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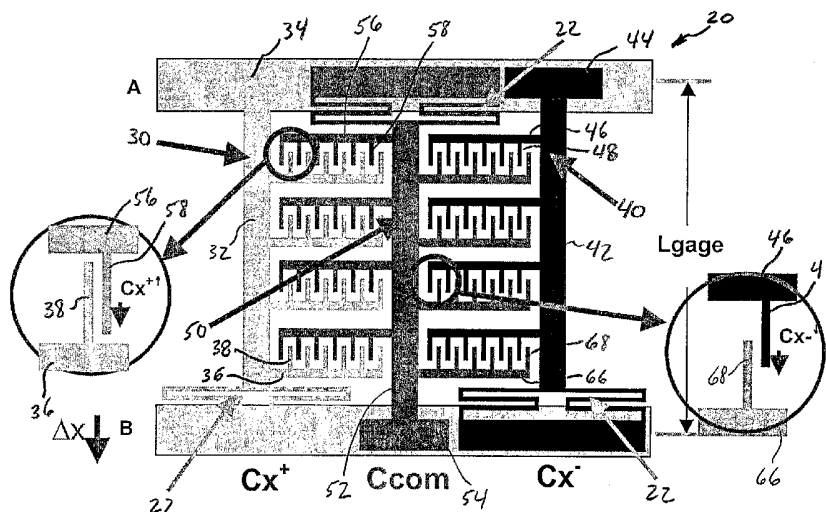
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- (71) Applicant (for all designated States except US): **CASE WESTERN RESERVE UNIVERSITY** [US/US]; Sears Building - 6th Floor, 10900 Euclid Avenue, Cleveland, OH 44106-7219 (US).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): **KO, Wen, H.** [US/US]; 1356 Forest Hills Boulevard, Cleveland, OH 44118 (US). **GUO, Jun** [CN/US]; 2555 Kemper Road #509, Cleveland, OH 44120 (US). **YOUNG, Darrin, J.** [US/US]; 4144 Twin Peaks Terrace, Fremont, CA 94538 (US). **KUO, Hung-I** [—/US]; 32759 Allenbury Drive, Solon, OH 44139 (US).
- (74) Agent: **MASSINA, Glenn, M.**; Michael, Best & Friedrich, LLP, Suite 3300, 100 East Wisconsin Avenue, Milwaukee, WI 53202-4108 (US).
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(54) Title: CAPACITIVE STRAIN SENSORS



(57) Abstract: A capacitive strain sensor comprising first and second anchors and first, second and third finger sets. The first finger set has a plurality of first fingers extending in a first direction. The second finger set has a plurality of second fingers extending in a second direction. The third finger set has a first plurality of third fingers overlapping the first fingers and a second plurality of third fingers overlapping the second fingers. The first, second and third finger sets are associated with the first and second anchors such that movement of the first anchor causes the third finger set to move relative to the first and second finger sets such that a differential capacitance is detected between the finger sets. The finger sets may be provided with buckled beams to provide a mechanical advantage that improves accuracy and sensitivity of the strain sensor.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

CAPACITIVE STRAIN SENSORS

BACKGROUND

[0001] The present invention relates to strain gages. More particularly, the present invention relates to capacitive strain sensors.

[0002] A strain gage is a device used to measure surface strains in structural materials. One type of strain gage used to measure surface strain is a foil type resistance strain gage. Another type of strain gage used to measure surface strain is a capacitive strain gage. A capacitive strain gage generally utilizes capacitors with capacitive plates or elements which are moveable relative to each other as a function of applied strain. As force is applied, causing strain to the structural material, relative movement of the capacitor elements causes the capacitance to change. The change in capacitance is measured by detecting a change in an applied electrical signal.

SUMMARY

[0003] The present invention provides a capacitive strain sensor comprising first and second anchors and first, second and third finger sets. The first finger set has a plurality of first fingers extending in a first direction. The second finger set has a plurality of second fingers extending in a second direction. The third finger set has a first plurality of third fingers extending in the second direction and positioned adjacent the first fingers such that the first plurality of third fingers overlap the first fingers and a second plurality of third fingers extending in the first direction and positioned adjacent the second fingers such that the second plurality of third fingers overlap the second fingers. The first, second and third finger sets are associated with the first and second anchors such that movement of the first anchor causes the third finger set to move relative to the first and second finger sets such that a first capacitance change is detected between the first fingers and the first plurality of third fingers and a second capacitance change is

detected between the second fingers and the second plurality of second fingers. The first and second capacitance changes provide a resultant differential capacitance which can be utilized to determine an applied strain.

