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A transducer is described comprising at least one torsion bar, said torsion bar defining a torsional axis, a piezoelectric film arranged on the at least one torsion bar; and electrodes arranged on said piezoelectric film. The transducer may e.g. be used as an energy conversion device, an energy harvesting device, inertial sensor, accelerometer, gyroscope, tilting mirror, torsional actuator, viscometer or to impose a controlled angular rotation.
ENERGY CONVERSION DEVICE

INTRODUCTION
The present invention relates to a MEMS device (microelectromechanical system) providing a torsional transducer. The torsional transducer may particularly be used for energy harvesting, and may also be used for sensing or imposing angular deformation or angular load (moment).

BACKGROUND
Harvesting energy effectively from vibrations with a miniaturised device is inherently limited by the high eigen frequency of micro devices compared to the frequency of typical vibration signals available. This is also often the case for other miniaturised inertial devices. Energy conversion for such devices can be achieved by several measures. One possibility is the usage of piezoelectric materials in combination with a silicon-based mechanical structure.

In the prior art, beams/plates in bending are used [1-3] often combined with a bigger mass at the end of the beam. The disadvantage of exploiting bending is that the bending moment can vary considerably along the structure so that the normal stress in the film is very position dependent. To avoid failure, the displacement has to be limited so that the maximum stress is below a certain threshold. Then the parts which are stressed below maximum, are not fully exploited in the transduction. A remedy for this is to taper the beam (up to the point of looking like a triangular plate).

In the prior art, transduction is done through an operation mode of the piezoelectric material in which the electric field and the normal stress have the same direction (d_{33} mode) or in a mode in which the directions are orthogonal (d_{3i} mode). The piezo-electric coefficients d_{i\mu} [C/N] are defined as the contribution to electric polarization due to stress component \mu. The d_{33} coefficient describes, therefore, the longitudinal effect and the d_{3i} coefficient the transversal effect. Both constants are a measure for the coupling between the electrical and mechanical domain for different deformations for a given piezo-electric material.
In the prior art a common technique is to use a piezoelectric film sandwiched between two conducting layers, all placed on top of a structural material. This is the $d_{31}$ mode for bending actuator/sensor. This has two important drawbacks: i) the film is typically thin, so the output voltage is quite low, and ii) $d_{31}$ mode has much lower electromechanical coupling than the $d_{33}$ mode.

It is also possible to exploit $d_{33}$ mode by use of an interdigital finger pattern [4], i.e. a pattern with electrodes with varying electrical potential, which overlap like fingers when two straight hands are fitted into each other. This solves the particular problems of $d_{31}$ mode operation, but does not solve the problem of maximizing the area and obtaining uniform stress within the transducer.

Outside the field of MEMS (Micro-electro-mechanical-systems) there exist piezoelectric transducer designs based on embedded fibres that work in torsion and exploit the $d_{33}$ mode for the fibre [5].

**SUMMARY OF THE INVENTION**

MEMS piezoelectric inertial devices such as accelerometers and motion energy scavengers are based on piezoelectric films deposited on a beam or plate structure that is deformed when a proof mass attached to the beam moves. There are several challenges, some depending upon application and use:

1) the mechanical structure should have a sufficient low eigenfrequency for the frequencies in the spectrum of the vibration signals to be used (typically: 1 Hz - 5kHz);
2) the deflection of the proof mass should be as large as possible;
3) it is desirable to have a uniform stress/strain over the entire transducer to obtain large electromechanical coupling;
4) it is desired to have a large area covered by the piezoelectric material in order to obtain a large short-circuit charge from the device;
5) the output voltage should be sufficient;
6) for materials that are subject to poling the same electrodes should be useful both for poling and transduction; and
7) the operation modes of the material should have a big electromechanical coupling factor.

The present invention provides a solution to these problems.

In a first aspect the invention provides a transducer, comprising:
- at least one torsion bar, said torsion bar defining a torsional axis;
- a piezoelectric film arranged on the at least one torsion and
- electrodes arranged on said piezoelectric material wherein said film and said electrodes are arranged inducing an electromechanical coupling between said film and said electrodes due to torsion of the torsion bar.

The piezoelectric film may be arranged on an entire surface area of at least one surface of the torsion bar. The piezoelectric film may in an embodiment be arranged so as to cover at least 75%, or alternatively 80%-90%, of a surface area of at least one surface of the torsion bar.

