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A MEMS Accelerometer

Field of the invention

The present invention relates generally to a MEMS sensor and method of fabricating it, and more particularly a MEMS accelerometer. The invention
5 further relates to applications of the MEMS accelerometer in a high performance system such as a hard disk drive.

Background of Invention

Microelectromechanical systems (MEMS) are regarded as providing
10 enormous opportunities for perceiving and controlling a variety of physical environments. Numerous MEMS sensors forming accelerometers have been demonstrated based on electrostatic operating principles, see, for example, US patent 6,230,566. In this regard, STMicroelectronics has developed
MEMS-based linear and rotational accelerometers for application in disk
15 drives, as described in an article entitled "MEMS technology adds manufacturing diversity" by Benedetto Vigna (Nikkei Electronics Asia, August 2001, 12~5). The accelerometer consists of interlocking fingers which are alternately moving and fixed. Acceleration is sensed by measuring the capacitance of the structure, which varies in proportion to changes in
20 acceleration. By building such a rotational sensor into the drive it is possible to compensate for rotational movements, ensuring that the head stays on the track when it is reading or writing. However, using the movement information of the drive base to control the head on the slider involves a large amount of calculation for movement transformation, which may lead to additional
25 possible errors. In addition, it may not be suitable to install the electrostatic MEMS accelerometer developed by STMicroelectronics onto the slider directly due to its size, which may affect the performance of head disk interface. However, the direct sensing of slider's motion is important since the



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read/write head is installed onto the slider, and any unwanted vibration of the slider contributes to track mis-registration errors (TMRs). In this regard, a small and light accelerometer is desirable. Also, such an accelerometer should be capable of being installed in the slider easily.

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Summary of the Invention

The present invention aims to provide a new and useful MEMS accelerometer, and in particular one having high sensitivity and small size.

- 10 In general terms, the invention proposes that a MEMS accelerometer employs one or more elements of piezoelectric material which are deformed when the accelerometer is subjected to acceleration, and generate a measurable electric signal.
- 15 As in conventional MEMS devices, the accelerometer employs fabrication techniques from the field of semiconductors, such as silicon micro-machining, to create a structure, and piezoelectric film is then deposited on the structure. The combination of silicon micro-machining and piezoelectric film deposition is attractive since piezoelectric coupling strength is significantly higher than
- 20 electrostatic coupling strength, and furthermore, the piezoelectric micro-mechanical device is usually not restricted by any geometrical configuration, in contrast to the electric gap required in conventional electrostatic micro-mechanical accelerometers. Thus, the invention provides the possibility to attain a simpler design/structure, smaller size and higher sensitivity than
- 25 conventional electrostatic structures. Such a cost-effective MEMS accelerometer is desirable in a high-performance system such as a hard disk drive.

One expression of the invention is a MEMS accelerometer having:

at least one flexible member including a semiconductor substrate, at least one element of piezoelectric material formed on the substrate, and at least two electrodes for detecting electrical voltages generated in the piezoelectric material and from them generating an output signal;

5 at least one proof mass member supported by the flexible member;
and

a base member attached to the flexible member;

wherein the proof mass is arranged to be movable relative to the base member upon acceleration of the accelerometer thereby causing flexing of the
10 flexible member, which causes the piezoelectric material to generate electrical voltages which are measured by the electrodes.

Although the invention is not limited to MEMS accelerometers for use in hard disk drives, an alternative aspect of the invention is a hard disk drive incorporating such an accelerometer. The invention further provides methods
15 of producing the accelerometer using semiconductor fabrication technology.

Brief Description of The Figures

Preferred features of the invention will now be described, for the sake of illustration only, with reference to the following figures in which:

FIG. 1, which is composed of Fig. 1(a) and 1(b), shows a piezoelectric
20 MEMS accelerometer which is a first embodiment of the current invention.

FIG. 2, which is composed of Figs. 2(a) to 2(c), illustrates use of the embodiment of Fig. 1.

