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An electromagnetically actuated micromirror with precise angle control for harsh environment optical switching applications

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ABSTRACT

An electromagnetically actuated micromirror with precise tilt angle control for application as a bi-stable optical switch is reported. A tilt angle control of ±2.3° is achieved by utilizing the 4 μm buried oxide (BOX) layer thickness of an SOI wafer together with a carefully controlled pulsed low frequency deep silicon backside etch to construct precise mechanical stoppers, while maximizing the torsion beam out-of-plane stiffness for angle fixing. The device is packaged with a KOH etched textured silicon encapsulation, which prevents reflection from the back cavity to promote high contrast, and also increases vibration resistance. By incorporating the magnetization response of the permalloy material, a compact analytical model for the quasi-static/dynamic analysis of the device was constructed, which corresponds well with the measured tilt angle versus applied magnetic field, frequency response, and switching time. A pulsed voltage driving circuit was also applied to increase the electromagnet response speed. Latchability can be easily established by employing an electro-permanent magnet or electrostatic clamping between the stoppers. The mirror reflectivity was measured to be 87.2% (0.6 dB) at a wavelength of 632.8 nm, and the static and dynamic deformation of the mirror was also measured and reported. The device is suitable for optical telecommunication in harsh environments that do not permit any electrical sparks.

1. Introduction

Electromagnetic actuation has long been used in MEMS devices, having the advantage of providing larger actuation force/torque over larger displacements, while being able to be applied under relatively far-field distances [1,2]. Conventional electromagnetic actuation is either modeled by the magnetic energy based method within a core intersecting air gap [3], or Lorentz force acting on a coil, with the former applied in induction motors or power relays [4,5], and the latter applied in membrane pumps and scanning mirrors [6–8]. Judy et al. [9] further demonstrated the feasibility of employing electroplated soft magnetic material, such as permalloy, on movable structures to obtain large out-of-plane tilt displacement, fundamentally based on utilizing the dominant easy axis magnetization due to shape anisotropy. Since then, many applications, such as out-of-plane inductors [10] and fluid dynamic control flaps [11], have been developed. This type of actuation can be achieved without directly sending in electrical signals to the device itself, allowing remote control of actuators under harsh environments, such as within conductive fluids or combustible material ambient.

In particular, electromagnetic actuation with magnetic films is a promising candidate for the area of optical switching. Horsley et al. [12] demonstrated a micromirror based fiber-optic switch array, with each mirror capable of 90° tilt angle by using large angle electromagnetic actuation of NiFe films and electrostatic clamping to a mechanical stop. Ji et al. [13] demonstrated another optical switch by fabricating a vertical mirror with out-of-plane actuation, with the bi-stable latching mechanism accomplished by the hysteresis of an electro-permanent magnet, thus either reflecting or allowing the optical beam to pass. Permalloy based electromagnetic actuation is also shown to be useful in scanning mirror applications [14].

In this paper, we present an electromagnetically actuated micromirror that is designed for a precise ±2.3° small angle "on–off" operation to direct the optical beam either back to the same fiber or to other fibers. Although placing more effort on fiber alignment assembly, this small angle specification enables the possibility to design a much more robust device for harsh environment applications, also permitting the usage of smaller sized higher speed electromagnets. Precise angle limiting stoppers are constructed by making use of the buried oxide (BOX) layer thickness of an SOI wafer together with an overlap between the frontside

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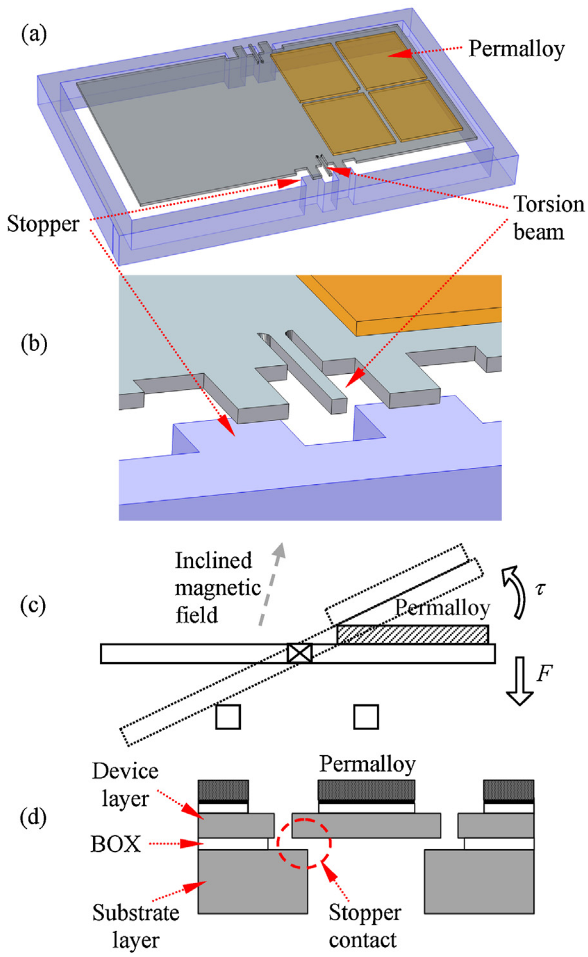

