Paper MAG-00-12
Conference on Magnetics, Japanese Electronic Society, Nagoya, Japan, February 2000, pp. 186-200

Stress Effect on the Magnetic State of Small Ferromagnetic Dots

V. Novosad, A. Ohsawa, Y. Otani, and K. Fukamichi,
Department of Materials Science, Graduate School of Engineering, Sendai 980-8579, Japan

O. Kitakami, and Y. Shimada
Institute for Scientific Measurements, Tohoku University, Sendai 980-8577, Japan

Abstract

The magnetic state of a single domain ferromagnetic particle subjected to stress is examined. The particle possesses a uniaxial shape anisotropy, which competes with an additional anisotropy governed by the magnetostriction. Micromagnetic calculations show that the magnetization reversal can be controlled only by rotatable stress. A dot array device is proposed, in which selective magnetization reversal can be realized.

Key words: stress effect, magnetic anisotropy, magnetostriction, and memory cell.

1 Introduction

Ferromagnetic materials exhibit the magnetostrictive properties due to magnetoelastic coupling. For example, the magnet subjected to the external magnetic field deforms depending on the orientation of the magnetization. Alternatively the stress exerted to the magnet generates an additional anisotropy energy, which provides an internal field. This may initiate the magnetization reversal if one can apply the stress strong enough to overcome the potential barrier. On the basis of this concept, the magnetostriction has been widely used in variety of applications [1]. An example is a Magnetic Random Access Memory (MRAM), composed of an array of magnetostrictive transducers coupled with magnetic elements [2]. The magnetization reversal of the element is assisted by the stress wave generated by a selected transducer in a homogeneous applied field slightly smaller than the coercive field. Another application is a magneto-/electro-strictive hybrid thin film memory consisting of a magnetostrictive film in contact with an electrostrictive film [3]. For writing, the electrostrictive film is actuated to impart a stress to a selected area of the ferromagnetic film, which nucleates a poled domain in accordance with the applied field direction. Magnetostrictive 3-dimentional memory cells driven by ultrasonic pulses have also been proposed [4]. However, all of the above mentioned devices require both magnetic and electric fields for the writing process.

In the present work we examined a possibility of stress operated selective magnetization reversal in a small magnetic particle array. Micromagnetic calculations show that the magnetization reversal can be realized by only applying a rotatable stress. This proves a possibility of a stress operated memory device in which the magnetic state is fully controlled by the magnetostrictive effect.

2 Magnetization rotation due to magnetostriction

The magnetic state of a small ferromagnetic particle is determined by the competition among exchange, anisotropy, magnetoelastic, and magnetostatic energies. When an ellipsoidal polycrystalline single domain particle is considered, the shape anisotropy and the magnetostriction are responsible to determine the stable magnetic state since other contributions are negligibly small. The angular dependent shape anisotropy energy is given by

$$F_d = K_u \sin^2 \alpha, \quad (1)$$

where $K_u = (N_x - N_y)/2M_s^2$ is the shape anisotropy constant, N_x and N_y are respectively the demagnetization factors parallel and perpendicular to the long axis of the particle, and α is the angle between the magnetization M_s and the long axis. The minimum of the shape anisotropy energy thus corresponds to the magnetization vector lying along the long axis. Once the stress is applied to the particle, an additional stress induced anisotropy is developed. As a first approximation, the contribution of the magnetostriction energy F_σ is expressed as follows by using the linear magnetostriction constant λ_s, the stress σ, and the angle $\theta - \alpha$ between the stress axis and M,

$$F_\sigma = -(3/2)\lambda_s \sigma \cos^2(\theta - \alpha), \qquad (2)$$

where θ is the angle between the stress axis and the long axis. When the magnetostriction constant λ_s is negative, the tensile stress gives a negative value of $\lambda_s\sigma$. Consequently the magnetostrictive energy becomes minimum when the magnetization M is perpendicular to the stress axis. The stable magnetization direction α of the stressed particle with the uniaxial shape anisotropy can be found by minimizing the total energy $F_\Sigma = F_d + F_s$ as follows;

$$\frac{\partial F_\Sigma}{\partial \alpha} = \sin 2\alpha + \eta \sin 2(\theta - \alpha) = 0, \qquad (3)$$

$$\frac{\partial^2 F_\Sigma}{\partial \alpha^2} = \cos 2\alpha - \eta \cos 2(\theta - \alpha) > 0, \qquad (4)$$

where $\eta = (3/2)\lambda_s\sigma / K_u$ is the ratio of the magnetostriction and the shape anisotropy energies.