FIG. 3, which is composed of Figs. 3(a) to 3(n), shows steps of a process for forming the embodiment of Fig. 1.

25 FIG. 4 shows one of surface patterns of the embodiment of Fig. 1 after fabrication.

FIG. 5, which is composed of Figs. 5(a) to 5(e), shows an alternative method for fabricating the piezoelectric MEMS device of Fig. 1.

FIG. 6 is schematic view of fabricated deep trenches in a possible realisation of the SOI wafer in the method of Fig. 5.

FIG. 7 shows an application of the embodiment of Fig. 1, between the suspension and the slider of a hard disk drive.

FIG. 8 is a block diagram of a servo system with an inner active vibration control loop suitable for use in the system of Fig. 7.

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Detailed Description of the embodiments

Referring to Fig. 1(a), a piezoelectric MEMS accelerometer 1 is shown which is an embodiment of the current invention. It is composed of a base member
 10 2, two parallel beams 3, 5 and a proof member 7 (having a mass significantly larger than that of the beams). The figure includes a set of axes x-y-z. As indicated in Fig. 1, the base member 2 and proof member 7 have a width in the x direction of about $1000\ \mu m$. They have a thickness in the direction marked as y of $300\ \mu m$. The beams 3, 5 have a length of about $1250\ \mu m$, and
 15 each of them includes at their surface two top electrode elements 11 which are each of length $600\ \mu m$. The size of the MEMS accelerometer may be substantially the same as the pico-slider widely adopted in most HDDs (hard disk drives). Thus, it is easy to install between the gimbal and slider in a HDD, without having an effect on the hard disk interface performance. However, of
 20 course, the accelerometer of the present invention is not limited to this application, and so its dimensions are not limited to those given above.

.Fig. 1(a) shows the proof mass 7 in a rest position, and, if the proof member
 7 is displaced from the rest position in the direction marked x, the beams 3, 5
 25 urge it back towards that position.

The parallel beams 3, 5 have a high aspect ratio (i.e. they are much wider in the direction y than their thickness in the direction x) and thus provide in-plane flexibility and out-of-plane stiffness. Fig. 1(b) is a cross-sectional view of the
 30 one of the beams 3 in the line A-A, and shows that each of the beams is

composed of several layers: a top electrode layer 11, e.g., Au or Pt; an adhesion layer (not shown); a piezoelectric film 13, e.g. PZT; a bottom electrode 15, e.g., Pt ; an adhesion layer (not shown), e.g. Ti; an insulation layer 19, e.g., SiO₂; and a substrate 21, e.g., Si. The top electrode 11 is
5 patterned, resulting in the distributed and optimized piezoelectric active zones as sensing elements.

The proof member 7 is designed in use to move relative to the base member 2 in the direction indicated as x, by bending of the beams 3, 5. One such
10 configuration of the accelerometer when the proof mass 7 is deflected is shown in Fig. 2(b) (it is an "S-shaped" deflection). The base member 2 functions as a stopper to avoid planar excursions caused by serious mechanical shocks. The bending of the beams 3, 5 causes a stress/strain distribution in the PZT-silicon composite beam structure and accordingly
15 electric signals are generated in the PZT layer 13 due to the piezoelectric effect.

Preferably, the piezoelectric elements are optimally located at high strain zones so as to improve sensitivity of the accelerometer. In the embodiment of
20 Fig. 1(a), four distributed piezoelectric sensing elements (i.e. areas which are covered by top electrodes 11) have been adopted.

FIG. 2(c) is the result of a numerical simulation of the electric charge output by the piezoelectric film 13 when the device is in the configuration shown in
25 Fig. 2(a). The area of the film 13 marked as 23 has a high charge of one polarity, and the areas marked 25 has a high charge of another polarity. The circuit configuration used for the measurement is shown in Fig. 2(a). The bottom electrodes 15 are connected to earth, and the voltages of the top elements 11 are measured. The induced charges in the PZT layers 13 are
30 proportional to changes in acceleration.

