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(54) **Title:** MEMS SCANNING MICROMIRROR

(57) Abstract: A MEMS scanning micromirror including a mirror body 50, the mirror body 50 having a rotation axis 58 with a pair of extension bars 56 parallel to the rotation axis 58; a frame 60 forming a mirror recess 62 with a recess periphery 64, the frame 60 having a pair of opposed frame bars 66 on the recess periphery 64 along the rotation axis 58; a pair of cantilever beam assemblies 70, each of the pair of cantilever beam assemblies 70 being fixed to one of the pair of opposed frame bars 66 and coupled to one end of the pair of extension bars 56; and a pair of vertical support beams 40 connected between each of the pair of opposed frame bars 66 to the mirror body 50 along the rotation axis 58.

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MEMS SCANNING MICROMIRROR

This application claims priority from U.S. provisional application no. 60/977,721, filed October 5, 2007. U.S. provisional no. 60/977,717, filed October 5, 2007 (Applicants' docket no. PH009047) and U.S. provisional no. 60/977,713, filed October 5, 2007 (Applicants' docket no. PH009046) are related applications.

The technical field of this disclosure is Micro Electro Mechanical Systems (MEMS), particularly, MEMS scanning micromirrors.

MEMS scanning micromirrors have been developed for the display of visual information. The MEMS scanning micromirror oscillates in one or two dimensions and a laser or other light beam reflects from the mirror surface. Varying the angle and timing of the beam incident on the mirror surface generates a visual image on a screen or other surface, such as a two dimensional display matrix. Different numbers of MEMS scanning micromirrors and lasers are used to produce images of different detail and colors. Exemplary uses for the MEMS scanning micromirrors are head up displays for automotive applications, wearable displays, projection displays, mobile phone and hand-held displays, and barcode scanners.

The present generation of MEMS scanning micromirrors includes a mirror plate attached to a frame by two collinear torsion beams, which create a scanning axis about which the mirror plate rotates. The torsion beams both support the mirror plate and provide the required torsional stiffness during rotation. The torsion beams are the only point of attachment between the mirror plate and the frame, and determine the resonant frequency of the MEMS scanning micromirror. The MEMS scanning micromirror also includes a driver to magnetically or electrically apply a torque to the mirror plate about the scanning axis without physical contact with the mirror plate. The driver typically drives the mirror plate at the resonant frequency. MEMS scanning micromirrors are made from single crystal silicon or polysilicon material using photolithography.

Problems with image quality in the present generation of MEMS scanning micromirrors occur due to undesired motion of the mirror and mirror deformation. High image resolution is desirable for better image quality and larger displays. Because the torsion beams are the only point of attachment between the mirror plate and the frame, the torsion

beams define the suspension stiffness in all directions, not only rotational stiffness about the scanning axis. The torsion beam geometry, with the mirror mass and the mass inertia moment for the corresponding rotation, influence the higher order resonant frequencies of the system. The most important higher order resonant modes are out-of-plane rocking mode, vertical translation mode, in-plane rotation mode, and horizontal translation mode. Out-of-plane rocking and the vertical translation resonant modes in the present generation of MEMS scanning micromirrors greatly reduce the image quality of the scanner display.

Micromirror dynamic deformation also reduces the image quality of the scanner display. Deformation should not be higher than $\pm \lambda/10$, where λ is the shortest laser wavelength used in the scanning application. Image resolution is proportional to the product of scanning angle and micromirror diameter. Higher image resolution requires larger scanning angles, which increase the stress in the torsion beam, and higher scanning frequencies, which increase micromirror dynamic deformation. Because the torsion beams are the only point of attachment between the mirror plate and the frame, the torsion beams deform the mirror plate and the micromirror.

It would be desirable to have a MEMS scanning micromirror that would overcome the above disadvantages.

One aspect of the present invention provides a MEMS scanning micromirror including a mirror body, the mirror body having a rotation axis with a pair of extension bars parallel to the rotation axis; a frame forming a mirror recess with a recess periphery, the frame having a pair of opposed frame bars on the recess periphery along the rotation axis; a pair of cantilever beam assemblies, each of the pair of cantilever beam assemblies being fixed to one of the pair of opposed frame bars 66 and coupled to one end of the pair of extension bars; and a pair of vertical support beams connected between each of the pair of opposed frame bars to the mirror body along the rotation axis.

Another aspect of the present invention provides a MEMS scanning micromirror including a mirror body, the mirror body having a rotation axis with a first extension bar and a second extension bar parallel to the rotation axis; a frame having a mirror recess with a recess periphery, the frame having a first opposed frame bar and a second opposed frame bar on the recess periphery along the rotation axis; a first cantilever beam fixed to the first opposed frame bar perpendicular to the rotation axis and coupled to a first end of the first

extension bar; a second cantilever beam fixed to the first opposed frame bar perpendicular to the rotation axis and coupled to a first end of the second extension bar; a third cantilever beam fixed to the second opposed frame bar perpendicular to the rotation axis and coupled to a second end of the first extension bar; a fourth cantilever beam fixed to the second opposed frame bar perpendicular to the rotation axis and coupled to a second end of the second extension bar; a first vertical support beam connected between the first frame opposed bar and the mirror body along the rotation axis; and a second vertical support beam connected between the second opposed frame bar and the mirror body along the rotation axis.

Another aspect of the present invention provides a MEMS scanning micromirror system including a frame; a micromirror body having a rotation axis; means for supporting the micromirror body in the frame; and means for providing torsional stiffness to the micromirror body about the rotation axis.

The foregoing and other features and advantages of the invention will become further apparent from the following detailed description of the presently preferred embodiments, read in conjunction with the accompanying drawings. The detailed description and drawings are merely illustrative of the invention, rather than limiting the scope of the invention being defined by the appended claims and equivalents thereof.

FIGS. 1A-1B are a top and cross section view, respectively, of a MEMS scanning micromirror in accordance with the present invention;

FIG. 2A is a detailed perspective view of comb fingers for a MEMS scanning micromirror in accordance with the present invention;

FIGS. 2B-2E illustrate the action of the mirror combs for a MEMS scanning micromirror in accordance with the present invention;

FIGS. 3A-3B are top views of other embodiments of a MEMS scanning micromirror in accordance with the present invention;

FIGS. 4A-4C are detailed cross section views of leaf springs for a MEMS scanning micromirror in accordance with the present invention.

FIGS. 5A-5E are detailed top views of flexible links of a mirror body for a MEMS scanning micromirror in accordance with the present invention; and

FIG. 6 is a detailed perspective view illustrating dimensions of a mirror body for a MEMS scanning micromirror in accordance with the present invention.

FIG. 7 is a plan view of a picobeamer micromirror in an embodiment of the present invention, showing electrical connections for device actuation.

FIG. 8 is a detailed cross section view of wafer layers and points of application of driving potentials in an embodiment of the present invention.

5 **FIG. 9** is a perspective view of flexible links of a mirror body of a picobeamer micromirror in accordance with an embodiment of the present invention.

FIGS. 1A -1B, in which like elements share like reference numbers, are a top and side view, respectively, of a MEMS scanning micromirror in accordance with the present invention. **FIG. 1B** is a cross section along section A-A of **FIG. 1A** with the mirror body 10 tilted about the rotation axis. The MEMS scanning micromirror uses a pair of cantilever beam assemblies coupled to a mirror body at its outer corners to set the torsional stiffness about the rotation axis. A pair of vertical support beams supports the mirror body vertically at the rotation axis, but have a negligible effect on the torsional stiffness, so that the natural frequency of the mirror body is substantially determined by the cantilever beam assemblies. 15 The natural frequency is substantially independent of the vertical support beams. The natural frequency as defined herein is the undamped frequency of the mirror body about its rotation axis. The vertical support beams define the out-of-plane rocking and vertical mode stiffness for the corresponding mode resonant frequencies. The torsional stiffness can be decoupled from the out-of-plane rocking and vertical mode stiffness so that the out-of-plane rocking and 20 vertical mode frequencies can be set to desired values, such as higher values, without influencing the torsional mode stiffness and resonant frequency. As defined herein, the Y axis is along the rotation axis, the X axis is perpendicular the Y axis on the mirror plane when the mirror is at rest, and the Z axis is perpendicular to and out of the mirror plane when the mirror is at rest.