[0004] In at least one embodiment, the first, second and third finger sets are provided with buckled beams to provide a mechanical advantage that improves accuracy and sensitivity of the strain sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Fig. 1 is a top plan view schematically illustrating overlapped capacitor figures of a linear strain sensor.

[0006] Fig. 2 is a top plan view of a linear comb strain sensor according to a first embodiment of the present invention.

[0007] Fig. 3 is a top plan view schematically illustrating a buckled beam of a linear strain sensor.

[0008] Fig. 4 is a top plan view of a buckled beam strain sensor according to a second embodiment of the present invention.

[0009] Fig. 5 is microphotograph of the strain sensor of Fig. 4 illustrating finger displacement before and after a strain is applied.

[0010] Fig. 6 is a graph showing the typical output versus an applied strain.

[0011] Fig. 7 shows an illustrative process of forming the sensor of Fig. 4.

[0012] Fig. 8 is an SEM picture of the sensor of Fig. 4.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0013] The present invention will be described with reference to the accompanying drawing figures wherein like numbers represent like elements throughout. Certain terminology, for

example, “top”, “bottom”, “right”, “left”, “front”, “frontward”, “forward”, “back”, “rear” and “rearward”, is used in the following description for relative descriptive clarity only and is not intended to be limiting.

[0014] Fig. 1 shows the principle of a simplified linear comb drive strain sensor. The structure includes a first set of capacitor fingers 10 extending from anchor A and a second set of capacitor fingers 12 extending from anchor B. The fingers 12 extend toward and overlap with the fingers 10. The capacitance between the fingers 10 and 12 is expressed as: $C_x = \frac{lh\epsilon}{G}$, where l is the overlapping length of the fingers 10, 12; h is the thickness of the fingers 10, 12 in the direction perpendicular to the paper; ϵ is the permeability constant of the material used to construct the fingers 10, 12, and G is the gap between the fingers 10, 12. When a strain is applied, as indicated by the arrow S in Fig. 1, it causes a lateral displacement, Δx , of the relative position of the fingers 10, 12. That is, the overlapping length l of the fingers 10, 12 changes, thereby resulting in a change in the capacitance. The capacitance change is expressed as:

$$\Delta C_x = \frac{\Delta x h \epsilon}{G}.$$

[0015] Fig. 2 shows a linear comb drive strain sensor 20 in accordance with a first embodiment of the present invention. The strain sensor 20 includes first and second finger sets 30 and 40 extending from anchor A and a third finger set 50 extending from anchor B. The first finger set 30 includes a trunk 32 attached to anchor A at base 34. A spring 22 may extend from the opposite end of trunk 32 to anchor B to stabilize the finger set 30. A plurality of branches 36 extend from the trunk 32. Each branch 36 includes a plurality of capacitor fingers 38 extending therefrom toward anchor A. The second finger set 40 includes a trunk 42 attached to anchor A at base 44. A spring 22 may extend from the opposite end of trunk 42 to anchor B to stabilize the finger set 40. A plurality of branches 46 extend from the trunk 42. Each branch 46 includes a plurality of capacitor fingers 48 extending therefrom toward anchor B.

[0016] The third finger set 50 includes a trunk 52 attached to anchor B at base 54. A spring 22 may extend from the opposite end of trunk 52 to anchor A to stabilize the finger set 50. A first set of branches 56 extend from the trunk 52 toward the first finger set 30. Each branch 56 includes a plurality of capacitor fingers 58 extending therefrom toward anchor B such that the capacitor fingers 58 overlap the capacitor fingers 38 of the first finger set 30. A second set of branches 66 extend from the trunk 52 toward the first finger set 40. Each branch 66 includes a plurality of capacitor fingers 68 extending therefrom toward anchor A such that the capacitor fingers 68 overlap the capacitor fingers 48 of the first finger set 40.