The steps of fabricating the device of Fig. 1 are shown in Fig. 3. In a first step, as shown in Fig. 3(a), a $\langle 110 \rangle$ silicon substrate 31 is oxidised at the surface to form layers of PECVD silicon dioxide 33. Then a photo-resist layer is

5 applied, and a photolithography technique is applied to the photo-resist layer to create a desired pattern. The pattern is transferred onto the silicon dioxide 33 using RIE (reactive ion etching) with Si etch stop, and by this process a shallow trench 37 is formed in the front side of substrate 31 using DRIE. The photo-resist is then removed to give the structure shown in Fig. 3(b).

10 Alignment marks (not shown) are also produced in this step. The same process is performed on the back surface of the substrate to obtain a shallow trench 39 and alignment marks (not shown), as shown in Fig. 3(c).

After that, a layer 41 of low stress nitride is conformably deposited on both

15 sides of the substrate 31, as shown in Fig. 3(d). A thick photo-resist layer is then applied and photography on this resist creates a second pattern to be transferred onto the silicon nitride using RIE with Si etch stop. This produces a through hole 43 by KOH (potassium hydroxide) etching of substrate, to give the structure of Fig. 3(e). The nitride and oxide mask layers 33, 41 are

20 removed by wet etching to give the structure shown in Fig. 3(f), in which the substrate 31 has been divided into the base member 2 and proof mass 7.

Note that, although the process described above is appropriate in the case that the silicon substrate is a $\langle 110 \rangle$ wafer 31, alternatively we may start from

25 a $\langle 100 \rangle$ wafer instead, and in this case DRIE may be used to fabricate the thorough hole 43 in the wafer.

In either case, the next step of the method is for the patterned wafer 31 to be double-bonded with two SOI structures 45, which are each composed of a

30 first silicon layer 47 adhered to a "handle wafer" 49 by a buried oxide layer 48,

to give the structure shown in Fig. 3(g). Prior to this, alignment marks (not shown) are made on the SOI structures 45. Preferably, Si-Si fusion bonding is adopted to bond the layers 47 to the substrate 31. Then, the two handle wafers 49 are removed by either KOH etching or DRIE, and the buried oxide layers 48 are removed by HF wet etching, to give the structure of Fig. 3(h).
 5 The remaining layers 47 form the substrates 21 of Fig. 1(b).

A layer 19 of oxide is deposited on the bonded wafer stack to insulate wafer electrically, giving the structure of Fig. 3(i). Following this, an adhesion layer (not shown) and a bottom electrode 15 are deposited, to give the structure of Fig. 3(j). Many materials may be chosen to form the bottom electrode 15, provided that they are electrically conductive, such as Au, Cu, Al. Preferably, the bottom electrode 15 is chosen to be Pt, since this gives good characteristics.

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A PZT film 13 is sol-gel multiple spin-coated on the wafers, to give the structure of Fig. 3(k). Alternatively, any of sputtering, CVD, PVD or screen printing method may be used to form the PZT thin film 13. Sol-gel multiple spin-coating of PZT film is a commonly used process in achieving a film thickness of around $1\ \mu\text{m}$ or more. To deposit the piezoelectric film on the Si substrate and optimize its performance one skilled in the art may use methods disclosed in the following references: Ryutaro Maeda, Zhanjie Wang and Jun Akedo et al (1998) "Deposition and patterning technique for realization of $\text{Pb}(\text{Zr}_{0.52}, \text{Ti}_{0.48})\text{O}_3$ thick film micro actuator", *Jpn. J. Appl. Phys.*, 37, 7116-7119; Chengkuo Lee, Toshihiro Itoh and Tadatomo Suga (1999), "Self-excited piezoelectric PZT microcantilevers for dynamic SFM – with inherent sensing and actuating capabilities", *Sensors and Actuators A72*, 179-188; Dragan Damjanovic, Paul Muralt and Nava Setter (2001), "Ferroelectric sensors", *IEEE Sensors Journal*, 1, 191-206; D. L. Polla and P. J. Schiller (1995),
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 30 "Integrated ferroelectric microelectromechanical systems (MEMS)", *Integrated*

Ferroelectronics 7, 359-370. Besides PZT, other piezoelectric materials, such as PZT/MN, ZnO and AlN may be alternatively adopted.