Fig. 1. (a) 3D schematic of the mirror device, (b) close up view of the torsion beam and stoppers, (c) illustration of the applied torque/force under an inclined field with stoppers for angle control, (d) practical implementation of the design.

and backside silicon structures, requiring a minimal amount of photolithography steps to fabricate. Process development has been done to alleviate notching/footing and oxide stress effects during the deep silicon etch steps for accurate structure fabrication, and the device is also packaged with a KOH etched low reflective encapsulation for high contrast. To further characterize the device performance, a compact analytical model has also been constructed and used to verify the quasi-static and dynamic measurement results, while a driving circuit has been designed to increase the current ramp-up speed of the electromagnet. The reflection loss as well as the static and dynamic deformation of the mirror was also measured and reported.

2. Device design

2.1. Concept and operation principle

A 3D schematic of the device is shown in Fig. 1(a), which consists of a mirror plate, two torsion beams, and four mechanical stoppers. One half of the mirror plate is coated with a soft magnetic permalloy film, with the separation within the film used to decrease the amount of warping of the mirror plate caused by the electroplated film stress. When an inclined magnetic field is applied, an upward torque is induced on the permalloy film to tilt the mirror plate. As shown in Fig. 1(b), on two sides of each torsion beam, there are two protrusions from the mirror plate, which overlap with similar protrusions on the backside substrate opening to form the four stopper

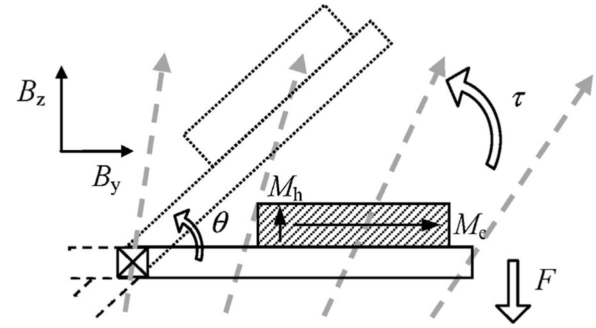

Fig. 2. Illustration of the inclined magnetic field induced anisotropic magnetization within the permalloy piece and the resulting torque and force.

contact surfaces/lines. As illustrated in Fig. 1(c), the tilt angle can be accurately controlled by properly selecting the gap between the stoppers and the mirror plate, and the distance between the rotation axis and the stopper contact edge, while designing the torsion beams to have large out-of-plane direction stiffness for angle fixing.

In this work, we propose to use the BOX layer of an SOI wafer to form the gap. As shown in Fig. 1(d), there is an overlap between the device layer and the substrate layer, and the placement of the stopper contact edge precisely defines the tilt angle. This stopper design has the advantage of introducing less unwanted beam and plate deformation and lower deceleration upon contact, together promoting better angle control and less violent contact, while simplifying the fabrication process. In this study, a conventional electromagnet was used to provide the external magnetic field and characterize the fundamental performance. To further implement bi-stable operation, a latchable electro-permanent magnet [13] or electrostatic clamping between the stoppers [12] could be incorporated.

2.2. Quasi-static analysis

Consider the applied magnetic field to be a two dimensional solenoid field composed of an in-plane component B_y (H_y) and an out-of-plane component B_z (H_z), which in turn causes an in-plane magnetization M_e and an out-of-plane magnetization M_h within the permalloy piece, as shown in Fig. 2. For a typical soft magnetic material, magnetic anisotropy is predominantly determined by its geometry, and since the lateral dimensions are much larger than the thickness, the easy axis is closely aligned with M_e, causing the permeability to be much larger in the in-plane direction. The permalloy piece, with a total magnetic volume of V_{mag}, can be viewed as containing numerous current loop magnetic dipoles aligned with B_y and B_z, so the resulting total upward magnetic torque τ and counteracting magnetic force F can be calculated as the superposition of the Lorentz force acting on all magnetic dipole moments. By the divergence theorem, the gradient of B_z is equal to the negative gradient of B_y, hence simplifying the τ and F versus tilt angle θ equations to

$$\tau = M_e V_{mag}(B_z \cos\theta\cos\theta - B_y \sin\theta\cos\theta) - M_h V_{mag}(B_z \sin\theta\cos\theta + B_y \cos\theta\cos\theta) \quad (1)$$

$$F = M_e V_{mag}\frac{dB_z}{dz}\cos\theta\sin\theta + M_h V_{mag}\frac{dB_z}{dz}\cos\theta\cos\theta \quad (2)$$

In typical situations, the torque caused by F is usually one to two orders of magnitude smaller compared to τ.

To further incorporate the nonlinear magnetization response of the soft magnetic material into the model, the M–H hysteresis loop must be taken into account. In this study, we employ two simple