Figure 1 shows the calculated magnetization direction α as a function of the stress direction θ for different values of η by assuming a negative $\lambda_s\sigma$. It is clearly seen that the magnetization can not be rotated from the easy axis when the stress is weak compared to the shape anisotropy (η > -1). On the other hand, the magnetization direction follows the stress axis when the stress is strong enough (η < -1). Therefore, the magnetization of the particle can be effectively rotated by the stress. Important thing to note is that the strong applied stress at a fixed angle can only deviate the magnetization ***M*** from the easy axis within ± 90° and does not allow a full magnetization reversal. These results are valid when the Stoner-Wohfarth coherent rotation of all spins within the particle is assumed. To test this idea, we extend the calculation to the more realistic way by employing the LLG (Landau-Lifshitz-Gilbert) equation. This involves a time evolution of the spin system. Here we show the results for a single nickel dot with an ellipsoidal shape. The length, width and height of the dot are 0.3 μm, 0.35 μm and 0.025 μm, respectively. The following parameters were used in this calculation: the saturation magnetization $M_s=480$ *A/m*, the magnetic exchange stiffness constant $A = 8. \times 10^{-12}$ *J/m*, the magnetocrystalline anisotropy constant $K_a=3.4 \times 10^3$ *J/m*^{3} and the magnetostriction constant $\lambda_s = -0.36 \times 10^{-4}$. These values yield the stress-induced anisotropy constant of $5.\times 10^4$ *J/m*^{3} within the elastic limit of nickel.

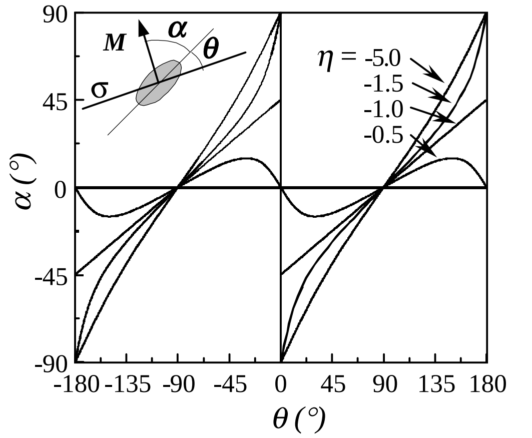

Fig. 1 The magnetization direction α as a function of the angle θ between the stress and the easy axis of the particle for the different ratio η between the magneto-striction and the shape anisotropy energies. (Stoner-Wohfarth model.)

A uniform cubic discretization scheme with 50 nm sized sub-elements has been applied. A set of calculations for different angles between the stress and the easy axis of the dot were performed.

Figure 2 shows a series of calculated MFM (Magnetic Force Microscopy) images. In the upper left image, the stress (black arrow) is first applied perpendicular to the easy axis. This results in the single domain dot with the magnetization (white arrow) along the long edge due to the negative magnetostriction. Then, the obtained spin configuration was used as an initial state for the next calculation with rotated stress axis. The calculations were carried out for every 10 degrees. Figure 2 shows the representative images for the stress angles 0, 60, 120 and 180 degrees. It is seen that the magnetization vector follows the stress axis with an angle delay of about 90°.

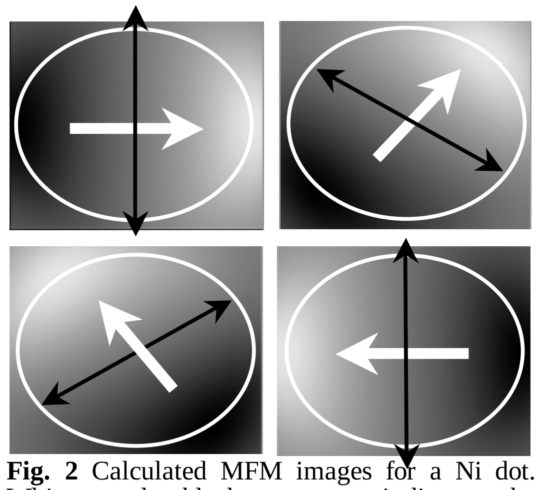
Fig. 2 Calculated MFM images for a Ni dot. White and black arrows indicate the magnetization and stress axis, respectively.