[0017] When displacement, Δx , is applied at anchor B, the third finger set 50 moves with anchor B while the first and second finger sets 30 and 40 remain stationary with the anchor A. Referring to Fig. 2, as anchor B moves away from anchor A, the first fingers 58 of finger set 50 move toward the fingers 38 of the first finger set 30 and the second fingers 68 of finger set 50 move away from the fingers 48 of the second finger set 40, as illustrated in the exploded portions of Fig. 2. As a result, a capacitance change Cx^+ is generated between the fingers 38 and 58 and a capacitance change Cx^- is generated between the fingers 48 and 68. By comparing capacitance change Cx^+ and capacitance change Cx^- , a differential capacitance change is generated. The differential capacitance is utilized to determine the applied strain. Utilizing a differential capacitance change compared to a single capacitance change provides greater accuracy and sensitivity by eliminating the common mode interferences and environmental error.

[0018] In the illustrated example, anchor B moves away from anchor A, but the principle is the same when anchor B moves toward anchor A. Sensor sensitivity can be optimized by carefully selecting parameters such as sensor gauge length, number of fingers, gap between fingers, finger thickness, and finger material.

[0019] Referring to Figs. 3-5, a capacitive strain sensor 120 that is a second embodiment of the present invention will be described. Fig. 3 shows the principle of the buckled beam

amplification scheme utilized in the present embodiment. The buckled beam scheme includes a center beam 114 supported by opposed supports 110 and 112. Support 110 extends from anchor A at an angle α relative to the horizontal and support 112 extends in the opposite direction from anchor B at an angle α relative to the horizontal. When a strain is applied to anchor A, it causes a small lateral displacement, Δx , of anchor A. For a small tilt angle α , the center deflection of the beam, Δw , is larger than Δx , thus resulting in a mechanical gain, A_{mech} , which is expressed

$$\text{as: } A_{\text{mech}} = \frac{\Delta w}{\Delta x} \cong \frac{1}{2} \text{ctg}(\alpha).$$

[0020] Referring to Fig. 4, a capacitive strain sensor 120 incorporating the buckled beam amplification scheme is shown. The sensor 120 includes three finger sets 130, 140, and 150 extending between anchors A and B. The first finger set 130 includes a center beam 132 supported by opposed supports 134 and 136 extending from anchors A and B, respectively. Each of the supports 134, 136 extends at a positive angle α relative to the horizontal, such that a compressive strain applied to anchor A will cause the center beam 132 to move upward as indicated by arrow O in Fig. 4. A plurality of fingers 138 extend from the center beam 132 toward the third finger set 150. The second finger set 140 includes a center beam 142 supported by opposed supports 144 and 146 extending from anchors A and B, respectively. Each of the supports 144, 146 extends at a positive angle α relative to the horizontal, such that a compressive strain applied to anchor A will cause the center beam 142 to move upward as indicated by arrow P in Fig. 4. A plurality of fingers 148 extend from the center beam 142 toward the third finger set 150.

[0021] The third finger set 150 includes a center beam 152 supported by opposed supports 154 and 156 extending from anchors A and B, respectively. Each of the supports 154, 156 extends at a negative angle α relative to the horizontal, such that a compressive strain applied to anchor A will cause the center beam 152 to move downward as indicated by arrow Q in Fig. 4.

A first plurality of fingers 158 extend from the center beam 152 toward the first finger set 130 such that the fingers 158 overlap fingers 138 and a second plurality of fingers 168 extend from the center beam 152 toward the first finger set 140 such that the fingers 168 overlap fingers 148.

[0022] Referring to Fig. 5, a microphotograph of finger displacement before and after a strain is applied is shown. In the illustrated microphotographs, an outward force is applied to anchor A such that the center beam 152 of the third finger set 150 moves upward and the center beams 132 and 142 of the first and second finger sets 130 and 140 move downward. In accordance with such center beam movement, the first fingers 158 of finger set 150 move toward the fingers 138 of the first finger set 130 and the second fingers 168 of finger set 150 move away from the fingers 148 of the second finger set 140. As a result, a capacitance change Cx^+ is generated between the fingers 138 and 158 and a capacitance change Cx^- is generated between the fingers 148 and 168. By comparing capacitance change Cx^+ and capacitance change Cx^- , a differential capacitance change is generated. The differential capacitance is utilized to determine the applied strain. Again, utilizing a differential capacitance change compared to a single capacitance change provides greater accuracy and sensitivity by eliminating the common mode interferences and environmental error.