25 The MEMS scanning micromirror **30** includes a mirror body **50**, a frame **60**, cantilever beam assemblies **70**, and vertical support beams **40**. The mirror body **50** has a mirror **52** on a mirror support **54**, and extension bars **56**. In one embodiment, the mirror **52** is formed on the mirror support **54**. In another embodiment, the mirror **52** is attached to the mirror support **54**. The mirror body **50** can be square, rectangular, circular, elliptical, or any 30 other planar shape desired for a particular application. The face of the mirror defines a mirror plane of the mirror support **54**. Those skilled in that art will appreciate that the shape of the

mirror **52** and the mirror support **54** are independent and can be any shape desired for a particular application, e.g., a circle, ellipse, square, rectangle, or other shape as desired. The extension bars **56** are parallel to rotation axis **58** of the mirror body **50**, which is the rotation axis for the MEMS scanning micromirror **30**. The mirror body **50** is disposed within a mirror recess **62** of the frame **60**.

The frame **60** forms the mirror recess **62** with a recess periphery **64**. Opposed frame bars **66** are located on the recess periphery **64** along the rotation axis **58** and provide the connection points for the cantilever beam assemblies **70** and the vertical support beams **40**.

The cantilever beam assemblies **70** include cantilever beams **72** fixed to the opposed frame bars **66** perpendicular to the rotation axis **58**. The cantilever beam assemblies **70** provide torsional stiffness to the micromirror body **50** about the rotation axis **58**. The cantilever beams **72** are also flexibly or compliantly coupled to the end of the extension bars **56** of the mirror body **50** with flexible links **74**. The flexible links **74** have low torsional stiffness around their axes parallel to the rotation axis **58** (around the Y axis) and reduced stiffness perpendicular to the rotation axis **58** (the X axis), which allows the mirror body **50** to rotate around the vertical support beams **40** relative to the rotation axis **58**. The attachment of the mirror body **50** to the four points away from the rotation axis **58** reduces dynamic deformation in the mirror body **50**. The torsional stiffness for rotation of the mirror around the Y axis is defined by the length, width, and most importantly the thickness of the cantilever beams **72** and the distance between flexible links **74** for the pair of cantilever beams **72** in a cantilever beam assembly **70**. The combined stiffness in X direction of the vertical support beams **40** and the flexible links **74** prevent the movement of the mirror body **50** perpendicular to the rotation axis **58** (in the X direction) during operation. More detail on the flexible links **74** is provided below for **FIG. 5**.

The vertical support beams **40** are connected between the opposed frame bars **66** and the mirror body **50** along the rotation axis **58** to support the micromirror body **50** in the frame **60**. In one embodiment, the vertical support beams **40** have narrow rectangular cross sections perpendicular to the rotation axis **58**, with the long axis of the rectangle perpendicular to the face of the mirror **52** and the mirror body **50**, and the short axis of the rectangle parallel to the face of the mirror **52**. The torsional stiffness of the MEMS scanning micromirror **30** is provided by the cantilever beam assemblies **70**, so the vertical support beams **40** are only

required for support of the mirror body **50** and have a negligible effect on the torsional stiffness. The torsional stiffness of the vertical support beams **40** is as low as possible so that the torsional stiffness of the micromirror body rocking movement about the vertical support beams **40** relative to the rotation axis **58** is dominated by the stiffness of the cantilever beams
5 **72**. The vertical support beams **40** are sized so that the stiffness against vertical displacement of the mirror body **50** and against its rocking movement perpendicular to the rotation axis **58** (around the X axis) is as high as possible.

The MEMS scanning micromirror **30** can also include actuator **80** to provide torque to drive the mirror body **50** about the rotation axis **58**. In one embodiment, the actuator **80**
10 includes mirror combs **82** attached to the extension bars **56** interleaved with frame combs **84** attached to the frame **60**. Applying a difference in electrical potential between an interleaved mirror comb **82** and frame comb **84** creates a driving force between the mirror combs **82** and the frame combs **84**, which creates a torque on the mirror body **50** about the rotation axis **58**. An oscillating electrical potential can be applied to drive the MEMS scanning micromirror **30**
15 at its natural frequency. Other exemplary actuation methods include electromagnetic actuation and piezoelectric actuators. In electromagnetic actuation, the micromirror is "immersed" in a magnetic field and an alternating electric current through the conductive paths creates the required oscillating torque around the rotation axis **58**. Piezoelectric actuators can be integrated in the cantilever beams or the cantilever beams can be made of
20 piezoelectric material to produce alternating beam bending forces in response to an electrical signal and generate the required oscillation torque.

The MEMS scanning micromirror **30** can be manufactured from single crystal silicon or polysilicon material using photolithography and DRIE techniques. **FIG. 3**, in which like elements share like reference numbers with **FIG. 1**, is a detailed perspective view of comb
25 fingers for a MEMS scanning micromirror in accordance with the present invention. The comb fingers **100** of the mirror comb **82** are interleaved with the comb fingers **110** of the frame comb **84**. In one embodiment, the MEMS scanning micromirror can be manufactured from a silicon-on- insulator (SOI) wafer having an upper silicon layer and a lower silicon layer, with an insulating layer between the upper silicon layer and the lower silicon layer. In
30 one embodiment, the mirror comb **82** and the frame comb **84** can be fabricated so that the insulating layer divides the combs parallel to the mirror, producing electrically isolated upper

electrical portions and lower electrical portions in each of the comb fingers. The comb fingers **100** of the mirror comb **82** include first electrical portions **102** and second electrical portions **104** separated by insulating layer **106**. The comb fingers **110** of the frame comb **84** include first electrical portions **112** and second electrical portions **114** separated by insulating layer **116**. Applying a difference in electrical potential between the upper electrical portions in the mirror comb **82** and the lower electrical portions in the frame comb **84**, or vice versa, can be used to generate an initial driving force between the mirror combs **82** and the frame combs **84** when the mirror combs **82** and the frame combs **84** are aligned and the mirror body **50** is at rest. The separation of the comb fingers in two (top and bottom) parts allows, by switching between opposed layers, to apply the driving potential (and eventually torque, depending on the comb fingers geometry) for duration greater then half oscillation period per oscillation cycle. In one embodiment, the cantilever beam assemblies can be fabricated in the upper silicon layer of the silicon on insulator wafer and can bring the electrical potential to the top first electrical portions **102** of the mirror combs **82**. In another embodiment, the vertical support beams can be fabricated in the lower silicon layer of the silicon on insulator wafer and can bring the electrical potential to the bottom second electrical portions **104** of the mirror combs **82**.

FIGS. 2B-2E illustrate the action of the mirror combs **82** for a MEMS scanning micromirror in accordance with the present invention. Referring to **FIG. 2B**, the mirror is oscillating, with the mirror comb fingers away from the frame fingers and moving towards them. 102 and 104 connected to ground potential. Driving potential is applied to 112 and 114 from max. amplitude to aligned position of the comb fingers.

Referring to **FIG. 2C**, the mirror is oscillating in the clockwise direction, when comb fingers are in aligned position. The driving cycle for the traditional monolith comb fingers stops here. T he driving potential must be switched off at aligned comb fingers position if there is no split of the comb fingers in top and bottom electric parts. For split comb fingers of the present invention: Potential is applied between 102 (grounded) and 114 until 102 became aligned with 114, so the split comb fingers inject more energy per oscillation cycle for equal other conditions.

Referring to **FIG. 2D**, the mirror is oscillating. When the opposing layers 102 and 114 of split comb fingers are in aligned position (no torque created); the driving potential between them must be switched off.

Referring to **FIG. 2D**, the mirror is oscillating at extreme (**FIG. 2B**) position. For
5 rotation in opposite direction the driving potentials are switched in "mirrored order" to the given in **FIGS. 2B-2D**:

1. 102, 104 grounded and 112,114 at driving potential;
2. Driving potential between 104 (grounded) and 112;
3. Driving potentials switched off.