In an embodiment at least one proof mass may be suspended in the at least one torsion bar. A centre of mass of said proof mass may be offset from the torsional axis or alternatively lie on the torsional axis depending on the application of the device.

In an embodiment the electrodes may be arranged on the piezoelectric film in a configuration/pattern providing a mixed $d_{33V3}$ mode coupling between said film and said electrodes. The electrodes may be arranged in an electrode pattern comprising a number of extended electrodes arranged adjacent to each other, and wherein a negative electrode is arranged adjacent to a positive electrode in an alternating pattern. In a further embodiment the electrodes may provide an angle of about 45° in relation to said torsional axis. The electrodes may in another embodiment provide an angle from about 30° to about 60° in relation to said torsional axis. The latter could be advantageous if the beam undergoes a combined bending and torsional deformation.
In another, further embodiment, the electrodes may be arranged on the piezoelectric film in a configuration/pattern providing a mode 15 coupling between said film and said electrodes. The electrodes may provide an angle of about 90° in relation to said torsional axis.

The arrangement of the electrodes on top of the piezoelectric film enables a desired electrical coupling to the piezoelectric material under operation and for poling purposes. The high electromechanical coupling between the film (and accordingly the torsion bar) and the electrode structure provides a high output voltage from the transducer. The electrodes may be arranged in an electrode pattern covering an entire surface area of said piezoelectric film.

In a further embodiment, the proof mass may be suspended in two torsion bars. The proof mass may have a plate like shape and said torsion bars may have either a plate like shape or a cantilever like shape.

The torsional transducer defined above may be used as an energy conversion device. Further, the torsional transducer defined above may also be used as an energy harvesting device, inertial sensors, accelerometers, gyroscopes, tilting mirror, torsional actuators, or viscometers. The transducer may also be used as a device to impose a controlled angular rotation on the torsion bar and any member fixed on it.

The invention uses the torsion of a bar. This gives uniform stress over the entire transducer element without tapering the bar. The excitation of the device may be made to couple strongly to torsional motion - also for lower frequencies i.e. a few Hz in terms of the requirement of application- by moving a centre of mass sufficiently (>10% of the mass width at the torsion bar) far away from the torsional axis at the design stage.

The novel electrode structure can be used for both transduction and poling, and which has a resulting electromechanical coupling factor comparable to that in $d_{33}$ mode.
BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the invention will now be described with reference to the following drawings, where:

Figure 1a shows a cross section side view of an inertial device according to an embodiment of the invention;

Figure 1b shows a top view of an inertial device according to an embodiment of the present invention consisting of a mass and a torsion bar,

Figure 2 illustrates the qualitative distribution of the shear stress and strain in the cross-section of a torsional rectangular beam according to the embodiment of Figure 1,

Figure 3 shows the stress components in a regular hexahedron element of the torsional rectangular beam in Figure 2,

Figure 4a shows the stress components in a regular hexahedron element as shown in Figure 3, where in Figure 4b the new coordinate system is rotated around the x'-axis from the original one with the angle of 45° clockwise,

Figure 5 shows an electrode configuration for a torsion based transducer according to an embodiment of the present invention operated at a mixed $d_{31}/d_{33}$ mode,

Figure 6 shows an electrode configuration for a torsion based transducer with $d_{15}$ mode coupling according to an embodiment of the present invention,

Figure 7 shows a top view of an embodiment of the present invention,

Figure 8 shows a 3D-view of an embodiment of the present invention (Frame not shown), and

Figure 9 is a cross-section view of an embodiment of the present invention. The structure is encapsulated by a top and bottom lid, and the triple-stack incorporates mechanical stoppers to prevent overload. The top and bottom lid can be made of i.e. glass or silicon.

DETAILED DESCRIPTION

An embodiment of the invention is illustrated in Figure 1a and 1b. Figure 1a shows a torsional transducer with a torsion bar. The torsion bar defines a torsional axis. A piezoelectric film is arranged on the torsion bar, providing a direct electromechanical coupling to the torsion bar. The piezoelectric film is thus
coupled to torsion through an electromechanical coupling factor. Electrodes are arranged on the piezoelectric material in a way that enables a desired electrical coupling to the piezoelectric material under operation and for poling purposes. The electrode structure arranged on the piezoelectric film provides a voltage signal from the piezoelectric film resulting from torsion of the torsion bar. The electrode structure and the electromechanical coupling will be explained in detail below.