Subsequently, an adhesion layer (not shown) and a layer 11 of Pt or Au are
 5 deposited as the top electrode, giving the structure shown in Fig. 3(l). A photo-resist is then applied, and photography on this resist creates a third pattern to be transferred onto the top electrode 11 using etching, to give the structure shown in Fig. 3(m). Various etching methods may be chosen, such as ion milling and selective wet etching. As an alternative, the top electrode
 10 11 (e.g. if it is Pt) may be evaporated on the PZT layer in a configuration such that etching is not required.

The final step is to etch the PZT and stop on a layer of bottom electrode 15. This gives the structure shown in Fig. 3(n), which is the same as Fig. 1(a)
 15 (although Fig. 3(a) is not to scale).

Fig. 4 shows a possible surface patterns after fabrication. It includes two areas 61, 63 of top electrode 11, an area 65 where the PZT 13 is exposed, and an area 67 where the bottom electrode 15 is exposed. Thus, electrical
 20 connections can be formed to the top electrodes in areas 61 and 63, and to the bottom electrode in area 67.

Fig. 5 shows the steps of an alternative method for fabricating the piezoelectric MEMS sensor of Fig. 1. The fabrication method starts from a
 25 SOI wafer 71, having the same structure as the SOI structures 45 described above: that is, a thin semiconductor layer 72 and a thick silicon wafer 74 connected by a sacrificial SiO₂ layer 76. In a first step, the surfaces of this SOI wafer 71 are oxidised to give masking layers of PECVD silicon dioxide 73, to give the structure of Fig. 5(a). These layers 73 are coated with photo-resist.
 30 Photolithography on the photo-resist layer creates a pattern, which is

transferred onto the silicon dioxide 73 using RIE with Si etch stop, giving the structure of Fig. 5(b). The silicon dioxide mask pattern is subsequently transferred to the silicon substrate using DRIE, giving the structure of Fig. 5(c), including holes 75

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Following the silicon etch, the holes 75 are used to remove the oxide 73 and etch the sacrificial buried SiO₂ insulator layer 76, to give the structure of Fig. 5(d). This step is critical to the process, and it is performed under time-control to obtain the required beam length. In order to accelerate it, the number of
10 holes 75 can be increased, and such a possibility is shown in Fig. 6, which is a perspective view of the structure of Fig. 5(d), but with a larger number of holes 75.

Two fabricated SOI wafers as shown in Fig. 5(d) are then bonded together, as
15 shown in Fig. 5(e). The structure is then used in place of the structure of Fig. 3(h), in process steps equivalent to those illustrated in Figs. 3(i) to 3(n).

SOI wafers are adopted the processes of Figs. 3 and 5 to maintain the thickness of the parallel beam accurately. However, the invention is not
20 limited in this respect, and one skilled in the art may use other fabrication methods in the formation of the MEMS device in the present invention.

The MEMS device of Fig. 1 may be used as an actuator, as a device combining the functions of sensor and accelerometer, and as a resonant filter.
25 As an actuator, it is suitable for dual-stage servo in a recording/reproducing apparatus, as disclosed in prior Singapore application No. 200104979-0 entitled "A Micro-Actuator for Dual-Stage Control in A Recording/Reproducing Apparatus", the disclosure of which is incorporated herein by reference. Furthermore, fabrication methods embodying the current invention are also

suitable for the formation of a 3-dimensional piezoelectric MEMS actuator and resonant filter.