[0023] Sensor performance can be optimized by selecting parameters with the developed finite element analysis simulation program. The mechanical amplification created by the buckled beams improves the sensor sensitivity; hence reducing the sensitivity requirement and power dissipation on the interface circuits. A sensitivity of 0.1 microstrain and a dynamic range of 10,000 can be expected with this design and a matching interface circuit. A typical output versus an applied strain is shown in Fig. 6. The measured non-linearity is 0.5%FS, and sensitivity is around 250aF/ $\mu\epsilon$, close to the predicted result using FEA simulation. The fundamental resolution limit of this sensor is the combined noise contributed from Brownian

motion and mechanical vibration, which is less than $0.1 \mu\epsilon$ over a 10kHz bandwidth, corresponding to a displacement of 0.1 nm ($1 \text{ \AA}$) according to the analysis.

[0024] A prototype fabrication with only one mask was made to verify the design and simulation results. The process, shown in Fig. 7, started with a SOI wafer with device layer and oxide layer of 20um and 2um, respectively. The wafer was patterned and followed by a DRIE process. The wafer was then diced, cleaned, and followed by a timed HF release process. A layer of $200 \text{ \AA}$ Aluminum was then sputtered on the device to reduce the sensor series resistance and resistive thermal noise.

[0025] An SEM picture of the sensor is shown in Fig. 8 with the following parameters: Gauge Length (Lg) -1000 um; Buckled Beam Length (Lb) - 300 um; Buckling angle (α) - 5.71° ; Number of Fingers – 37; Finger gap - 3 um; Measured Sensitivity - $250 \text{ aF}/\mu\epsilon$. The prototype fabrication achieved a yield close to 100% due to the simplicity of the design and fabrication process.

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What is claimed is:

1. A capacitive strain sensor comprising:
first and second anchors;
a first finger set having a plurality of first fingers extending in a first direction;
a second finger set having a plurality of second fingers extending in a second direction;
and
a third finger set having a first plurality of third fingers extending in the second direction
and positioned adjacent the first fingers such that the first plurality of third fingers overlap the
first fingers and a second plurality of third fingers extending in the first direction and positioned
adjacent the second fingers such that the second plurality of third fingers overlap the second
fingers;
wherein the first, second and third finger sets are associated with the first and second
anchors such that movement of the first anchor causes the third finger set to move relative to the
first and second finger sets such that a first capacitance change is detected between the first
fingers and the first plurality of third fingers and a second capacitance change is detected
between the second fingers and the second plurality of second fingers with a resultant differential
capacitance.
2. The capacitive strain sensor of claim 1 wherein the first finger set includes a first trunk
extending from the first anchor, the second finger set includes a second trunk includes a second
trunk extending from the first anchor and the third finger set includes a third trunk extending
from the second anchor between and parallel to the first and second trunks.
3. The capacitive strain sensor of claim 2 wherein the first finger set includes one or more
first branches extending therefrom toward the third trunk, the second finger set includes one or

more second branches extending therefrom toward the third trunk and the third finger set includes one or more third branches extending therefrom toward the first trunk and one or more fourth branches extending therefrom toward the second trunk, the one or more first branches supporting the first fingers, the one or more second branches supporting the second fingers, the one or more third branches supporting the first plurality of third fingers and the one or more fourth branches supporting the second plurality of third fingers.

4. The capacitive strain sensor of claim 2 wherein a first spring extends between a free end of the first trunk and the second anchor, a second spring extends between a free end of the second trunk and the second anchor, and a third spring extends between a free end of the third trunk and the first anchor.

5. The capacitive strain sensor of claim 1 wherein the first finger set includes a first center beam supported by first and second first supports extending from the first and second anchors respectfully, the second finger set includes a second center beam supported by first and second second supports extending from the first and second anchors respectfully, and the third finger set includes a third center beam supported in between and parallel to the first and second center beams by first and second third supports extending from the first and second anchors respectfully, the first fingers extending from the first center beam toward the third center beam, the second fingers extending from the second center beam toward the third center beam, the first plurality of third fingers extending from the third center beam toward the first center beam and the second plurality of third fingers extending from the third center beam toward the second center beam.