10

FIGS. 3A-3B, in which like elements share like reference numbers with each other and with **FIG. 1**, are top views of other embodiments of a MEMS scanning micromirror in accordance with the present invention. In these embodiments, leaf springs flexibly coupled between the cantilever beams of the cantilever beam assemblies and the mirror body can be
15 used to stiffen the mirror body of the MEMS scanning micromirror against in-plane disturbances and increase in-plane slide and rotation stiffness of the mirror suspension. The leaf springs springily couple the micromirror body to the cantilever beam assemblies.

The leaf springs can be positioned along the cantilever beams as desired for a particular application. Referring to **FIG. 3A**, leaf springs **90** are flexibly coupled between
20 the cantilever beams **72** of the cantilever beam assemblies **70** and the mirror body **50**. In this example, the leaf springs **90** are near the vertical support beams **40** and the opposed frame bars **66**. Referring to **FIG. 3B**, the leaf springs **90** are flexibly coupled between the cantilever beams **72** of the cantilever beam assemblies **70** and the mirror body **50**. In this example, the leaf springs **90** are near the flexible links **74**.

25 **FIGS. 4A-4C**, in which like elements share like reference numbers with each other and with **FIG. 3A-3B**, are detailed cross section views along section B-B of **FIG. 3A** of leaf springs for a MEMS scanning micromirror in accordance with the present invention. The leaf springs **90** have different shapes to provide different stiffness. Referring to **FIGS. 4A**, **4B**, and **4C**, the leaf springs **90** are L shaped, V shaped, and flat, respectively. The leaf
30 springs **90** can be placed at about the same height relative to the mirror (in the Z direction) as the vertical support beams **40**. In one embodiment, the lower leg of the L in the L shaped leaf

spring is at the same height as the rotation axis **58**. In one embodiment, the lower tip of the V in the V shaped leaf spring is at the same height as the rotation axis **58**. In one embodiment, the flat leaf spring is at the same height as the rotation axis **58.**

FIGS. 5A-5E are detailed top views of flexible links of a mirror body for a MEMS scanning micromirror in accordance with the present invention. In **FIG. 5A**, the flexible link **74** is a high aspect ratio flexure connected to the cantilever beam at both ends and in the middle to the extension bars. Typical dimensions for 1 mm micromirror device are: Width 2,5-4μm, length 60-80μm, the height is the same as the thickness of the cantilever beams. The width at the connection points is around 10μm. In **FIG. 5B**, the flexible link **74** includes additional flexure elements allowing small X-axis translations. In **FIGS. 5C-5D**, the flexible link **74** allows a greater deformation in X direction while keeping a high bending stiffness in vertical direction and a high stiffness against in-plane rotation of the micromirror. The flexible links length is increased to reduce the stress caused by translation in X direction. In **FIG. 5C**, the flexible link is made in the same layer as the cantilever beams, so the stiffness of the flexure is limited by the thickness of the cantilevers. In **FIG. 5D**, the flexible link **74** has increased stiffness in the vertical direction and against bending in the Y-Z plane achieved by fabricating them with increased height in the bulk single crystal silicon material under the insulating layer. In this case, additional structure as an electrical connection is needed to provide the potential to the top part of the moveable comb fingers. In **FIG. 5E**, the flexible link **74** the L shaped flexible links (rotated at 45 degrees) connecting the extension bar and the cantilever beam.

FIG. 6 is a detailed perspective view illustrating dimensions of a mirror body for a MEMS scanning micromirror in accordance with the present invention. In one exemplary embodiment, the dimensions of the cantilever beams are:

- Cantilever beam length l_b=420μm
- Cantilever beam width w_b=100μm
- Cantilever beam thickness t_b=17.5μm
- Distance between opposite suspension points a=950μm.

In one exemplary embodiment, the dimensions of the vertical support beams are:

- Vertical support beam width w_{vs}=6.2μm
- Vertical support beam height h_{vs}=36μm

- Vertical support beam length l_{vs}=62µm

In another exemplary embodiment, the dimensions of the vertical support beams providing a combined stiffness of the links in X direction is 1.25x 10^3N/m are:

- Vertical support beam width w_{vs}=6.2µm
- Vertical support beam height h_{vs}=36µm
- Vertical support beam length l_{vs}=62µm

The combined stiffness of the vertical beams in X direction is 1.0x 10^4N/m. The beam stiffness dominates the horizontal slide natural frequency. The links and cantilever beam stiffness in Y direction define the in-plane rotation mode resonance frequency.

The oscillation frequency of the micromirror scanners depends from the torsional stiffness of the suspension and its mass inertia moment around the tilt axis. The torsional stiffness contributed by the cantilever beams bending stiffness dominates the fundamental mode resonant frequency of the micromirror. For small oscillation angles, this stiffness can be found from the following formula:

$$S_t = E\frac{a^2.w_b t_b^3}{4l_b^3}$$

For a 1 mm micromirror, the torsional stiffness contributed by the cantilever beams is $2.3x10^{-4}$ Nm/rad.

The torsional stiffness from the vertical support beams with the above given dimensions is $4.6x10^{-6}$ Nm/rad, which is 50 times less than the delivered by the cantilever beams torsional stiffness. The vertical support beams influence with less than 1% the 18.7 kHz fundamental mode resonant frequency of our 1 mm micromirror design. The mass inertia moment is about $1.7x10^{-14}$ kgm^2

The flexible links **74** with combined torsional stiffness around $1x10^{-6}$ Nm/rad contribute even less to the increase of the micromirror fundamental mode frequency.

In the same design, the cantilever beams contribute with around $1.1x10^3$N/m bending stiffness to the out-of-plane oscillation mode, while the stiffness of the vertical support beams is $6.1x10^5$N/m.

The cantilever beams dominate the torsional stiffness of the micromirror. The vertical support beams dominate the stiffness for the out-of-plane oscillation modes, which have great impact on the image quality. The possibility to define the fundamental mode and the higher

order resonance frequencies with a greater flexibility makes it easier to design better quality scanning systems. FEM Simulations showed that the combined suspension has advantages in preventing parasitic mode oscillations, as vertical and out-of-plain rocking, by increasing their resonance frequencies to greater values compared to torsion-beam suspended
5 micromirrors.

The table below shows the simulation results for optimized geometries of two torsion-beam suspended micromirrors and a micromirror with combined suspension (having the same micromirror size; similar tilt stiffness, mass inertia moments, stress in the suspension elements and surface deformation):
10

Frequency kHz	Torsion beam suspended micromirror with rectangular shape	Torsion beam suspended micromirror with circular shape	Micromirror with combined suspension
Fundamental mode	18.6	18.7	18.7
Vertical mode	93	84	144
Out of plane rocking	230	245	255

FIG. 7 is a plan view of a picobeamer micromirror in an embodiment of the present invention. Electrical connections for device actuation are at a wafer handle layer and bottom part of a micromirror **30**, a top half of moveable comb fingers **117**, a top-half of stator comb
15 fingers **118** and a bottom half of stator comb fingers **119**. An area of the micromirror **30** is left as “free real estate” **121**. Potentials V0 at the wafer handle layer and bottom part of the micromirror **30**, V1 at the top half of the moveable comb fingers **117**, V2 at the top-half of stator comb fingers **118** and V3 at the bottom half of stator combfingers **119** may be applied during operation of a display. Driving potentials used may be, for example: during
20 oscillation launch V0 grounded, V2 driven with square pulses. During steady state oscillation V0=V1=grounded and V2=V3. The device layer around the micro-mirror allows integrating of control electronics.

FIG. 8 is a detailed cross section view of wafer layers and points of application of driving potentials in an embodiment of the present invention. A picobeamer micromirror has
25 a silicon top/device layer **231** and a silicon bottom/handle layer **232**. The silicon top/device layer **231** has aluminum bonding pads and wirebonds **233** and vias **234**, **235** extending to the

silicon bottom/handle layer **232** through a buried oxide (BOX) layer **236**. The picobeamer micromirror has moveable **237** and stationary **238** comb fingers and vertical support beam **239**. V0. V1, V2 amd V3 are applied as shown. Driving potentials used may be, for example: during oscillation launch V0 grounded, V2 driven with square pulses. During
5 steady state oscillation, V0=V1=grounded and V2=V3.

