Novel magnetostrictive memory device

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A stress-operated memory device consisting of an ellipsoidal magnetic particle array and an electrostrictive grid is proposed. In the device, the magnetic state of the particle can be controlled only by the magnetostriction effect. Each particle is located at the intersection of the grid and has an in-plane uniaxial anisotropy. A pair of electric contacts is connected to the end of each wire. In the writing process, the driving voltages are simultaneously applied to two pairs of the selected contacts. This allows to apply a local electric field whose direction and amplitude can be regulated by varying the voltage intensity and polarity. The exerting stress on the magnetic particle results in the linear magnetostriction and hence an additional anisotropy energy in the particle. The in-plane total energy minimum, corresponding to the magnetization direction, follows the local electric field. Consequently the magnetization of the single magnetic particle located at the intersection can therefore be selectively switched. © *2000 American Institute of Physics.*
[S0021-8979(00)55508-X]

I. INTRODUCTION

There has been a growing interest in high-density nonvolatile magnetic random access memory (MRAM). The MRAM is generally composed of an array of patterned magnetic multilayer cells that exhibit giant or tunnel magnetoresistive properties.[1,2] The data bits are written in the cell by applying a local magnetic field excited by a pulsed current in an attached conductive strip. Another possible phenomenon to control a magnetic state of the memory element is the magnetostriction originated from the magnetoelastic coupling, which is defined as a change in dimensions of a ferromagnetic specimen under applying magnetic field. Alternatively, the applied stress generates an internal magnetic field along which the magnetization favors to align.

Several ideas of the magnetic memory device based on the magnetostriction behavior have been proposed so far. One is the MRAM composed of an array of magnetostrictive transducers coupled with magnetic elements.[3] 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 example is a magneto-/electro-strictive hybrid thin film memory consisting of a magnetostrictive film in contact with an electrostrictive film.[4] 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 three-dimensional memory cells driven by ultrasonic pulses have also been proposed.[5] However, all of the above mentioned devices require both magnetic and electric fields for the writing process. Here, we propose a novel stress operated memory device in which the magnetic state is fully controlled by the magnetostrictive effect.

II. ROTATION MAGNETIZATION 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 in determining the stable magnetic state since other contributions are negligibly small. The angular dependent shape anisotropy energy is given by

$$F_d = K_u \sin^2 \alpha, \tag{1}$$

where $K_u = (N_x - N_y)/2M^2$ 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 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,

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

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:

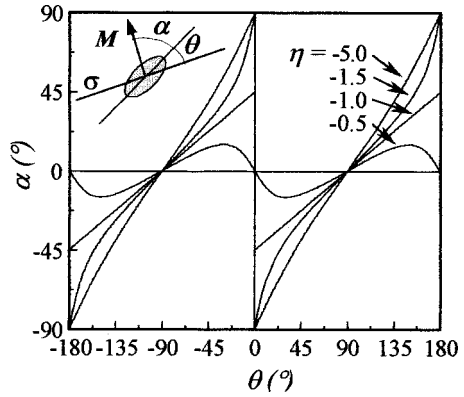

FIG. 1. The magnetization direction α as a function of the angle θ between the stress and the easy axis of the particle for the different ratio η between the magnetostriction and the shape anisotropy energies.

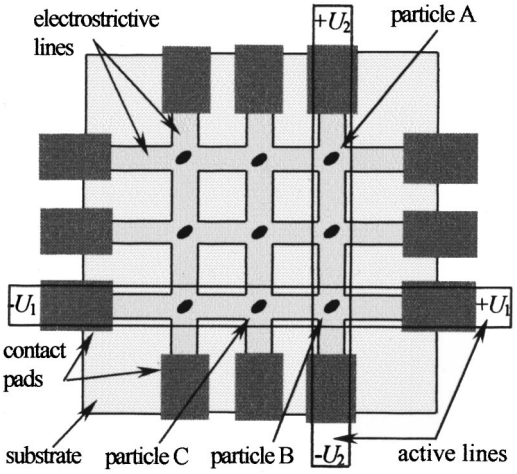

FIG. 2. Schematic design of a proposed stress-operated memory device.

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

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

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 cannot rotate from the easy axis when the stress is weak compared to the shape anisotropy ($\eta > -1$). On the other hand, the magnetization direction follows the stress axis when the stress is strong enough ($\eta < -1$). Therefore, the magnetization of the particle can be effectively rotated by the stress. An 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 $\pm 90°$ and does not allow a full magnetization reversal. The design of the memory cell based on the above mentioned model is described in the following section.

