by,

$$v = v_0 \exp\left[-\left(\frac{U_C}{k_B T}\right)\left(\frac{H_{dep}}{H}\right)^{\mu}\right] \qquad (14)$$

Where μ is the scaling co-efficient, which depends on the dimensionality as well as the wandering exponent.

STUDY OF DOMAIN WALL DYNAMICS IN Pt/Co THIN FILMS.

This section gives a glimpse of a study on the effect of voltage-induced strain on the magnetic properties of Pt/Co/Pt film with perpendicular magnetic anisotropy. Ta(4.5 nm)/Pt(2.5 nm)/Co(t)/Pt(1.5 nm) multilayers were deposited by dc magnetron sputtering onto 150 mm thick glass substrates at room temperature. The domain wall velocity was measured using wide field Kerr microscopy. A reverse domain is nucleated in a small region. The domains expand so that an approximately straight domain wall seems to move in the field of view of the microscope. Strain was induced using piezoelectric transducers. To obtain domain wall velocity, an image is recorded and after applying a short pulse of magnetic field, another image is taken. The distance travelled by the domain wall is found out using the images and the velocity is calculated by dividing the distance by the time interval of the magnetic pulse.

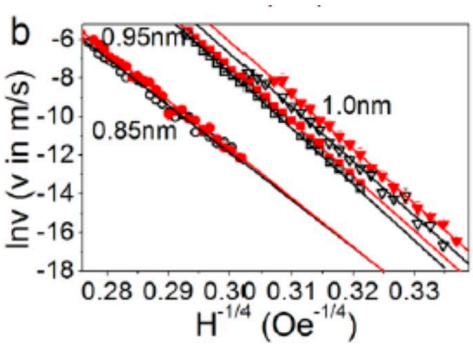

Fig 5(a)

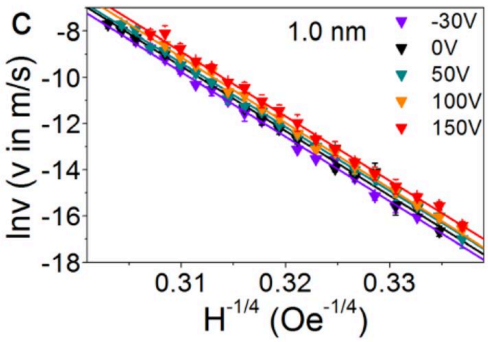

Fig 5(b)

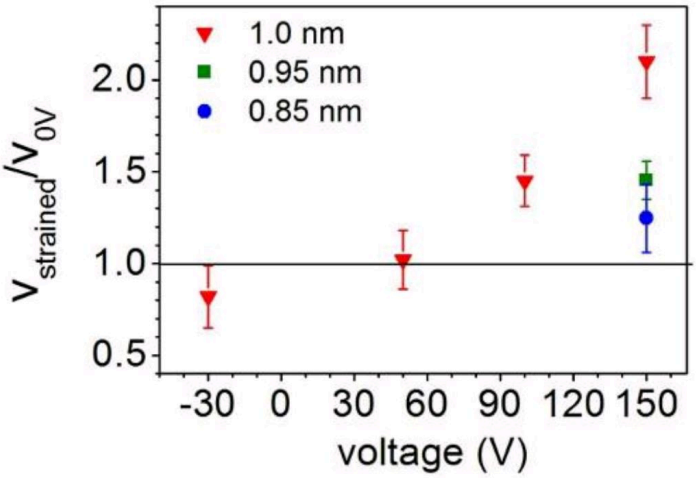

Fig 5(c)

Fig 5: (a) Plot showing natural log of v against $H^{-1/4}$. The plots show data for unstrained(black open shapes) and strained Pt/Co/Pt films. (b) Natural log of v against $H^{-1/4}$ for Pt/Co/Pt films at constant thickness(1 nm) but varying tensile strain. (c) The ratio of domain wall velocity in the unstrained Pt/Co(t)/Pt to the velocity in strained Pt/Co(t)/Pt plotted against transducer voltage for t51.0 nm, 0.95 nm and 0.85 nm.[8]

The domain wall creep motion under strain was studied. it was observed that under tensile strain, the velocity of the domain walls increased corresponding to decreased magnetic anisotropy. The change in the domain wall velocity withs strain increased with the thickness of the cobalt layer. The reduced anisotropy results in increased width of wall and decreased wall energy. Thus, reduced anisotropy reduces the energy barrier and increases domain wall velocity. For thicker films, the domain wall energy is further reduced which leads to greater velocity of domain walls.

CONCLUSION

With the recent developments in skyrmion research, researchers are looking forward to use skyrmions in storage devices in place of magnetic domains as skyrmions require low driving current and hence can be used to store data more efficiently and without much energy loss. However, the domain wall driven storage devices are currently used and effort is being made to make these devices faster and efficient. Using strain to modify the magnetic properties of magnetic materials seems to be a viable option to further develop storage devices.

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