6. The capacitive strain sensor of claim 5 wherein the first first support is at an angle W relative to a plane perpendicular to the first anchor, the first second support is at an angle X relative to a plane perpendicular to the second anchor, the second first support is at an angle Y relative to the plane perpendicular to the first anchor, the second second support is at an angle Z relative to the plane perpendicular to the second anchor, and the third first support is at an angle A relative to the plane perpendicular to the first anchor and the third second support is at an angle B relative to the plane perpendicular to the second anchor.
7. The capacitive strain sensor of claim 6 wherein angles W, X, Y, and Z are positive angles and angles A and B are negative angles.
8. The capacitive strain sensor of claim 6 wherein angles W, X, Y, and Z are negative angles and angles A and B are positive angles.
9. The capacitive strain sensor of claim 6 wherein angles W, X, Y, and Z are equal.
10. The capacitive strain sensor of claim 6 wherein A and B are equal.

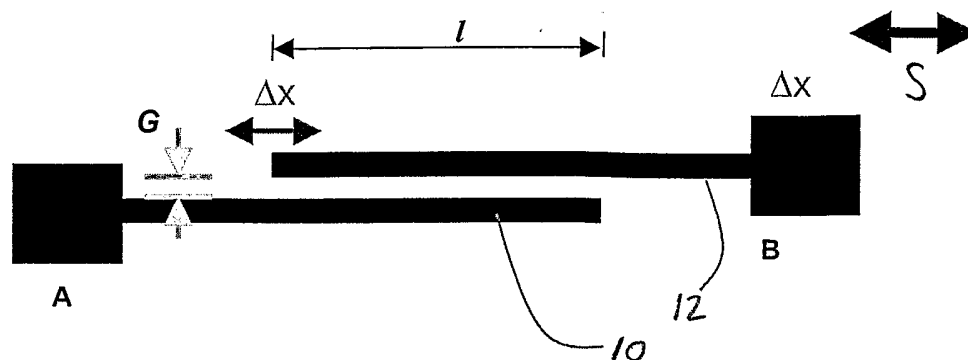


Fig. 1

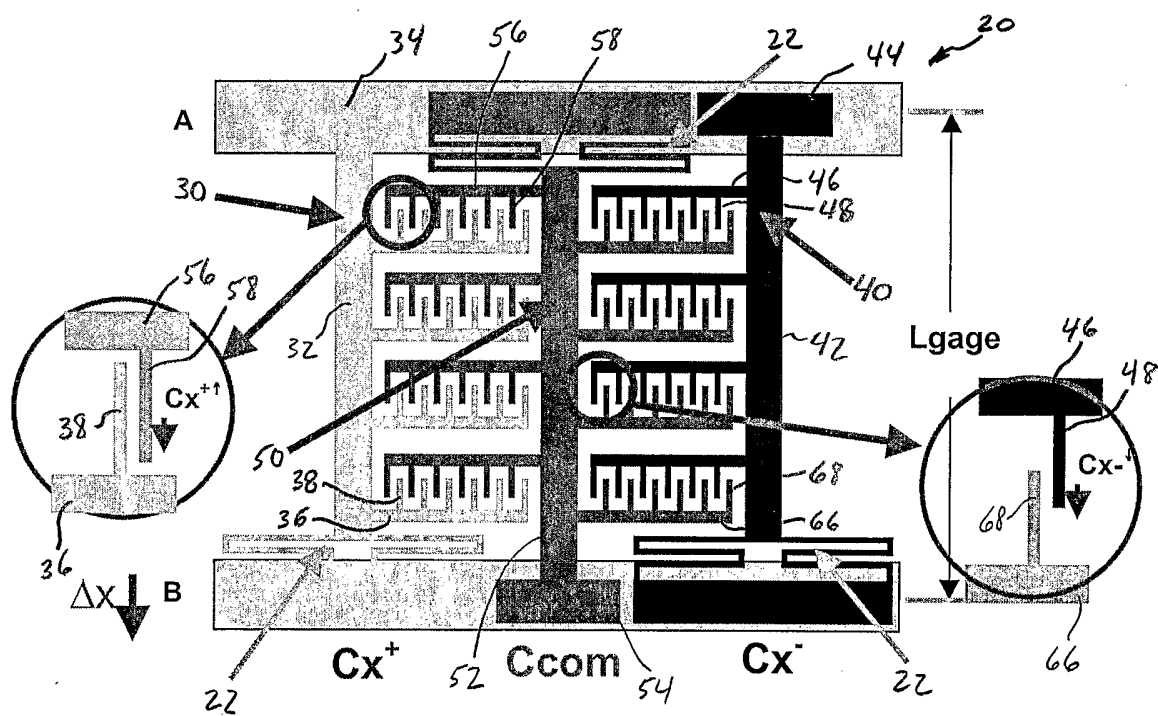


Fig. 2

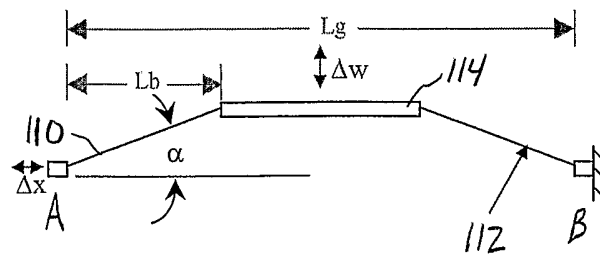


Fig. 3

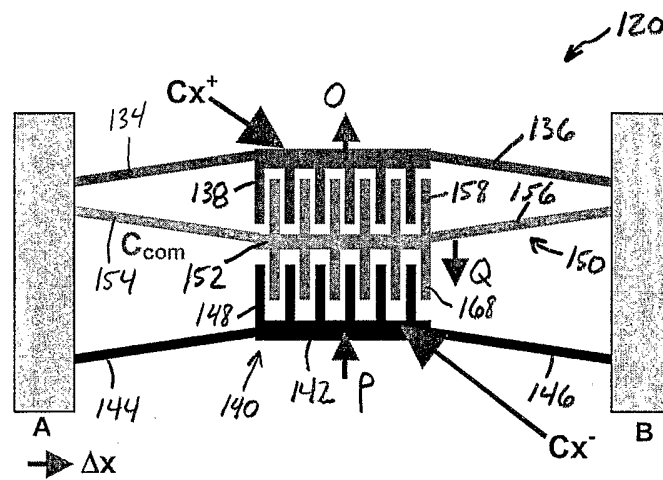
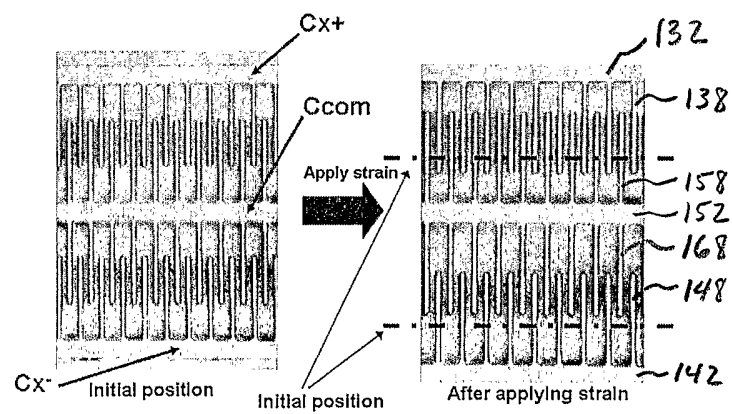