FIG. 9 is a perspective view of flexible links of a mirror body of a picobeamer micromirror in accordance with an embodiment of the present invention. Flexible link **74** is fabricated in second silicon layer **206**. Additional electrical connections **240** are provided to link **74** and an electrical portion **102**.

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While the embodiments of the invention disclosed herein are presently considered to be preferred, various changes and modifications can be made without departing from the scope of the invention. The scope of the invention is indicated in the appended claims, and all changes that come within the meaning and range of equivalents are intended to be
15 embraced therein.

CLAIMS

1. A MEMS scanning micromirror comprising:

a mirror body **50**, the mirror body **50** having a rotation axis **58** with a pair of
5 extension bars **56** parallel to the rotation axis **58**;

a frame **60** forming a mirror recess **62** with a recess periphery **64**, the frame **60** having a pair of opposed frame bars **66** on the recess periphery **64** along the rotation axis **58**;

a pair of cantilever beam assemblies **70**, each of the pair of cantilever beam assemblies **70** being fixed to one of the pair of opposed frame bars **66** and coupled to one end
10 of the pair of extension bars **56**; and

a pair of vertical support beams **40** connected between each of the pair of opposed frame bars **66** to the mirror body **50** along the rotation axis **58**.

2. The MEMS scanning micromirror of claim 1 further comprising an actuator **40**
15 operably connected to the mirror body **50** to provide torque about the rotation axis **58**.

3. The MEMS scanning micromirror of claim 2 wherein the actuator **40** comprises:

a first mirror comb **82** attached to one of the pair of extension bars **56**;

a second mirror comb **82** attached to the other one of the pair of extension bars **56**;

20 a first frame comb **84** and a second frame comb **84** attached to the frame **60**;

wherein comb fingers **100** of the first mirror comb **82** are interleaved with comb fingers **110** of the first frame comb **84**, and comb fingers **100** of the second mirror comb **82** are interleaved with comb fingers **110** of the second frame comb **84**.

25 4. The MEMS scanning micromirror of claim 3 wherein the first mirror comb **82** has a first electrical portion **102** and a second electrical portion **104**, the first electrical portion **102** and the second electrical portion **104** being separated by an insulating layer **106**.

5. The MEMS scanning micromirror of claim 1 wherein natural frequency of the
30 mirror body **50** is substantially determined by the pair of cantilever beam assemblies **70**.

6. The MEMS scanning micromirror of claim 1 wherein natural frequency of the mirror body **50** is substantially independent of the pair of vertical support beams **40**.

7. The MEMS scanning micromirror of claim 1 wherein each of the pair of cantilever beam assemblies **70** is coupled to one end of the pair of extension bars **56** through a flexible link **74**.

8. The MEMS scanning micromirror of claim 1 wherein each of the pair of vertical support beams **40** have a rectangular cross section, with a long axis of the rectangular cross section perpendicular to the mirror body **50**.

9. The MEMS scanning micromirror of claim 1 further comprising leaf springs **90** coupled between each of the pair of the cantilever beam assemblies **70** and the mirror body **50**

10. The MEMS scanning micromirror of claim 9 wherein the shape of the leaf springs **90** is selected from the group consisting of L shaped, V shaped, and flat.

11. A MEMS scanning micromirror comprising:

a mirror body **50**, the mirror body **50** having a rotation axis **58** with a first extension bar **56** and a second extension bar **56** parallel to the rotation axis **58**;

a frame **60** having a mirror recess **62** with a recess periphery **64**, the frame **60** having a first opposed frame bar **66** and a second opposed frame bar **66** on the recess periphery **64** along the rotation axis **58**;

a first cantilever beam **72** fixed to the first opposed frame bar **66** perpendicular to the rotation axis **58** and coupled to a first end of the first extension bar **56**;

a second cantilever beam **72** fixed to the first opposed frame bar **66** perpendicular to the rotation axis **58** and coupled to a first end of the second extension bar **56**;

a third cantilever beam **72** fixed to the second opposed frame bar **66** perpendicular to the rotation axis **58** and coupled to a second end of the first extension bar **56**;

a fourth cantilever beam **72** fixed to the second opposed frame bar **66** perpendicular to the rotation axis **58** and coupled to a second end of the second extension bar **56**;

a first vertical support beam **40** connected between the first frame opposed bar **66** and the mirror body **50** along the rotation axis **58**; and

a second vertical support beam **40** connected between the second opposed frame bar **66** and the mirror body **50** along the rotation axis **58**.

12. The MEMS scanning micromirror of claim 11 further comprising an actuator **80** operably connected to the mirror body **50** to provide torque about the rotation axis **58**.

13. The MEMS scanning micromirror of claim 12 wherein the actuator **80** comprises:

a first mirror comb **82** attached to the first extension bar **56**;

a second mirror comb **82** attached to the second extension bar **56**;

a first frame comb **84** and a second frame comb **84** attached to the frame **60**;

wherein comb fingers of the first mirror comb **82** are interleaved with comb fingers of the first frame comb **84**, and comb fingers of the second mirror comb **82** are interleaved with comb fingers of the second frame comb **84**.

14. The MEMS scanning micromirror of claim 13 wherein the first mirror comb **82** has a first electrical portion **102** and a second electrical portion **104**, the first electrical portion **102** and the second electrical portion **104** being separated by an insulating layer **106**.

15. The MEMS scanning micromirror of claim 11 wherein natural frequency of the mirror body **50** is substantially determined by the first cantilever beam, the second cantilever beam, the third cantilever beam, and the fourth cantilever beam.

16. The MEMS scanning micromirror of claim 11 wherein natural frequency of the mirror body **50** is substantially independent of the first vertical support beam and the second vertical support beam.

17. The MEMS scanning micromirror of claim 11 wherein:

the first cantilever beam is coupled to the first end of the first extension bar through a first flexible link;

the second cantilever beam is coupled to a first end of the second extension bar through a second flexible link;

the third cantilever beam is coupled to a second end of the first extension bar through a third flexible link; and

the fourth cantilever beam is coupled to a second end of the second extension bar through a fourth flexible link.

18. The MEMS scanning micromirror of claim 11 wherein the first vertical support beam and the second vertical support beam each have a rectangular cross section, with a long axis of the rectangular cross section perpendicular to the mirror body **50**.

19. The MEMS scanning micromirror of claim 11 further comprising:

a first leaf spring coupled between the first cantilever beam and the mirror body **50**;

a second leaf spring coupled between the second cantilever beam and the mirror body **50**;

a third leaf spring coupled between the third cantilever beam and the mirror body **50**; and

a fourth leaf spring coupled between the fourth cantilever beam and the mirror body **50**.

20. The MEMS scanning micromirror of claim 19 wherein the shape of the first leaf spring, the second leaf spring, the third leaf spring, and the fourth leaf spring is selected from the group consisting of L shaped, V shaped, and flat.

21. A MEMS scanning micromirror system comprising:
a frame;
a micromirror body having a rotation axis;
5 means for supporting the micromirror body in the frame; and
means for providing torsional stiffness to the micromirror body about the rotation axis.

22. The MEMS scanning micromirror system of claim 21 wherein the supporting
10 means are vertical support beams and the torsional stiffness providing means are cantilever beam assemblies.

23. The MEMS scanning micromirror system of claim 21 further comprising means for applying torque to the micromirror body about the rotation axis.
15

24. The MEMS scanning micromirror system of claim 21 further comprising means for springily coupling the micromirror body to the torsional stiffness providing means.