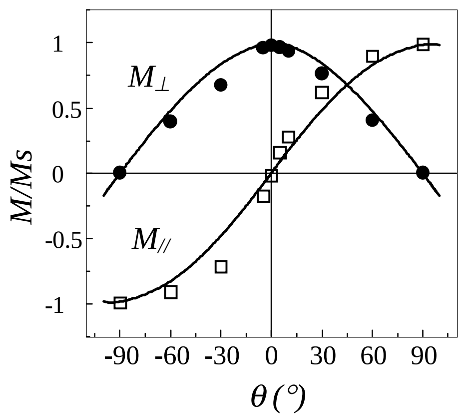

Fig. 3 The magnetization components, parallel and perpendicular to the long edge of the particle as a function of the angle θ between the stress and the easy axis. (Micromagnetic calculations.)

The magnetization components parallel $M_{//}$ and perpendicular $M_{\perp}$ to the long edge of the dot are shown in Fig. 3. The variations of $M_{//}$ and $M_{\perp}$ are well described by the sine and cosine functions, as indicated by the solid lines, and their vector sum $\sqrt{M_{//}^2+M_{\perp}^2}$ remains almost constant for all the stress angles. This implies that the stress-driven demagnetization in the nickel dot of a given geometry takes place *via* coherent rotation. It should be noted that the magnetization reversal is completed only by rotatable stress, without applying any magnetic field. In the following section we propose a MRAM memory cell in which the magnetic state is fully controlled by the magnetostrictive effect.

3. Stress-controlled memory cell

The proposed memory device consists of an array of small magnetostrictive ferromagnetic particles attached to an electrostrictive grid with a large piezoelectric strain constant as shown in Fig. 4. The particles are located at the intersections of the piezoelectric wires with the easy axis at an angle of 45° from the wire axis. Electric contact pads are connected to the wires. The generated electric field is thus confined in the wire because of its high dielectric constant. For example, when the voltage is applied to the pads $\pm U_1$, the electric field induces a stress in all the particles on the same wire due to the magnetostriction. However the magnetization reversal cannot be initiated since the stress vector cannot be rotated. When the electric field is applied by using

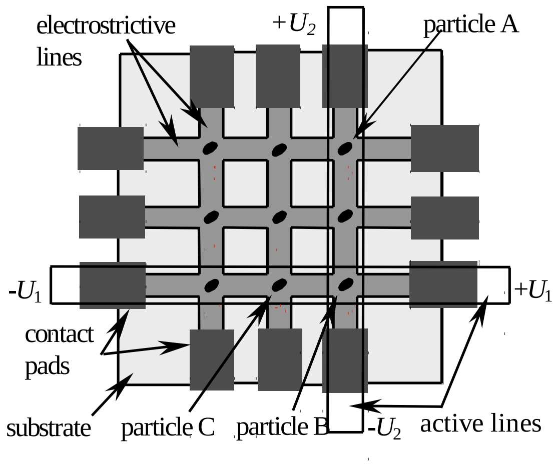

Fig. 4 Schematic design of a proposed stress-operated memory device.

two pairs of contacts $\pm U_1$ and $\pm U_2$, the resultant electric field is a vector sum of two electric fields. Varying the intensity and the polarity of the applied voltage can effectively rotate the direction and the amplitude of the electric field. Consequently the rotatable stress can be generated at the selected intersection in the piezoelectric grid, which initiates the magnetization reversal of the magnetic particle.

Figure 5 shows the time evolution of the magnetic states for the particles A, B and C. The driving voltages are modulated in the form of two triangular pulses with a time delay of a few nanoseconds. The magnetization of the particle B is switched, whereas the final magnetic states of the particles A and C are not affected. The time delay and the pulse length are important in determining the dynamics of the magnetization reversal. The

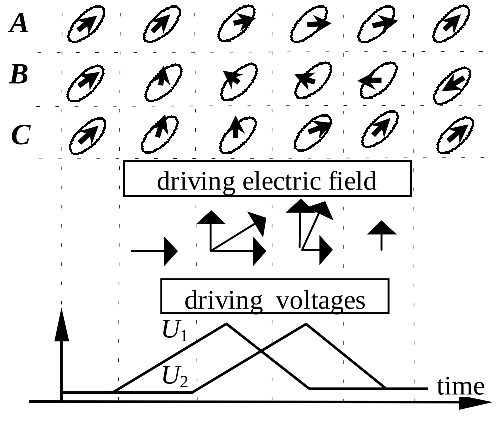

Fig. 5 The magnetic states of particles A, B, and C in Fig. 4 as a function of a driving electric field.

Speed of the reversal is limited by the ferro-magnetic resonance frequency of order a few GHz. The non-destructive reading process can be effectuated by incorporating the magnetoresistive junctions into the magnetostrictive/piezoelectric memory cell.

