Microactuators Systems of Torsion Silicon Cantilever

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Abstract: - Magnetic microactuation systems of torsion silicon cantilever is described. Devices are constructed in a batch fabrication process which combines electroplating with conventional photolithography , materials, and equipment. The magnetic transducers are applied to generation of motion in micromechanical structures such as cantilever, beam, membrane. Microelectromechanical systems (MEMS) with magnetic transducers are fabricated in order to combine the conventional silicon based micromachining techniques with the techniques of the magnetic thin film (nickel-iron). The mechanical and magnetic analysis of the silicon cantilever in the magnetic field was also described. Theoretical expressions for the displacement and torque are developed and compared to experimental results.

Key-Words: - magnetic microactuators, cantilever, silicon structures, magnetic transducers, sensors

1 Introduction

The torsion structure constrains motion to rotation about a single axis which can be an advantage for a number of applications (e.g. scanning, beam chopping) [1, 6]. The magnetic microactuators were made in a relatively simple process [2, 11]. This process combines electroplated NiFe films with surface micromachined silicon and polysilicon. Low-pressure chemical-vapor deposited (LPCVD) polysilicon was chosen as the mechanical spring material. Polysilicon has been used extensively in booth high-Q and highly compliant microelectromechanical systems because of its excellent mechanical properties. In particular, polysilicon has a fracture strain of 1 to 2% and very long lifetime.

LPCVD phosphosilicate glass (PSG) was chosen as the sacrificial layer primarily because of its proven compatibility with LPCVD polysilicon.

Nickel-Iron is frequently used in microfabricated thin film magnetic recording heads, was the magnetic material chosen for the magnetic microactuator. An electroplated nickel-iron alloy is used as the magnetic material because of its relatively high saturation magnetization.

The saturation magnetization of NiFe is a function of nickel content. Specifically, permalloy offers a higher saturation magnetization (M_s=1 T) than nickel and is less susceptible to stress induced magnetic effects because it has low magnetostrictive properties.

The NiFe composition approximately 50% Ni and 50% Fe was chosen. A composition of 50% nickel provides improved corrosion resistance and corresponds to local maximum of the saturation magnetization [5,8].

The forces and displacements for magnetic cantilever (Fig.1) are larger than those generated by most electrostatic microactuators [9,14]. This type of control magnetic field can conveniently actuate structures both in and out of the plane of the wafer [10]. Integration of magnetically actuated elements into microsystems will add new dimensions to MEMS.

2 Mechanical Analysis

The mechanical structure of the microactuator were shown in Fig.1. It consists of narrow cantilever beam made of polysilicon which is anchored to the substrate at one end. The cantilever of magnetic material attached on one side . If a uniform magnetic field is applied to this beam, a pure moment without a translation force is induced. Since the magnetic material is much wider, thicker, and stiffer than the cantilever beam, the magnetic material can be assumed to be mechanically rigid.

A concentrated load at a position x on a uniform cantilever beam results in a deflection at the tip of the beam [13]

$$\delta = w\int_0^l \frac{3l-x}{6EI}x^2 f(x)dx \tag{1}$$

Where: w- beam width, l- cantilever length, I- moment of inertia depends on the cross section, E- elastic modulus,,$f(x)$- the force per unit area, $0\leq x \leq l$

If we assume that the cantilever beam has a uniform cross section, the application of a torque results in pure bending.

The angular mechanical deflection can be expressed as a function of the bending torque T [3,4]:

$$\alpha = \frac{l}{EI} T \tag{2}$$

The moment of inertia of a rectangular cross section cantilever ($h_2 >> h_1$):

$$I \cong \frac{1}{12} w^3 h_2 \tag{3}$$

Where: h_2, h_1- the thickness of the beam NiFe and polysilicon.

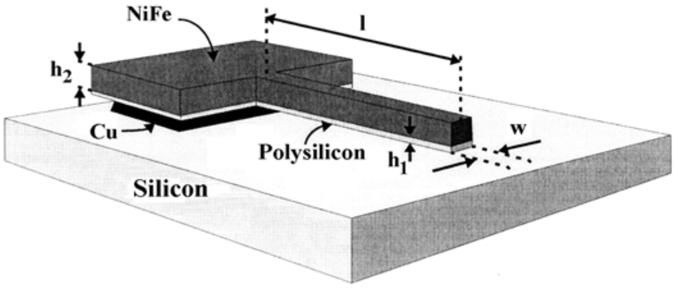

Fig.1 Geometry of the cantilever structure

3 Magnetic Analysis

A permanent magnetic material is a unidirectional magnetic material because the magnetization vector can only point in the one direction. A unidirectional magnetic material has only one stable direction in a large external magnetic field. If the external magnetic field H_e is large enough to generate a magnetic field torque T_m .

$$T_m = V_m [\overrightarrow{M} \times \overrightarrow{H_e}] \tag{4}$$

The magnetic torque can be expressed as (Fig.2)

$$T_m = V_m M H_e \sin(\beta - \alpha) \tag{5}$$

Where: α- angle to deflect the structure, β-α- angular difference between the axis of the magnet and direction of magnetic field H_e, M- magnetization vector of the cantilever, V_m – magnet volume