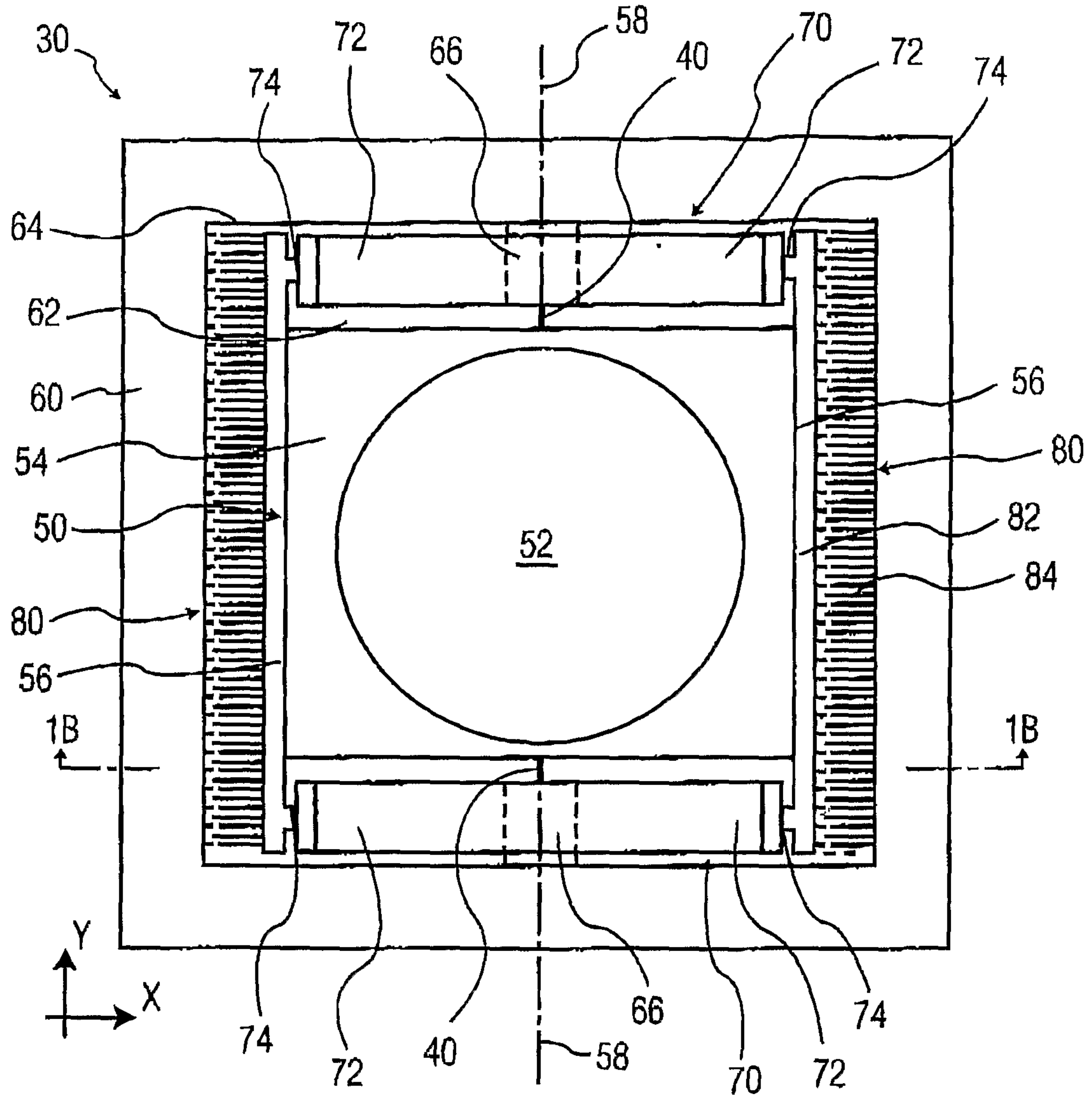

FIG. 1A

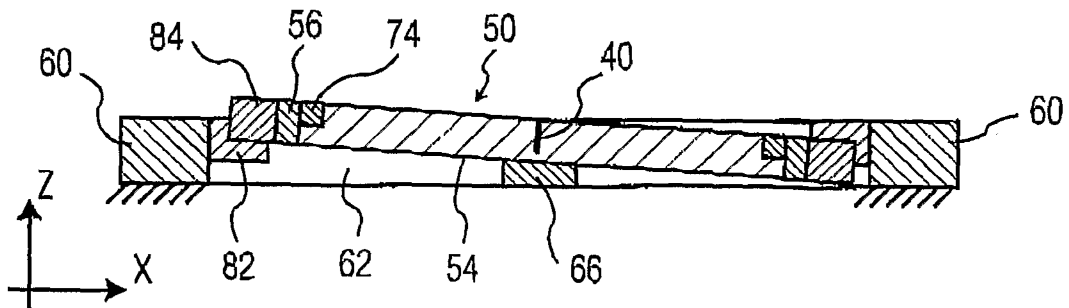

FIG. 1B

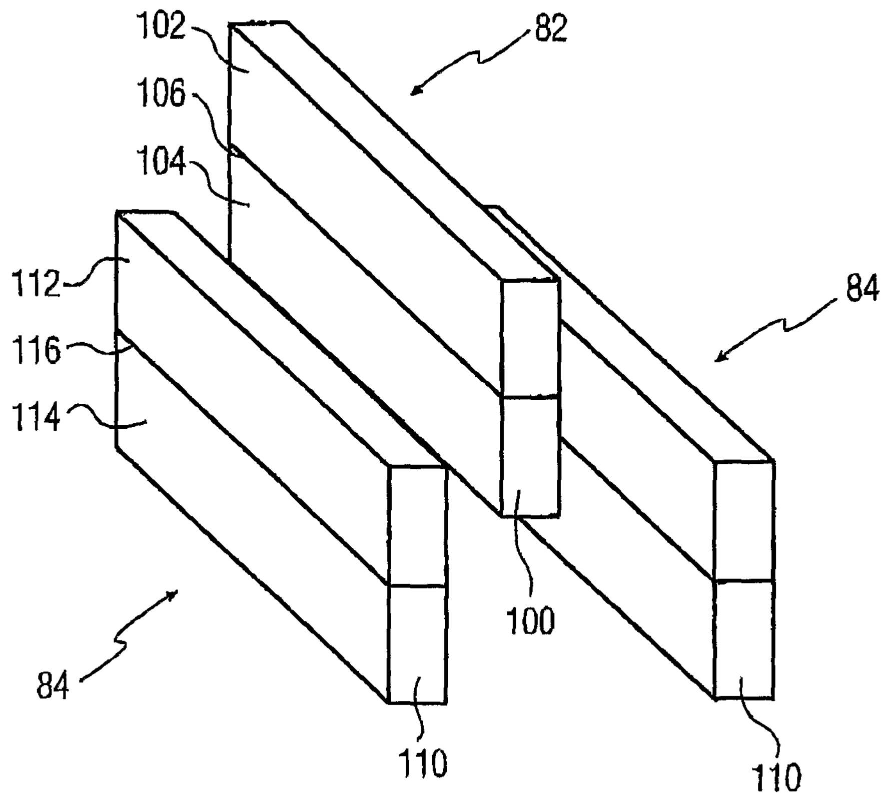

FIG. 2A

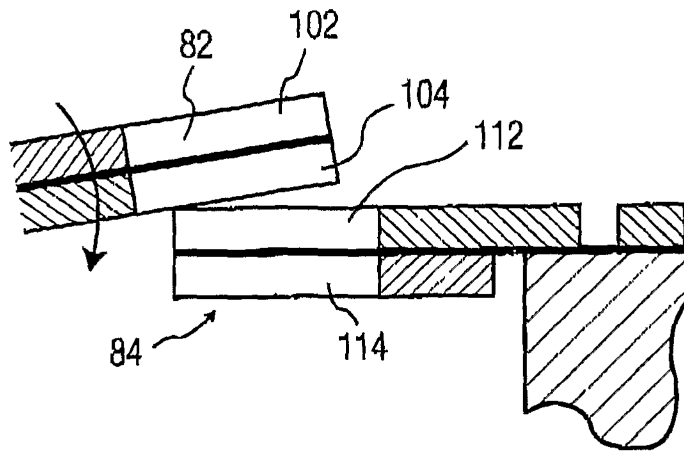

FIG. 2B

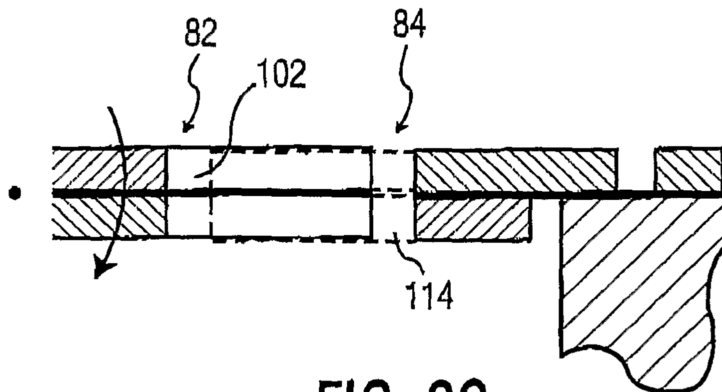

FIG. 2C