It is well known that the measurement of acceleration has applications to a wide variety of industrial and commercial problems, such as crash detection for air-bags in cars, vibration analysis of industrial machinery, and provision of feedback signals to steady the image in a video recorder against hand-held vibration. Besides these applications of the MEMS accelerometer disclosed in the present invention, one preferred application is for embodiment of Fig. 1 to function as a small MEMS accelerometer in a hard disk drive to detect mechanical resonance and suppress them with a feedback loop. Fig. 7 shows such a system, in which the MEMS accelerometer 1 of Fig. 1 is sandwiched between the suspension 81 and the slider 83 of a hard disk drive, with its base 2 connected to the suspension 81 and the slider 83 by any type of adhesive such as epoxy. Thus, the accelerometer 1 is capable of measuring any vibration of slider 83.

FIG. 8 is a block diagram of a servo system with an active vibration control. The built-in MEMS accelerometer which is an embodiment of the invention is used to detect the acceleration. In this diagram the slider position is denoted as y_2 and the VCM output force is denoted as F . The measured acceleration of the mass is denoted as a . The boxes indicated as $R(s)$ denotes the relationship (response function) between the applied force F and the acceleration a . An active damping loop 102 is present for the sensed acceleration signal. The active damping loop 102 is inserted into the inner current control loop 101 and the outer position loop 103. In this regard, the multi-sensing signals by the accelerometer and the magnetic sensor in the read/write head are transferred into a voice coil motor (VCM) through a feedback controller so as to actively suppress structural resonance and increase servo bandwidth.

The active damping loop 102 for the measured acceleration uses the output signal from the MEMS sensor and a controller C_a to close a feedback loop, to actively damp mechanical resonance of head actuator. The two feedback loops 101 (a current control loop, which uses the controller denoted as C_i and operates on an input signal denoted as i^* to produce an output denoted as i) and 103 (a position control loop, which uses the controller denoted as C_y , and operates on an input signal denoted y_2^*) are both known already in to a skilled reader. The feedback control loops in Fig. 8 are cascaded from inner to outer are the current control loop, the active damping loop and the position control loop, respectively. The most important feature of cascaded control is that the loops are separated in the frequency domain and the design can be carried out one by one from inner to outer. The most inner current control loop has a very wide bandwidth when compared with the other two outer loops and can be considered as ideal in the frequency range of interest for the damping, that is, $i = i^*$. Therefore, the transfer function from a^* to a is

$$\frac{a(s)}{a^*(s)} = \frac{k_i C_a(s) R(s)}{1 + k_i C_a(s) R(s)}. \quad (1)$$

If we can design an active damping controller $C_a(s)$ such that

$$k_i C_a(s) R(s) \gg 1, \quad (2)$$

in the frequency range of interest for the outer position loop, then we have

$$\frac{a(s)}{a^*(s)} \approx 1. \quad (3)$$

Thus, the oscillation system becomes an ideal double-integrator system for the outer position loop. Actually, equation (2) implies that the active damping loop needs a robust controller, and thus an H_∞ controller is preferable to be adopted in implementing this system.

Since the piezoelectric MEMS accelerometer of the invention is small and lightweight, it can also be installed in other locations in a HDD, such as the carrier arm, base or pivot etc. to detect and suppress structural vibration with
5 a feedback control loop.

Claims

1. A MEMS accelerometer having:

at least one flexible member including a semiconductor substrate, at least one element of piezoelectric material formed on the substrate, and at least two electrodes for detecting electrical voltages generated in the piezoelectric material and from them generating an output signal;

at least one proof mass member supported by the flexible member;
and

a base member attached to the flexible member;

wherein the proof mass is arranged to be movable relative to the base member upon acceleration of the accelerometer thereby causing flexing of the flexible member, which causes the piezoelectric material to generate electrical voltages which are measured by the electrodes.

