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A novel elastomer-based magnetoresistive accelerometer

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Abstract

In this paper, we present a novel type of biaxial accelerometer based on a polydimethylsiloxane (PDMS) structure as the mass–spring system and using magnetoresistive (MR) sensors as the detection method. The proof mass of the sensor is a mushroom-shaped polymer magnet made of PDMS filled with permanent magnet powder, whose minute movement under lateral acceleration is precisely sensed by a set of MR sensors. The device aims at consumer electronics applications of low g range and low frequency, such as inclination measurements and motion sensing. An experimental device has been successfully fabricated which showed a linear transfer curve without significant hysteresis. A sensitivity of 0.32 mV/(V g) was obtained.

Keywords: Accelerometer; Polydimethylsiloxane; Magnetoresistive sensor

1. Introduction

Accelerometers are devices for measuring the acceleration vector of motion, tilt (inclination) angles or vibration of an object. These devices are widely used in various applications such as automotive, vibration monitoring, impact/shock detection, navigation systems, gaming, robotics, data entry for mobile phones, human motion monitoring, etc. Many different operating principles are used for these devices. Even though capacitive MEMS seems to be the most advantageous and common principle of accelerometers nowadays [1], variety of principles and technologies such as gas convection [2] and magnetoimpedance [3] are still seen in commercial products. In this paper, we present a novel type of biaxial accelerometer based on a polydimethylsiloxane (PDMS) structure as the mass–spring system and using magnetoresistive (MR) sensors as the detection method. The proof-mass of the sensor is a polymer magnet made of PDMS filled with permanent magnet powder, whose deflection under acceleration is precisely sensed by a set of MR sensors.

PDMS is an elastomer material having excellent elasticity and flexibility (low Young's modulus). It has a low loss tangent, a low glass transition temperature and an unchanged Young's modulus over a wide range of temperature [4]. The material becomes increasingly popular in modern technologies such as microfluidic chips, microcontact printing and is sometimes used as springs in some types of capacitive accelerometers, gyroscopes and actuators [5–8]. Moreover, integrated magnets made of polymer materials such as PDMS and SU-8 filled with magnetic powder have been used in micro-actuators such as micro-pumps, micro-robots and micro-motors [9–11]. In this paper, the use of the integrated polymer magnet in a novel accelerometer concept is reported. Since the fabrication process of the device involves some simple molding steps and MR sensor technology is a mature and cheap technology, this concept is considered an attractive alternative technology for accelerometers of low cost for the consumer electronics market. The design aims at applications of low g range and low frequency, such as inclination measurements and motion sensing.

2. Working principle

Fig. 1 explains the construction and working principle of the device. On a Si substrate, two Wheatstone bridges of MR sensors for detecting acceleration components in X and Y directions are arranged in radial directions. Each Wheatstone bridge contains four elements made of long NiFe thin film strips. Thanks to the

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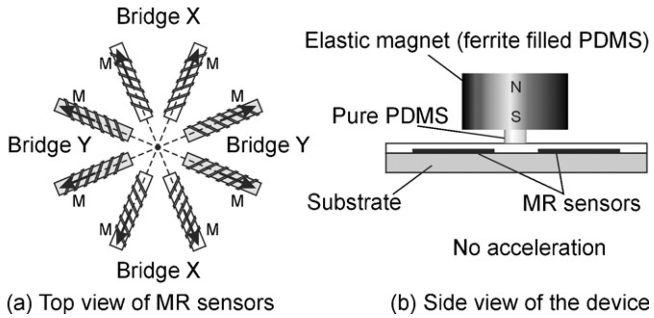

Fig. 1. Top view (a) and side view (b) showing the construction and working principle of the accelerometer at zero acceleration. The connections between the sensor elements are not shown in this figure.

so-called "barber-poles" made of aluminum bars [12] patterned at 45° with respect to the direction of the NiFe strips, the resistance of each MR element along the strip depends linearly on the angle of the magnetization of the NiFe strip with respect to the strip direction. In addition, there are two extra orthogonal MR sensors located outside the radial sensor bridges *X* and *Y* (not included in the figure) for correction of the influence of the external magnetic field.

On top of the sensor substrate, a mushroom-shaped structure made of PDMS is mounted at the center of the MR sensor configuration. The mushroom consists of two parts: the upper massive part (the mushroom cap) is made of PDMS filled with Sr/Ba–ferrite particles and the lower thin part (the mushroom stem) is made of pure PDMS. After the whole sensor is fabricated the mushroom structure is magnetized along the *Z* direction and the mushroom cap becomes a polymer permanent magnet.