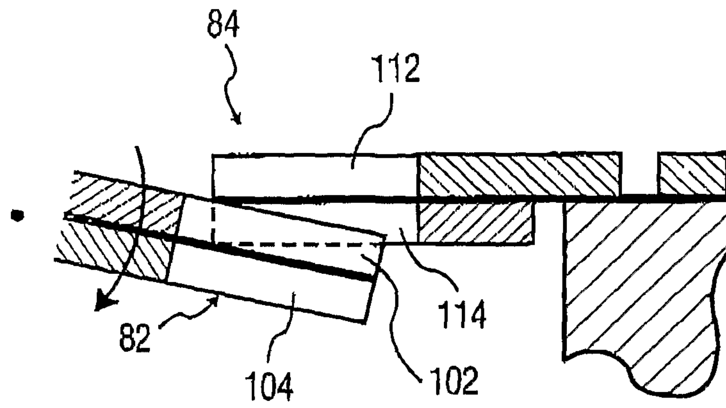

FIG. 2D

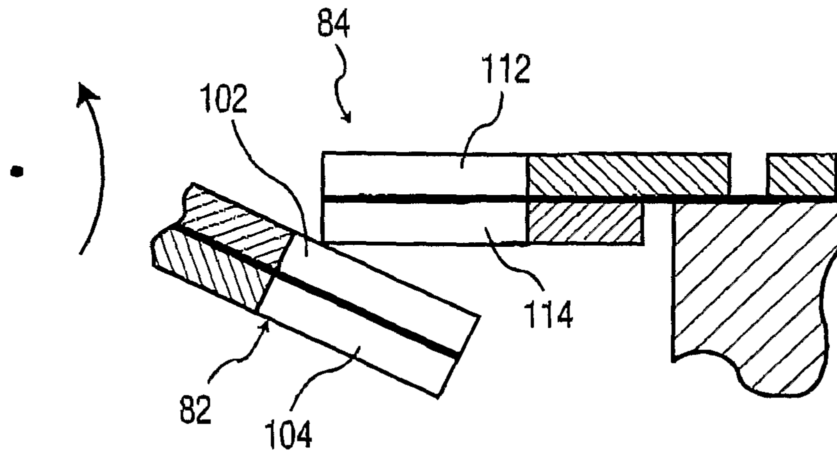

FIG. 2E

FIG. 3A

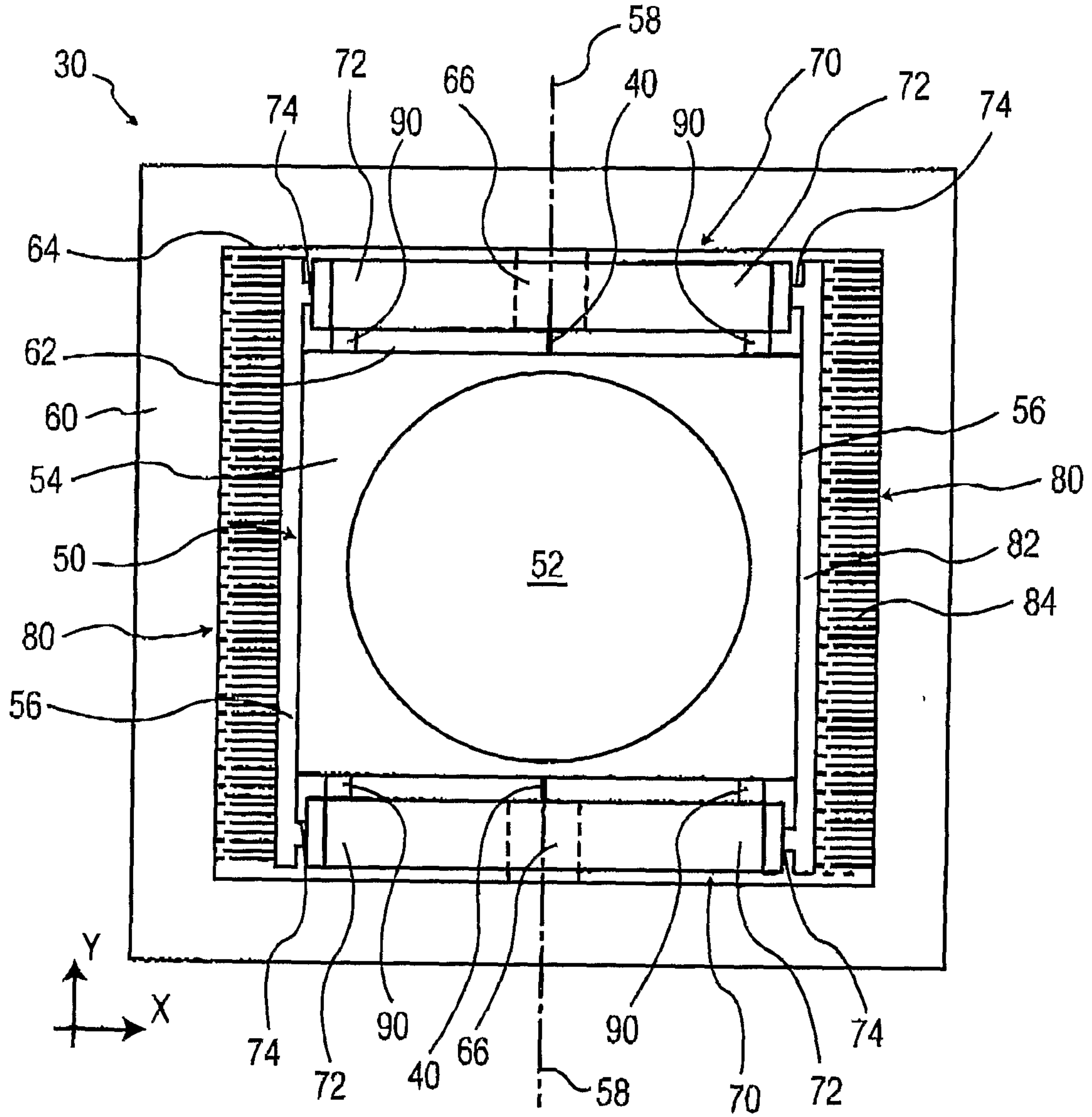

FIG. 3B

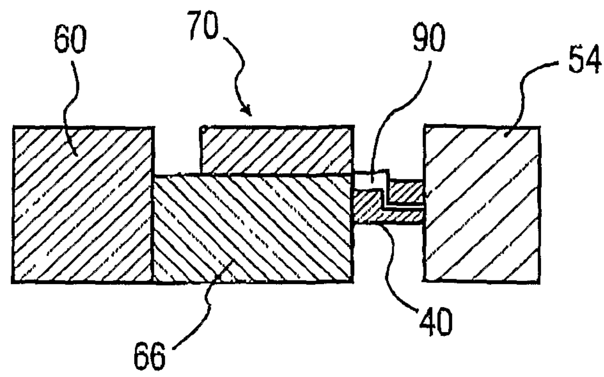

FIG. 4A

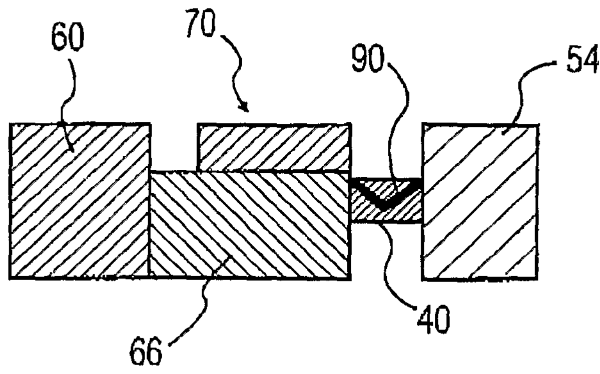