As the torsion bar is provided with the piezoelectric film on top of said bar, and the electrodes are arranged on top of the piezoelectric film, deformation of the bar due to torsional movement of the bar therefore electromechanically couples directly to the piezoelectric film and the electrodes arranged on top of the film. The piezoelectric film and the electrodes may be arranged on one or more of the surfaces of the bar, on the top side, on the underside, or on the sides depending on the use and other design details. The piezoelectric film may be arranged on an entire surface of the torsion bar. Due to practical design adaptations and production methods for the transducer, the entire surface means that the piezoelectric film covers at least 95 % of the surface area of at least one side of the torsion bar. It is also possible to design transducers with less surface area covered, but this will reduce the voltage signal from the transducer. A surface area coverage of 75%-95%, or alternatively, 80%-90% for the piezoelectric film is also possible. Whether the voltage signals from such transducers is sufficient, depends on the actual design and use of the transducer. In the embodiment in Figure 1a, the entire top surface area of the torsion bar is covered. The electrode structure/configuration is arranged on the piezoelectric film to provide a voltage signal from the entire surface area of said film. Embodiments of the electrode configuration will be explained in detail later.

Figure 1b shows a top view of the inertial device from Figure 1a. A large mass is suspended by two beams. In the embodiment shown in Figure 1a and 1b the mass is suspended off-centre, as the centre of mass of said proof mass is offset from a torsional axis defined by the two beams. However, embodiments where the centre of mass lies on the torsional axis are also equally feasible. Embodiments with the centre of mass offset form the torsional axis enable excitation from a linear
acceleration. The mass in Figure 1a and 1b has a rectangular shape, with a thickness (not shown) substantially smaller than the width and the length, providing a plate like shape. The mass may however have any suitable form depending on the application and frequency range for sensing and harvesting applications. The two beams are shown as torsion bars attached to opposite sides of the mass in Figure 1. Due to the torsion moment produced by acceleration on the mass or (for an actuator) by an electrical field across the electrodes, the two beams are twisted and shearing stress is generated in the cross-section of the beam, providing a transducer based on torsional motion. The size of the assembly might be in the range of several 100µm to approximately 20mm in both the in-plane directions and several 100µm up to 5mm in the thickness direction. According to practical applications, there is no certain limitation for the dimensions of the assembly, which may be designed and fabricated with MEMS technology.

The deflection of the proof mass should be as large as possible without destroying the torsion bar; i.e. avoiding inducing too much stress in the bar which may lead to cracks in the structure. The maximum amplitude of deflection for a given transducer is determined by its design, choice of materials etc.

Figure 2 shows the shear stress distribution in the cross section of one of the torsion bars in Figure 1. The Z axis represents the longitudinal axis, i.e. the axis from which the mass is offset. A represents the middle point of the length of the torsion bar, B (middle point of the height of the torsion bar), X-axis the axis along which the proof mass is suspended off-centre, H (height of the torsion bar), O (neutral axis), W (width of the torsion bar), t_B (mechanical stress at point B), t_A (mechanical stress at point A).

When a piezoelectric film is deposited on top of the bar shown in Figure 1, it will experience the stress distribution shown in Figure 2, which shows the qualitative shear stress and strain distribution in the cross-section of a rectangular bar in torsion. When the bar is much wider than its thickness, the stress distribution shown in Figure 2 will be very flat with a less prominent maximum. That is to say, a wide bar resembles more the property of a plate than of a beam, i.e. when the
fraction of H/W is less than about 1/3. For example, as a feasible case, the dimensions are W=850 µm, H=30.5 µm, and L=1700 µm.

Figures 3a and 3b show the stress components in a regular hexahedron element of the torsion bar as shown in Figure 1.

As shown in Figure 3a, the torsion bar with piezoelectric film deposited on top of the bar is subjected to a torsional moment, $M_i$, acting on the right end in the coordinate system which we now refer to as $x'y'z'$. Consider the regular hexahedron element near the top surface of the bar (Figure 3b, $\sigma$ represents the principal stress component, and $T$ represents the shear stress component), there are only shear stresses in the four side surfaces and no normal stress on the side surfaces. Figure 3a thus represents a pure shear case in the $y'o'z$ plane.

The piezoelectric film is deposited on the top surface of the torsion bar as defined by the $yz'$ surface. In some embodiments it might be deposited on the bottom surface in addition. In Figure 3, the entire area of the top surface of the torsion bar is covered by the piezoelectric film, i.e. by entire meaning at least 95% of the area. To exploit the torsional movement effectively, different electrode structures are feasible. These are described in the following.