There are various piezoelectric materials suitable for application in the proposed stress-operated memory. Their electrostrictive properties and deposition methods have been well-studied for different micro-actuators [5]. For example, a lead zirconate titanate based ceramics exhibits a linear expansion of order 10^{-4} by applying an electric field of 0.1 V/μm. This induces the stress of order ~10^8 Pa. The material for memory element should be magnetically soft and exhibit a large saturation magneto-striction λ_s. The promising materials are polycrystalline Fe-Co (λ_s = 0.8×10^{-4}) [1], Pd-Co alloys ($\lambda_s = 1.5 \times 10^{-4}$) [6] and rare earth transition metal based multilayers ($\lambda_s = 3 \times 10^{-4}$) [7]. The magnetostriction of order 10^{-4} gives stress-induced anisotropy of order 10^5 J/m^3 by assuming the deformation within elastic limit of the material. The lateral aspect ratio of the particles has to be optimised so that the shape anisotropy is less than the stress-induced energy due to magnetostrictive and electrostrictive properties of the chosen material. The circular particles with a uniaxial anisotropy can also be used.

Figure 6 shows a scanning electron microscope (SEM) image of a prototype hybrid piezoelectric / magnetostrictive memory prepared in the present study. The PZT film 250 nm in thickness was deposited by a sol-gel method on an oxidized silicon substrate. A perpendicular grid structure with a line width of 2 μm was cut into the PZT film by electron-beam lithography followed by wet etching in $H_2O/HF/HNO_3$ solution.

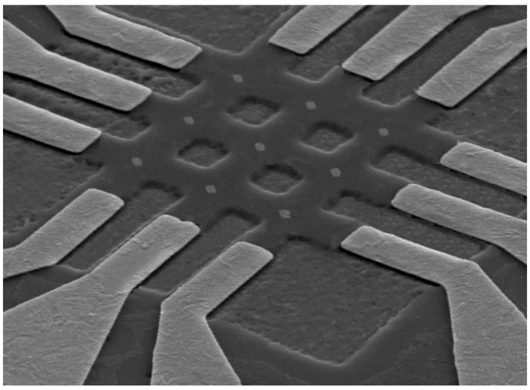

Fig. 6 Oblique view of the prepared piezoelectric/ magnetostrictive memory observed by SEM.

The gold voltage pads and nickel ferromagnetic particles were then fabricated by means of electron beam lithography and lift-off process. The distance between a pair of voltage pads is 10 μm. The dimensions of Ni particles are 0.3 μm × 0.6 μm × 0.02 μm. SEM and magnetic force microscope (MFM) images are shown in Fig. 5. The particle exhibits a single domain structure in the remanent state. The size and geometry of the system were chosen for ease of the production and the measurements. The size can be easily scaled down to submicrons by using current micro-fabrication techniques. Further investigation on the proposed magnetostrictive memory cell is in progress.

4. Summary

We have examined a stress effect on the magnetic state of isolated ferromagnetic dot. The results of Stoner-Wohfarth modelling and micromagnetic calculations clearly show that the magnetization reversal can be completed by only applying a rotatable stress. A memory cell using this principle is proposed. The system consists of an array of magnetic particles formed on a grid patterned piezoelectric film. The operation principle is based on the magnetostriction induced by the electrostrictive grid. A rotatable stress generated in a selected memory cell leads to the magnetization reversal of the particle.

Acknowledgments

This work is partly supported be the RFTF of Japan Society for the promotion of Science, and the Grant-in-Aid for Scientific Research from the Ministry of Education, Science, and Culture in Japan.

References

1. E. Lacheisserie. “Magnetostriction: theory and applications of magnetoelasticity”, Boca Raton: CRC Press, 1993. 408p.
2. K. Schröder, J. Appl. Phys., **53** (1982) 2759.
3. M. Brady, S. Dana and R. Gambino, “Magneto-strictive/electrostrictive thin film memory”, Patent US005239504A, 1993.
4. K. Schröder, IEEE Trans. Magn., **MAG-10** (1974) 567.
5. N. Floquet, J. Hector, P. Gaucher, J. Appl. Phys., **84** (1998) 3815-3826.
6. T. Tokunaga, M. Kohri, H. Kadomatsu, H. Fujiwara, J. Phys. Soc. Jap. Lett., **50** (1981) 1411.
7. E. Quandt, A. Ludwig, J. Betz, K. Mackay, D. Givord, J. Appl. Phys., **81** (1997) 5420.