FIG. 4B

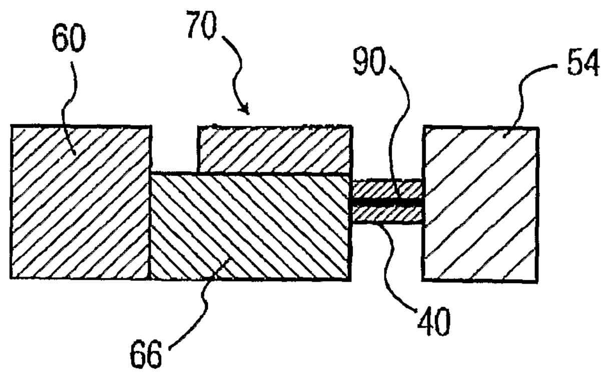

FIG. 4C

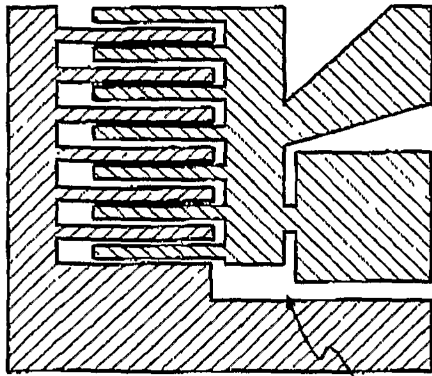

FIG. 5A

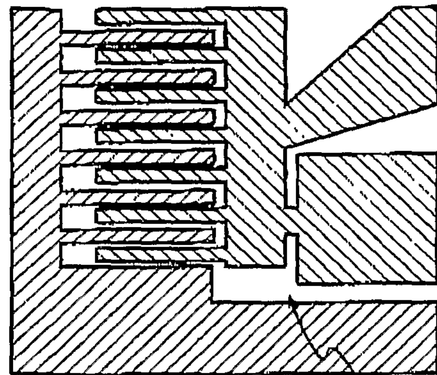

FIG. 5B

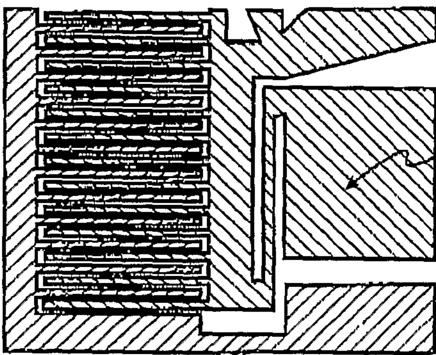

FIG. 5C

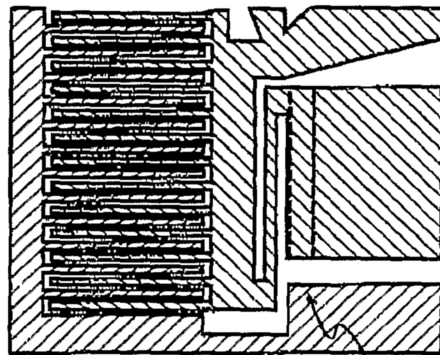