Fig. 4



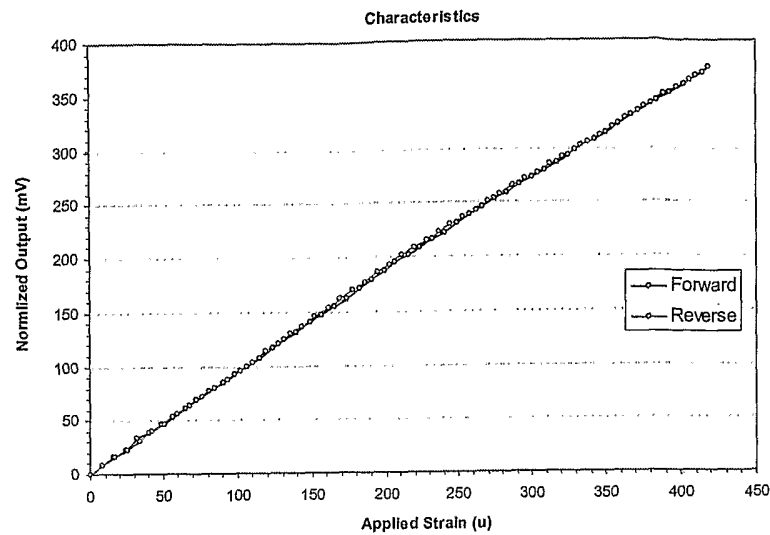


Fig. 6

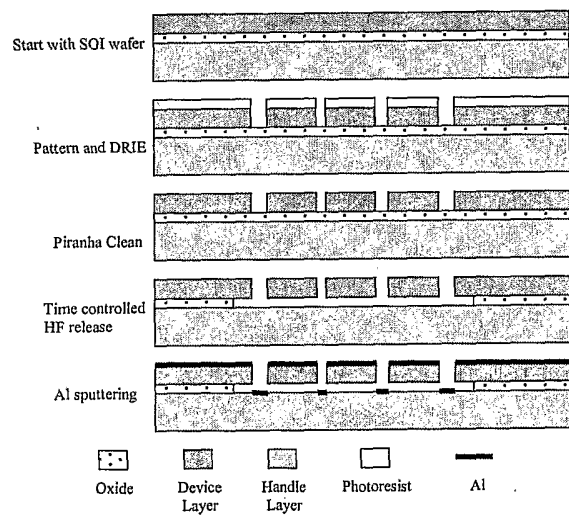


Fig. 7

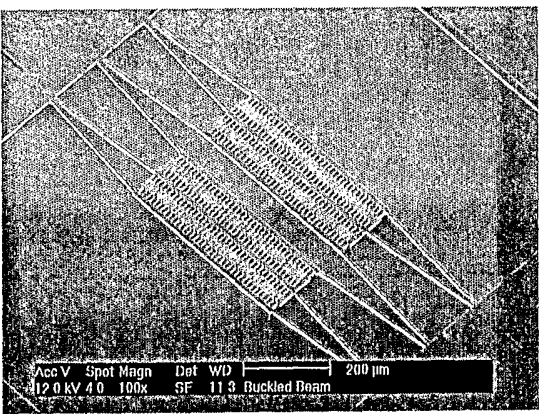


Fig. 8

INTERNATIONAL SEARCH REPORT

Inter I Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 7. G01L1/14 G01L5/00 G01B7/16

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)

IPC 7 G01L G01B

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

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

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 6 606 913 B1 (GIANCHANDANI YOGESH B) 19 August 2003 (2003-08-19) abstract; figures 1,9,10 column 2, line 29 - column 3, line 20 column 5, line 59 - column 7, line 15 column 10, line 43 - column 11, line 15 -----	1-10
Y	GIANCHANDANI Y B ET AL: "BENT-BEAM STRAIN SENSORS" JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, IEEE INC. NEW YORK, US, vol. 5, no. 1, 1 March 1996 (1996-03-01), pages 52-58, XP000591377 ISSN: 1057-7157 abstract; figure 3 page 53, right-hand column, last paragraph - page 54, left-hand column, paragraph 2 ----- -/--	1-10

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

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- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
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Date of the actual completion of the international search

19 April 2005

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02/05/2005

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Helm, B

INTERNATIONAL SEARCH REPORT

Intern: Application No
PCT/US2005/000258

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 767 405 A (BERNSTEIN ET AL) 16 June 1998 (1998-06-16) abstract; figure 9A column 5, line 21 - line 49 -----	1-10

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter

Application No

PCT/US2005/000258

Patent document cited in search report		Publication date		Patent family member(s)	Publication date
US 6606913	B1	19-08-2003	AU WO	1465700 A 0028277 A2	29-05-2000 18-05-2000
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