Now rotate the coordinate system 45° clockwise, as shown in Figures 4a and 4b. Figure 4a shows the stress components in a regular hexahedron element, whereas Figure 4b shows the new coordinate system rotated around the $x'$-axis from the original one with the angle of 45° clockwise. Just as in Figure 3, $\sigma$ represents the principal stress components in the $x$, $y$, $z$-axis respectively and $T$ represent the shear stress components along the $x$, $y$, $z$-axis respectively. $P$ is the polarisation direction of the electric field in a piezoelectric film, when deposited in the $yz$-plane on top of said regular hexahedron element in Figure 3. Figure 4b represents an electrode configuration working in a mixed $d_{31}/33$ mode, which will be explained below.
With an original in-plane stress

\[
\begin{bmatrix}
0 & \tau \\
\tau & 0
\end{bmatrix}
\]  \hspace{1cm} (7)

the principal stress in coordinate system xyz can be written as

\[
\begin{bmatrix}
\tau & 0 \\
0 & -\tau
\end{bmatrix}
\]  \hspace{1cm} (8)

The piezoelectric constitutive equations for the electric displacement component \( D_j \) as described in the prior art [7, 8], can be written as:

\[
D_i = d_{ikl} T_{kl} + \varepsilon_{ik}^{T} E_k
\]  \hspace{1cm} (9)

In this equation \( D \) is the electric displacement, \( d \) is a piezoelectric constant (in [CVN]), \( T \) is a stress component, \( \varepsilon \) is the dielectric constant and \( E \) is the electric field strength - all constants in the respective directions given by the indices. For the piezoelectric constant this is normally noted in a short form with only two indices.

From these general equations the coupling of stress to electric displacement in this coordinate system can be deduced as

\[
D_3 = d_{33} T_3 + d_{13} T_1 + \varepsilon_{33}^{T} E_3 = (d_{31} - d_{33}) \tau + \varepsilon_{33}^{T} E_3
\]  \hspace{1cm} (10)

The electromechanical coupling factor \( k \) of a piezoelectric slab for this mixed \( d_{33} \) mode \( 33 \) coupling is

\[
k'_{33/31} = \frac{-d_{31} + d_{33}}{\sqrt{\varepsilon_{33}^{E} (s_{11}^{E} - 2s_{13}^{E} + s_{33}^{E})}}
\]
With $S_{ki}$ being the elastic compliance coefficients.
The mixed $d_{33/3i}$ mode is provided by the beam(s) being subjected to a torsion moment. The angle between the axis of the beam(s) and the electrode finger(s) is then 45° for its optimum. The electrodes may in another embodiment also be arranged at an angle of between about 30-60°. This might be beneficial when the beam(s) are subjected to a combined torsion/bending situation dependent on which kind of movement dominates the operation.

Some example electromechanical coupling factors working on different modes are listed in Table 1, based on available values for the different piezoelectric materials PZT (lead-zirkonium-titanate) -5H, PZT-5A, and AlN (aluminium nitride).

<table>
<thead>
<tr>
<th>Coupling</th>
<th>PZT-5H</th>
<th>PZT-5A</th>
<th>AlN</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>12.0</td>
<td>10.3</td>
<td>2.1</td>
</tr>
<tr>
<td>33</td>
<td>56.4</td>
<td>49.4</td>
<td>9.4</td>
</tr>
<tr>
<td>15</td>
<td>45.5</td>
<td>46.9</td>
<td>2.4</td>
</tr>
<tr>
<td>mixed 31/33</td>
<td>46.2</td>
<td>39.8</td>
<td>7.6</td>
</tr>
</tbody>
</table>

*The values are $k'$-given in %.

We notice that the $d_{3i/33}$ mixed coupling is comparable in strength to that of $d_{33}$ coupling for all materials; $d_{33}$ mode and the mixed mode are both much stronger than demode, which is common in conventional unimorph or bimorph applications. The dis coupling is very strong and comparable to $d_{33}$ and mixed $d_{3i/33}$ for PZT, while for AlN it is relatively weak.

Mode dis coupling in PZT and related materials is provided by electrodes perpendicular (about 90°) to the bar axis, and is only for transduction. This embodiment will be described in more detail later.