2. An accelerometer according to claim 1 in which there are two flexible members, supporting opposite side of said proof mass member.

3. An accelerometer according to claim 1 or claim 2 in which the or each flexible member is more flexible in a first direction than in a second orthogonal direction and than in a third direction, the first, second and third directions being mutually orthogonal, whereby the proof mass member is permitted to move in the first direction and substantially prevented from moving in the second and third directions.

4. An accelerometer according to claim 1 in which the or each flexible member comprises a piezoelectric layer sandwiched between top and bottom electrode layers.

5. An accelerometer according to claim 4 in which at least one of the top and bottom electrode layers is patterned.
6. An accelerometer according to claim 4 or claim 5 in which an insulating layer is provided between the substrate and the bottom electrode layer.
- 5 7. A hard disk drive incorporating a MEMS accelerometer according to any preceding claim, the accelerometer being provided between a slider and a flexure for measuring movement of the slider.
8. A hard disk drive according to claim 7 including a feedback loop for controlling motion of the slider based on the output of the accelerometer.
- 10 9. A method of forming an accelerometer according to any of claims 1 to 6 which includes:
 - forming a proof mass member, a base member and at least one flexible member attached to the base member and supporting the proof mass member, the flexible member including a semiconductor substrate;
 - 15 forming at least one element of piezoelectric material and at least two electrodes on the substrate, the electrodes sandwiching the piezoelectric material, the electrodes being arranged to detect voltages generated in the piezoelectric material and from them generate an output signal.
- 10 10. A method according to claim 9 in which the semiconductor substrate is attached to the proof mass member when the semiconductor substrate is already attached to a handle wafer, and the handle wafer is subsequently removed.
11. A method according to claim 9 in which the proof mass member is formed by etching a handle wafer attached to the semiconductor substrate.

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12. A method for forming a MEMS device for use as an actuator, a sensor, an accelerometer or a filter, the method including:

providing a first Si wafer, which is a $\langle 110 \rangle$ Si wafer or a $\langle 100 \rangle$ Si wafer,

etching the first wafer to form a through-hole through it;

providing at least one silicon-on-insulator structure comprising a handle wafer and a second silicon wafer;

5 bonding at least one side of the first wafer to the second silicon wafer of a respective one of the silicon-on-insulator structures, with the second silicon wafer extending over the through hole; and

removing the handle wafers.

13. A method according to claim 12 further including forming shallow trenches in the first silicon wafer proximate the through hole before the first
10 silicon wafer is attached to the second silicon wafer(s).

14. A method according to claim 12 or claim 13 further including providing at least one piezoelectric layer in a location where it is flexed if the second wafer is flexed, and at least two electrodes for measuring electric fields generated by the piezoelectric layer.

15 15. A method for forming a MEMS device for use as an actuator, a sensor, an accelerometer or a filter, the method including:

(i) providing at least one silicon-on-insulator structure comprising a handle wafer and a silicon wafer joined by an interface material;

20 (ii) dividing the handle wafer into at least separate two handle elements by forming a hole through it extending at least as far as the interface material; and

(iii) introducing an etchant into the hole, the etchant etching the interface material between the handle wafer and the silicon wafer to either side of the hole so as to form a chamber between the handle wafer and the
25 silicon wafer, whereby, when a first one of the handle elements is fixed, the

second handle element is resiliently supported from the first handle element via the silicon wafer.

16. A method according to claim 15 which includes:

repeating steps (i) to (iii) to produce a second device having two handle
5 elements mutually connected by a silicon wafer, and

attaching the handle elements of one of the devices to the respective handle elements of the other device.

17. A method according to claim 15 or claim 16 further including providing at least one piezoelectric layer in a location where it is flexed if one of the
10 silicon wafers is flexed, and at least two electrodes for measuring electric fields generated by the piezoelectric layer.

18. A MEMS device produced by a method according to any of claims 12 to 17.