An unconstrained magnetic element will rotate until it is aligned with the magnetic field ($\alpha = \beta$, α- angle to deflect the structure). If the rotation of the magnet is constrained by mechanical spring, the magnetic torque causes the magnet to rotate until the mechanical restoring torque of the spring.

$$T_b = k_1 \alpha \tag{6}$$

Where: $k_1 = \frac{EI}{l}$ of equation (2)

By equating Eq.'s (5) and (6) for $T_m = T_b$, the equilibrium angular mechanical deflection of the cantilever structure is found

$$\alpha = \frac{M V_m l}{EI} H_e \sin(\beta - \alpha) \tag{7}$$

Equation (7) can be solved numerically. A soft magnetic materials, such as NiFe, are more accurately modeled using concept of magnetic anisotropy and the demagnetizing field. The magnetic anisotropy constant can be subdivided into contributions due shape, stress, crystalline and inducted anisotropy [7]. Because low stress magnetic films are polycrystalline and have no induced anisotropy, shape anisotropy is the essential determinant for K

$$K = \frac{N_t - N_l}{2\mu_0} M_s^2 \tag{8}$$

Where: K- magnetic anisotropy constant, N_t and N_l - thickness and length shape anisotropy [12,15], μ_0 – permittivity of free space, M_s- saturation magnetization

In the soft magnetic material, torque T_m will rotate M an angle γ away from its equilibrium direction (easy direction).

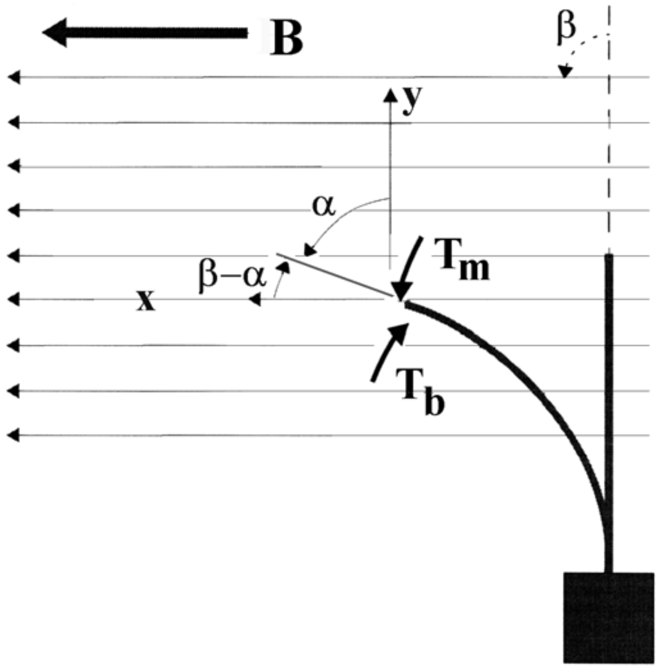

Fig.2 Schematic drawings of the mechanical structure (β=90^0)

When vector M rotates away from the easy axis, it increases the magnetic anisotropy energy W

$$W = K\sin^2\gamma \qquad (9)$$

If the direction of the external magnetic field at a constant angle β to the original direction of the easy axis, allowing equation (5) to be rewritten as

$$T_m = V_m M H_e \sin(\beta - \alpha - \gamma) \qquad (10)$$

In a permanent-magnet analysis, the assumptions $M=M_s$ and $\gamma=0$ are made. As a sample is magnetized by an increasing field H_o, applied along vector M

$$H_o = H_e \cos(\beta - \alpha - \gamma) \qquad (11)$$

These poles generate a filed, called the demagnetizing field H_d , that opposes H_o . The magnitude of the demagnetizing field is

$$H_d = -\frac{NM}{\mu_0} \qquad (12)$$

Where N-shape anisotropy coefficient of the sample [12]

In the case of cantilever $N = \sqrt{N_t^2 \sin^2\gamma + N_l^2 \cos^2\gamma}$

The field inside a magnetic sample H_i is the sum of the applied and demagnetization fields. Domain walls in a soft magnetic material move reduce H_i . In result $H_o \approx H_d$ and allowing equation (12) to be rewritten as

$$M \approx \frac{1}{N}\mu_0 H_e \cos(\beta - \alpha - \gamma) \qquad (13)$$

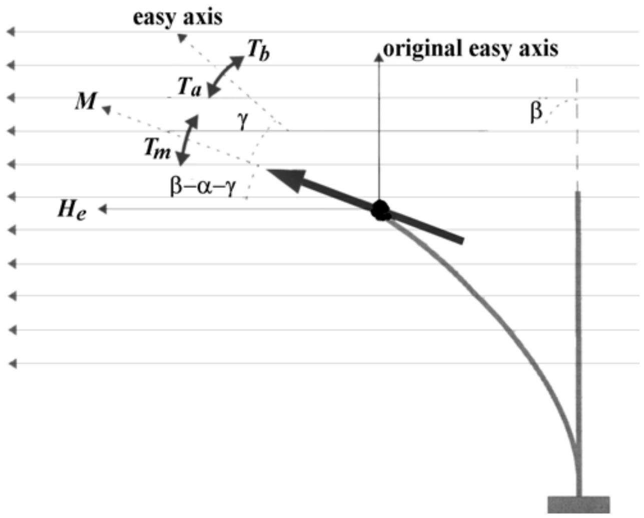

Fig.3 The rotation of the magnetization vector M by an angle γ and the rotation of the magnetic material by an angle α due to uniform external magnetic field H_e