FIG. 5D

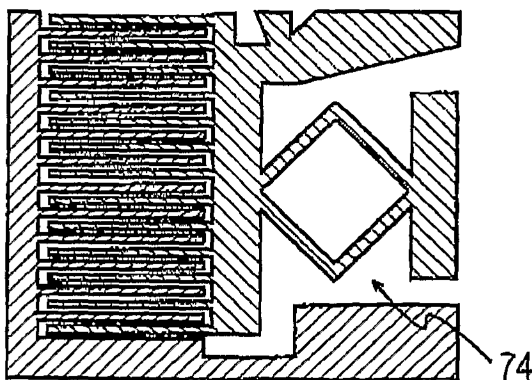

FIG. 5E

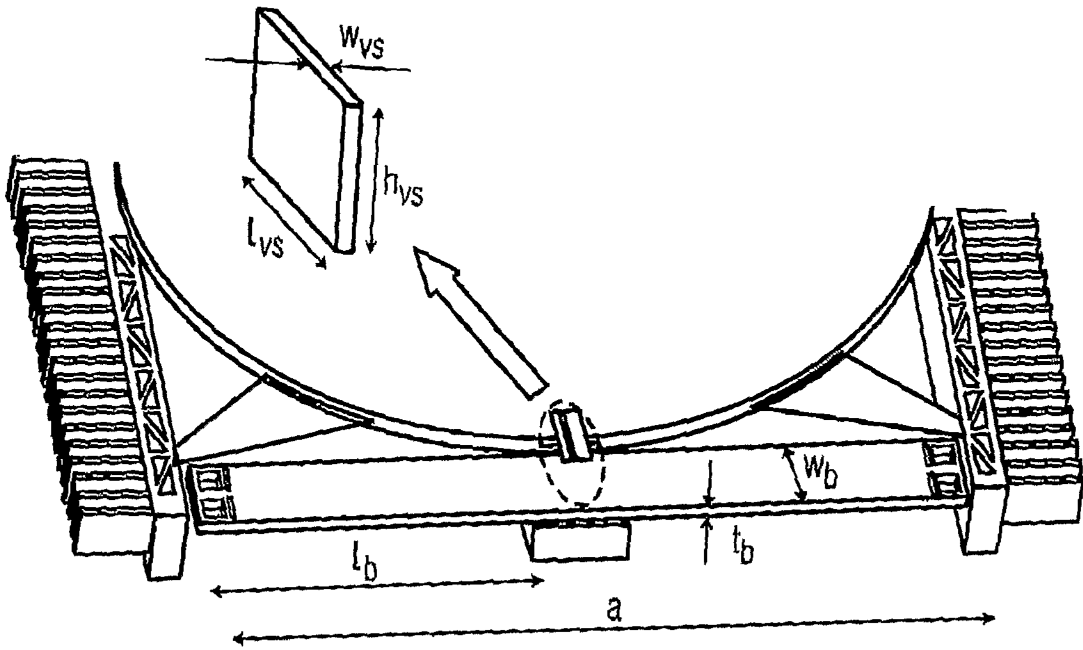

FIG. 6

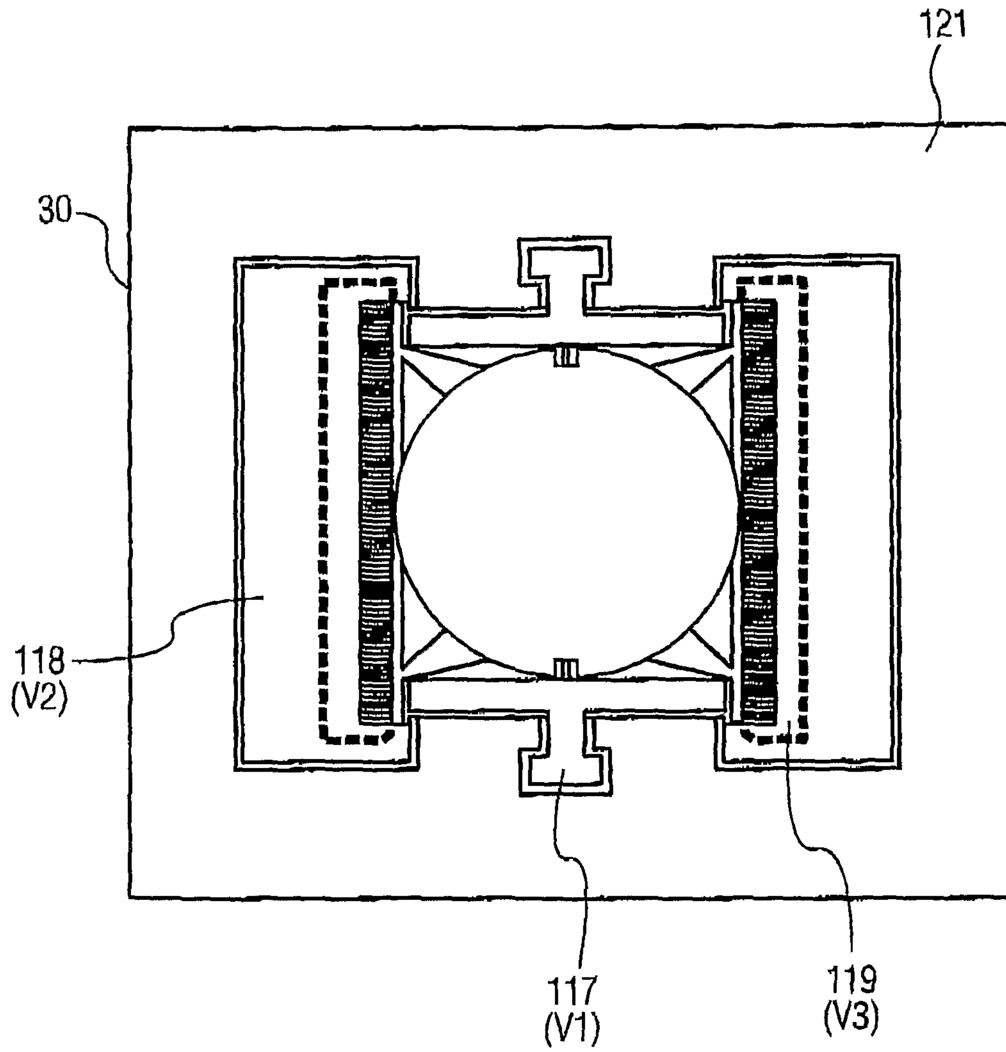

FIG. 7

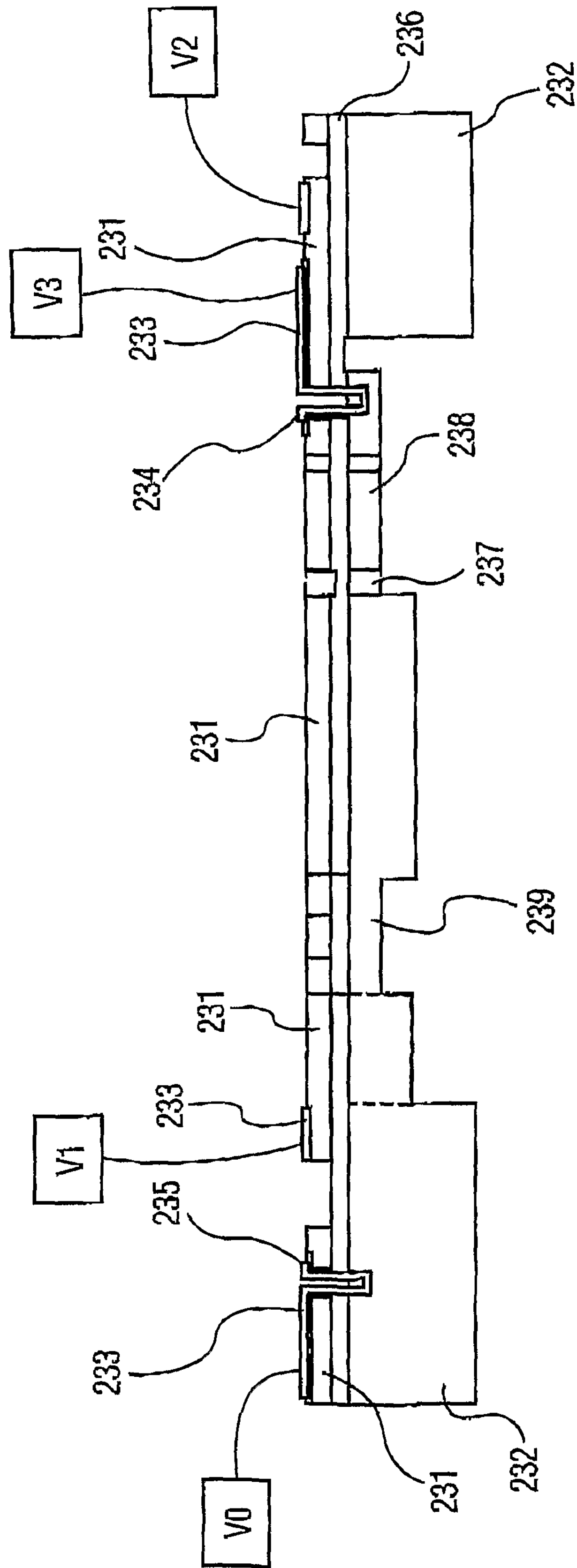

FIG. 8

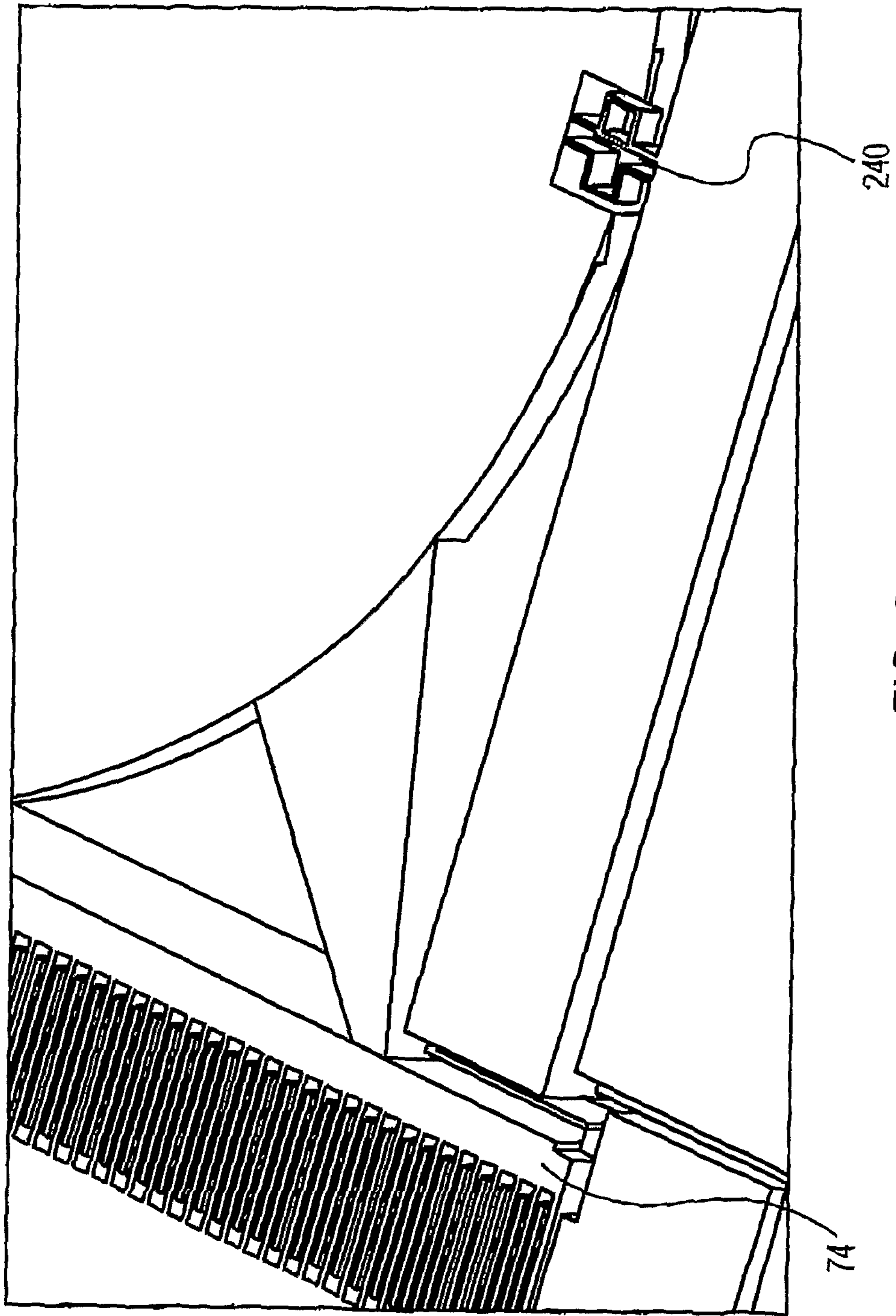

FIG. 9