An electrode configuration working in this mixed $d_{3i/33}$ mode is shown in Figure 5. A piezoelectric film is arranged on the torsion bar, and the electrode fingers are arranged in an angle of 45° in relation to the direction of the torsional axis on top or bottom of the piezoelectric film. This provides the mixed mode $d_{3i/33}$ according to Figure 4b, and a coupling factor according to equation 10. In this device, the
directions of the polarization and electric field are the same, that is, the two adjacent areas in the piezoelectric film PZT separated by an electrode finger should have the reversed polarization. The direction of the polarization and electric field is at an angle of 45° in relation to the direction of the torsional axis for the embodiment of Figure 5. The electrode pattern may also be described as a number of extended, straight, electrodes arranged adjacent to each other, and wherein a negative electrode is arranged adjacent to a positive electrode in an alternating pattern. Each such extended electrode may be called a finger, and the electrodes provide a pattern looking like overlapping fingers when two straight hands are fitted into each other. Each finger is connected to an electrode extending along the edge of the torsion bar, and which connects the fingers to electrode terminals. The electrode pattern in Figure 5 covers the entire surface area of the piezoelectric film; i.e. by entire meaning at least 95% of the area. It is the total pattern of electrodes that covers at least 95% of said film, and not the area covered by each individual electrode stripe. The embodiment of Figure 5 provides a micromechanical device with a large voltage signal for even small torsion moments. For a feasible case with dimensions of L=1700µm, W=566.7 µm, and electrode width d=40µm, the output voltage is over 20 V with a pure torque of 2.66x10⁻⁵Nm taking effect.

The output voltage signal from the electrodes is provided across the electrode terminals. When the transducer is used as an energy harvesting device, this voltage signal may be used to supply a device, e.g. an inertial or optical sensor with read-out electronics, signal processing and RF unit, with power. The transducer may however also be used for other purposes as an inertial sensor, accelerometer, gyroscope, torsional actuator, sensors for other applications, e.g. viscometer, etc.

Other electrode configurations are also possible. Figure 6 shows a schematic configuration of electrodes for the polarization in the direction of the beam width (dis mode). The mass is cut at its symmetrical axis to the right i.e. only one half the structure is shown. A torsional bar is suspended at the left in the figure, and with the proof mass at its end. The offset of the mass centre is indicated in figure 6 as
the dotted line with "offset mass". The centre of mass is offset from the torsional axis. The torsional axis is the dotted line in the middle of and along the length of the torsion bar.

In Figure 6, the $d_{15}$ mode coupling is realized with the transduction electrodes perpendicular (90°) to the torsional axis. The transduction electrodes are arranged in a side-by-side pattern at a fixed interval. A negative electrode is arranged adjacent to a positive electrode in an alternating pattern. This provides an electrode pattern looking like overlapping fingers when two straight hands are fitted into each other. Each positive finger is connected to an electrode extending along the edge of the torsion bar, and which connects the fingers to the positive electrode terminal. Each negative finger is connected to another electrode extending along the edge of the torsion bar, and which connects these fingers to the negative electrode terminal. These transduction electrodes are connected by longitudinal electrodes along the length of the bar forming an electrode pattern/configuration electrode. A longitudinal electrode pair separate from the transduction electrode pair, is also arranged along the length of the bar at its edges, forming poling electrodes. A proof mass is arranged at the end of a torsion bar, but with the centre of mass offset (offset mass) from the torsional axis (dotted centre line in torsion bar). This provides both a torsional moment on the bar, as well as a bending moment due to the end location of the proof mass. The polarization direction and the shear stress $\tau_{23}$ is perpendicular to the longitudinal axis of the bar. The direction of the electrode field is along the longitudinal axis of the bar. The electrode configuration in Figure 6 is only for transduction, not for poling. Moreover, the electromechanical coupling factor in Figure 6 is much less than for the embodiment in Figure 5. Therefore, the electrode configuration in Figure 5 may be preferred for practical use since a larger fraction of energy can be converted per cycle. The piezoelectric film is also in this embodiment arranged on the entire torsion bar, and the electrodes deposited on top and/or bottom of the film. Also in the embodiment in Figure 6, the electrode pattern covers the entire area of the piezoelectric film; i.e. by entire meaning at least 95% of the area. Mechanically, this system is equal to that presented before, but the following
piezoelectric constitutive equations for the electric displacement components \( D_i \) and \( D_2 \) hold for the exploitation of the \( d_{15} \) mode:

\[
D_1 = d_{15} T_5 + \varepsilon_{11}^e E_1 = d_{15} \tau_{x5} + \varepsilon_{11}^e E_1 \text{ or }
\]

\[
D_2 = d_{15} T_4 + \varepsilon_{12}^e E_2 = d_{15} \tau_{y5} + \varepsilon_{12}^e E_2
\]

where \( d \) is a piezoelectric constant (in [C/N]), \( T \) is a stress component, \( \varepsilon \) is the dielectric constant and \( E \) is the electric field strength - all constants in the respective directions given by the indices. For the piezoelectric constant this is normally noted in a short form with only two indices.

First of all, to exploit the \( d_{15} \) mode coupling effect we see that the electric field must be orthogonal to the polarization direction. That is in the \( x(1) \) or \( y(2) \) directions as shown in Figure 6. Based on the above discussion of the stress distribution we can then distinguish the following three cases:

1. Polarization along the thickness dimension of the bar (perpendicular to \( yz \)-plane): The dominating stress component is \( \tau_{x5} \) and there is no coupling.

2. Polarization along the width dimension \( W \) of the bar: The dominating stress component is \( \tau_{y5} \) if the \( x \)-axis is along the length dimension of the bar or \( \tau_{x5} \) if the \( y \)-axis is along the length dimension. Therefore an electric field along the length direction of the bar is generated and we have coupling.

3. Polarization along the length dimension of the bar: The dominating stress (strain) component is \( \tau_{y5} \) if the \( x \)-axis is along the width dimension of the bar or \( \tau_{x5} \) if the \( y \)-axis is along the width dimension. Therefore an electric field along the width direction of the bar is generated and we have coupling.

Figure 6 shows the second case as described above. If polarisation in either the width dimension or along the length dimension is used, the electromechanical coupling factor for this mode is then:

With $S_{55}$ being the elastic compliance coefficient.

3. Example embodiments

A further embodiment for the torsional transducer is shown in figures 7 and 8. Figure 7 provides a top view of the torsional transducer, where the mass is suspended in a pair of torsional beams arranged in a frame. A centre of mass of said proof mass is offset from the torsional axis provided by the torsional beams. The mass is suspended in the beams in a horizontal plane defined by the width and height of the mass. Gravitational forces may act perpendicular to said horizontal plane providing a torsional moment on the torsion bars.

Figure 8 provides a 3D-view of the embodiment in Figure 7, but with the frame not shown. A preferred electrode configuration on the torsional beams is equal to what is shown in figure 5, as this configuration provides the largest electromechanical coupling factor for the mixed $d_{31}/33$ mode.

It is also possible to design a transducer with the proof mass arranged on both sides of the torsional beams. This provides a transducer which is also sensitive to angular acceleration.

In the embodiment shown in Figures 7 and 8, the substrate is silicon, with mass and frame having full substrate thickness. Typical substrate thicknesses span from 200µm up to 2mm. The torsion beams are etched to be much thinner (less than 20% of the substrate thickness). In most practical embodiments, the torsion beams are normally within the thickness range from 10µm to 45µm.

The torsional beams are layered structures including:
- a structural layer determining mainly the mechanical behaviour; preferably Si;
- a layer for stress compensation, preferably SiO2;

\[
k_{15} = \frac{d_{15}}{\sqrt{\varepsilon_{11}^T S_{55} E}}.
\]

(14)
- a piezoelectric layer for energy conversion, preferably PZT. Though PZT has the largest electromagnetic coupling factor, it should be noted that the piezoelectric material is not limited within PZT materials. In terms of the application situation, other materials, such as relaxor ferroelectrics, and piezoelectric polymers, can also be considered in the present invention;
- at least one electrode layer.

The structure (mass and beam, frame of middle wafer) may be encapsulated by a top and bottom lid, made of glass or silicon, as shown in Figure 9. Figure 9 is a cross-section view of the embodiment of the present invention shown in Figures 7 and 8. The structure with the suspended mass and torsion beams is encapsulated by a top and bottom lid, and the triple-stack incorporates mechanical stoppers to prevent overload. The top and bottom lid can be made of i.e. glass or silicon, preferably assembled with the transducer on the wafer scale prior to dicing the devices.