III. DEVICE DESIGN AND DISCUSSION

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. 2. 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 two pairs of contacts $\pm U_1$ and $\pm U_2$, the resultant electric field is a vector sum of two electric fields. The direction and the amplitude of the electric field can be effectively rotated by varying the intensity and the polarity of the applied voltage. 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 3 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. Only the magnetization of the particle *B* can be successfully switched. The time delay and the pulse length are important in determining the dynamics of the magnetization reversal. The speed of the reversal is limited by the ferromagnetic resonance frequency of order a few GHz. The nondestructive reading process can be effectuated by incorporating the magnetoresistive junctions into the magnetostrictive/piezoelectric memory cell.

A ferroelectric lead zirconate titanate (PZT), a barium strontium titanate (BST), and a lead lanthanum zirconate titanate (PLZT) would be suitable for application in the proposed stress-operated memory. The electrostrictive properties and deposition technology of these materials are well known for their application in different microactuators.[6,7] For example, a polycrystalline PZT film exhibits a linear expansion of order 10^{-4} by applying an electric field of 0.1 V/μm.

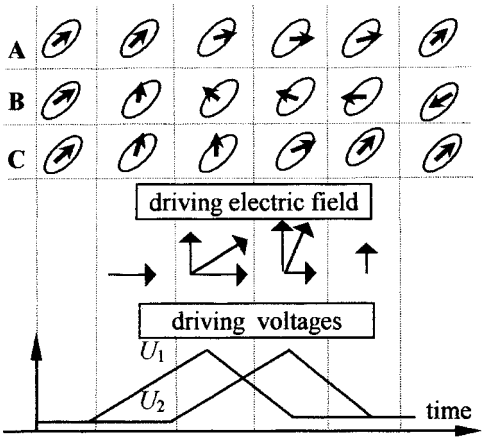

FIG. 3. The magnetic states of particles *A*, *B*, and *C* in Fig. 2 as a function of a driving electric field. The magnetization of the particle *B* is switched, whereas the final magnetic states of the particles *A* and *C* are not affected.

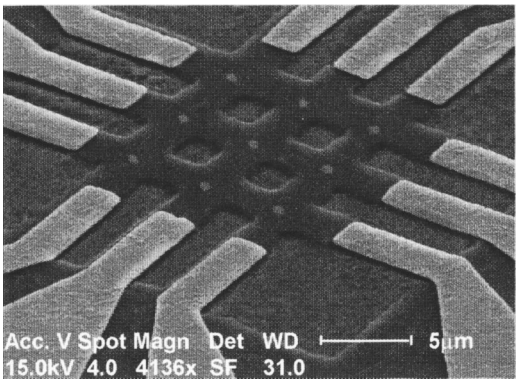

FIG. 4. Oblique view of the prepared piezoelectric/magnetostrictive memory observed by SEM.

This gives the stress of $\sim 10^8$ Pa. The ferromagnetic particles should be magnetically soft with a large saturation magnetostriction λ_s. The promising materials are polycrystalline Ni ($\lambda_s = 0.36 \times 10^{-4}$),[8] Pd–Co alloys ($\lambda_s = 1.5 \times 10^{-4}$) (Ref. 9) and rare earth transition metal based multilayers ($\lambda_s = 3 \times 10^{-4}$).[10] The lateral aspect ratio of the particles has to be optimized 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 4 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 with a 50 nm Ti buffer layer. A perpendicular grid structure with a linewidth of 2 μm was cut into the PZT film by electron-beam lithography followed by wet etching in $H_2O/HF/HNO_3$ solution. The copper 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$\times$0.6 μm$\times$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 microfabrication techniques. Further investigation on the proposed magnetostrictive memory cell is in progress.

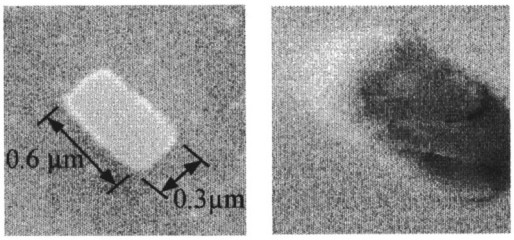

FIG. 5. SEM (left) and MFM (right) images of the deposited Ni particle.

IV. SUMMARY

A fully voltage-controlled nonvolatile magnetic random access memory 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. The prototype system was prepared for further measurements.

ACKNOWLEDGMENTS

This work is partly supported be the RFTF of the 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.

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