In equilibrium, the field torque T_m , which rotates M away from the easy axis, is balanced by the anisotropy torque T_a, which acts to align M with the easy axis. Using this equilibrium condition , α, γ and T_m, M can be solved by equating Eqns. (6),(10),(11),(13). This set of transcendental equations can be solved numerically. Plots of the angular mechanical deflection α as functions of magnetic field intensity H_e is given in Fig.4.

The calculations are compared with experimental values. For the cantilever l=500μm, w=10μm, h_1=2μm, h_2=10μm, E=150 GPa.

Theoretical curves for α as a function of H_e (fig.4) are also plotted under the condition of constant magnetic saturation $M=M_s$=0,8T and also for the model described by equation (13). The difference in results substantiates our assumption that the demagnetizing field reduces M as predicted by equation (13). The accuracy of the model can be enhanced, particularly at low magnetic fields (where agreement with experimental results is least accurate), by accounting for the coercivity H_c of the magnetic material (Eq.13).

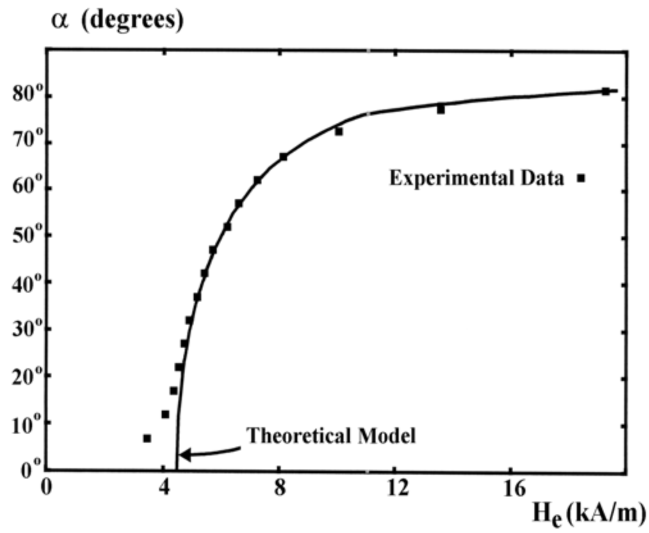

Fig.4 Comparison of the theoretical model for angular deflection versus external field and experimental data

The actuators were placed in a magnetic fields created by an off-chip electromagnet. The magnetic filed, which was varied from 0 to 20 kA/m (B= 0.04T), was maintained at a constant direction $\beta=90^0$ with respect to the original cantilever direction. The angular deflection of the device was measured optically. The angular deflection was measured to reflect of the optical power of a laser beam, which was scanned over micromirror.

The amount of mechanical force that can be applied by this cantilever is limited by the stiffness of the mechanical flexure. If the flexure is very compliant, then large deflections are possible. If the mechanical flexure is made stiffer, the actuator is able to apply larger forces to an object, but the maximum displacement is reduced.

4 Conclusion

Microactuation of magnetomechanical structures by off-chip magnetic fields has several advantages. First, the integration of on-chip electromagnetic coils adds considerable fabrication complexity that can be avoided. Second, forces and displacements that are larger than those generated with electrostatic microactuators are readily obtained. Third, the devices can operate in a conductive fluid because the off-chip magnetic field can be placed outside the conductive fluid.

Magnetic actuation's of flexural MEMS elements have following features:

1. Large deflections (>1mm) are achieved using magnetic force,
2. These large deflections can be achieved both parallel and perpendicular to the plane plate,
3. Actuation can be achieved using magnetic fields generated by either on- or off –chip sources.

For a given microactuator geometry there is a limit on the maximum torque and the maximum angular deflection that can be achieved for even extremely large applied magnetic fields. The performance of the actuator technology can be improved in at least two ways. Increasing the iron concentration of the NiFe film can increase the torque for a given magnetic field. Second, since the torque is proportional to the volume of the magnetic material. A much thicker magnetic material could be utilized to increase the torque for a given magnetic field.

A much cheaper alternative to the LIGA technique is available, when the features of the electroplated magnetic material do not need to be precisely defined.

An important application area for individually controllable ferromagnetic microactuators with polycrystalline silicon torsion-bar flexures is to microphotonic applications, such as optical scanners, displays, and switches.

Similarly microstructures might be applied to micromanipulators, magnetometers.

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