Having described preferred embodiments of the invention it will be apparent to those skilled in the art that other embodiments incorporating the concepts may be used. These and other examples of the invention illustrated above are intended by way of example only and the actual scope of the invention is to be determined from the following claims.
1 References


1. A transducer, comprising:
- at least one torsion bar, said torsion bar defining a torsional axis;
- a piezoelectric film arranged on the at least one torsion bar; and
- electrodes arranged on said piezoelectric film, wherein said film and said electrodes are arranged inducing an electromechanical coupling between said film and said electrodes due to torsion of the torsion bar.

2. Transducer according to claim 1, wherein the piezoelectric film is arranged on an entire surface area of at least one surface of the torsion bar.

3. Transducer according to claim 1, wherein the piezoelectric film is arranged so as to cover at least 75%, or alternatively 80%-90%, of a surface area of at least one surface of the torsion bar.

4. Transducer according to one of claims 1-3, comprising at least one proof mass suspended in the at least one torsion bar.

5. Transducer according to claim 4, wherein a centre of mass of said proof mass is offset from the torsional axis.

6. Transducer according to claim 4, wherein a centre of mass of said proof mass lies on the torsional axis.

7. Transducer according to one of claims 1-6, wherein the electrodes are arranged on the piezoelectric film such that a shear stress, due to torsion of the bar, induces a coupling between said film and said electrodes from both $d_{31}$ and $d_{33}$ mode coupling simultaneously.

8. Transducer according to claim 7, wherein said electrodes are arranged in an electrode pattern comprising a number of extended electrodes arranged
adjacent to each other, and wherein a negative electrode is arranged adjacent to a positive electrode in an alternating pattern.

9. Transducer according to one of claims 1-8, wherein said electrodes provide an angle of about 45° in relation to said torsional axis.

10. Transducer according to one of claims 1-8, wherein said electrodes provide an angle from about 30° to about 60° in relation to said torsional axis.

11. Transducer according to one of claims 1-6, wherein the electrodes are arranged on the piezoelectric film in a configuration/pattern providing a $d_{15}$ mode coupling between said film and said electrodes.

12. Transducer according to claim 11, wherein said electrodes provide an angle of about 90° in relation to said torsional axis.

13. Transducer according to one of claims 1-12, wherein said electrodes are arranged in an electrode pattern covering an entire surface area of said piezoelectric film.

14. Transducer according to one of claims 2-13, wherein said proof mass having a plate like shape and is suspended in two torsion bars, and wherein said torsion bars having either a plate like shape or a cantilever like shape.

15. Use of the torsional transducer according to one of claims 1-14 as an energy conversion device.

16. Use of the torsional transducer according to one of claims 1-14 as an energy harvesting device, inertial sensor, accelerometer, gyroscope, tilting mirror, torsional actuator, or viscometer.
17. Use of the torsional transducer according to one of claims 1-14 as a device to impose a controlled angular rotation on the torsion bar and any member fixed thereon.
Figure 1 a) Cross-section side view  b) Top view of inertial device.
Figure 2 Qualitative distribution of the shear stress and strain in the cross-section of a torsional rectangular beam.

Figure 3 The stress components in a regular hexahedron element. [8, 9]
Figure 4a The stress components in a regular hexahedron element. Figure 4b The new coordinate system rotated around the $x'$-axis from the original one with the angle of 45$^\circ$ clockwise.

Figure 5 Electrode configuration for torsion based transducer. [8, 9]
Figure 6 Schematic configuration of electrodes for the polarization in the direction of beam width (mode 15). The mass is cut at its symmetrical axis to the right i.e. only one half the structure is shown. The offset of the mass centre is indicated in the figure.
Figure 7 Top view of a preferred embodiment.

Figure 8 3D-view of a preferred embodiment (Frame not shown).
**Figure 9** Cross-section view of a preferred embodiment. Structure encapsulated by a top and bottom wafer. Note that the triple-stack incorporates mechanical stoppers to prevent overload. The top and bottom wafer can be made of glass or silicon.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L41/09 H01L41/113 B81B3/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L B81B GO1P GO1C GO1L H02N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>EP 2 045 906 A1 (PANASONIC CORP [JP]) 8 April 2009 (2009-04-08)</td>
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<td>Y</td>
<td>paragraphs [0001], [0020], [0021], [0028], [0035] - [0047], [0078], [0081]; figures 1,8</td>
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Date of the actual completion of the international search 6 September 2010

Date of mailing of the international search report 16/09/2010

Name and mailing address of the ISA/
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Meul, Hans

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