The cap and the stem of the mushroom thus form a mass–spring system. When there is no acceleration the mushroom stands up right (Fig. 1). The projection of its magnetic stray field on the sensor substrate forms a radial pattern, with the center of the radial field coinciding with the center of the sensor configuration. The radial magnetic field of the magnet is designed so that it is strong enough to saturate the sensor strips. In this case, the radial field forces the magnetization of all sensor elements to orient along the strips. All four elements of each sensor bridge thus have the same resistance and the outputs of the bridges give zero voltage. When a lateral acceleration (in the *X*–*Y* plane) is applied to the accelerometer (Fig. 2), due to the low stiffness of the stem, the cap tilts elastically a fraction of a degree. The symmetry is, therefore, broken: the center of the radial field is displaced to a new position depending on the direction and magnitude of the acceleration vector and the magnetization vectors of the sensor elements are also dragged along to new directions accordingly. Consequently non-zero signals *X* and *Y* can be obtained from the outputs of the Wheatstone bridges indicating the two components of acceleration on the sensor plane.

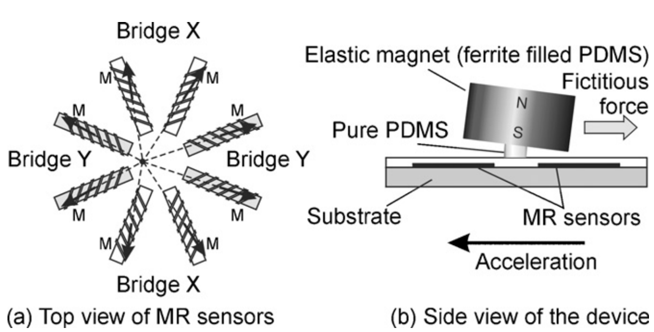

Fig. 2. Top view (a) and side view (b) of the accelerometer when a lateral acceleration (e.g. in the *X* direction) is applied. The mushroom is slightly tilted due to the fictitious force, resulting in a signal at the output of bridge *X*.

3. Material investigation

Prior to designing the sensor, a number of material investigations have been carried out. It has been found that PDMS, even being pure, has a small creep (time dependent) behavior, which raises a problem of hysteresis in the sensor transfer function. When filling PDMS with magnetic powder, elasticity of the material degrades fast and the Young's modulus increases drastically with powder concentration. On the other hand increasing the filling concentration increases the remanent magnetic induction (B_r) of the magnet (see Fig. 3), which is necessary to saturate the MR sensor strips. A theoretical curve predicts rather well B_r for up to 50 wt%, beyond which the experimental B_r was found to be smaller than the theoretical one, due to the formation of too many air bubbles in the material. The MR sensors will work correctly when the strips are saturated. To fulfill this condition, a high B_r, thus higher powder concentration is desired; however, too high concentration leads to difficulty during molding and results in large air bubbles inside the material. An optimum concentration of 50 wt% of Sr/Ba–ferrite has been found at which the polymer magnet has a B_r of 37 mT. It is known from the manufacturer of the Sr/Ba–ferrite particles that the particles have a disc shape and their magnetic anisotropy direction is perpendicular to the plane of the disc. If the particles are physically aligned and the structure is magnetized along the anisotropy axis, B_r can be maximized. The alignment can be induced by mechanically compressing the material during the curing process. In Fig. 3, samples with and without using compression

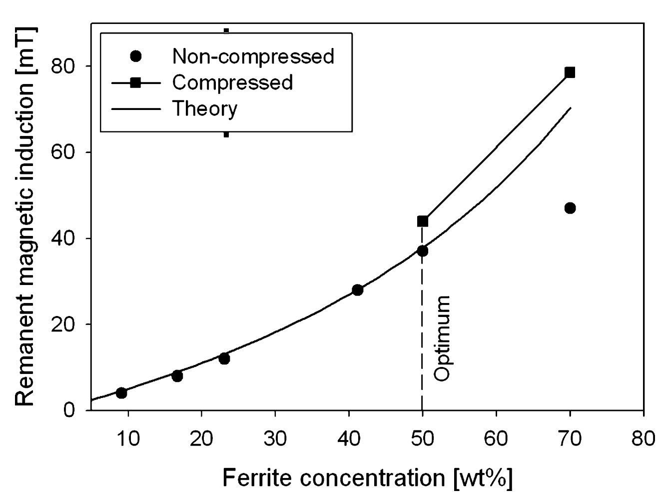

Fig. 3. Remanent magnetic induction (B_r) of the polymer magnet as a function of Sr/Ba–ferrite powder concentration (wt%) for the compressed and non-compressed cases. If the magnet is compressed during the curing process, B_r along the direction of compression is found to be improved.