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(54) **METHOD AND APPARATUS FOR AN INTEGRATED LASER BEAM SCANNER**

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Filed: **Dec. 1, 1998**

(51) **Int. Cl.**
G02B 26/08 (2006.01)

(52) **U.S. Cl.** **359/201**; 359/224; 359/850
(58) **Field of Classification Search** 359/201, 359/202, 212–14, 220, 221, 223, 224, 275, 359/850
See application file for complete search history.

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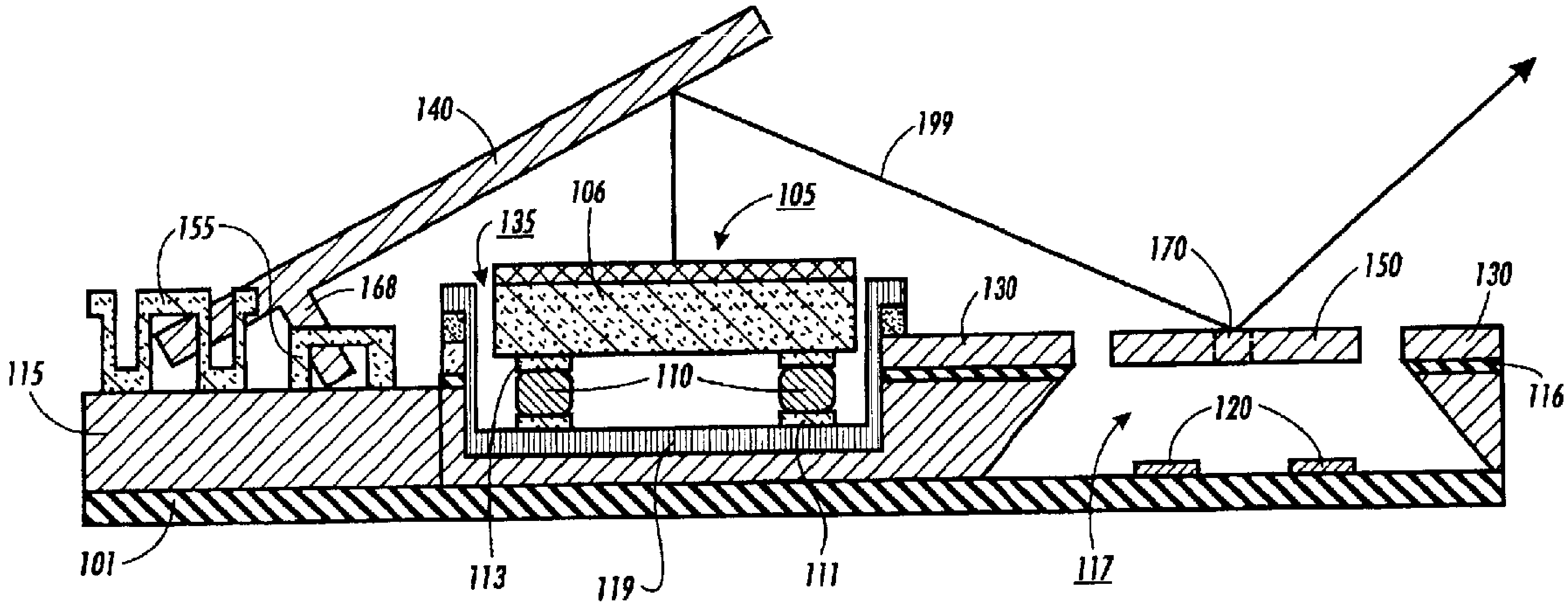
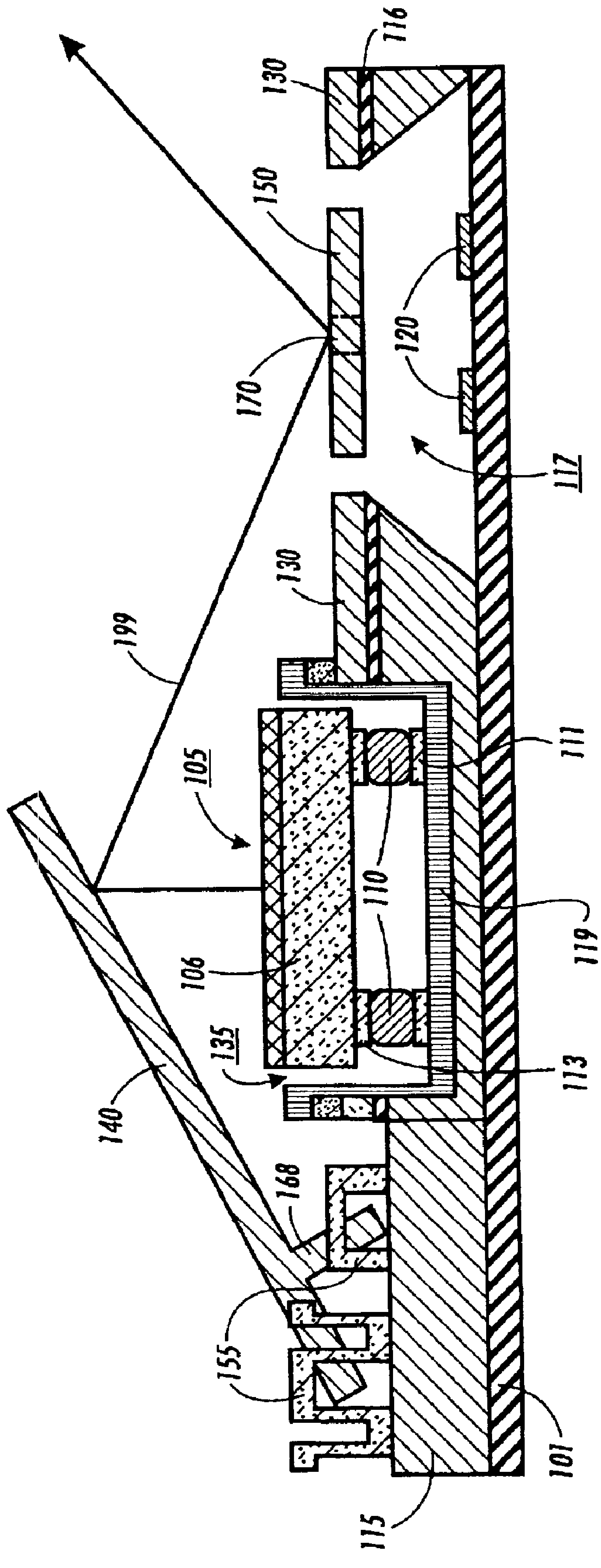
(57) **ABSTRACT**

A solid state laser beam scanning system having a single crystal silicon deflection and scanning mirror integrated with a laser diode. By combining the techniques of deep reactive ion etching of silicon with solder bump bonding techniques, completed and tested laser diodes are integrated with silicon substrates supporting micro-electro-mechanical systems layers.

32 Claims, 11 Drawing Sheets




116
130
150
120
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117
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199
111
105
110
119
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135
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168
155
101
115

FIG. 1

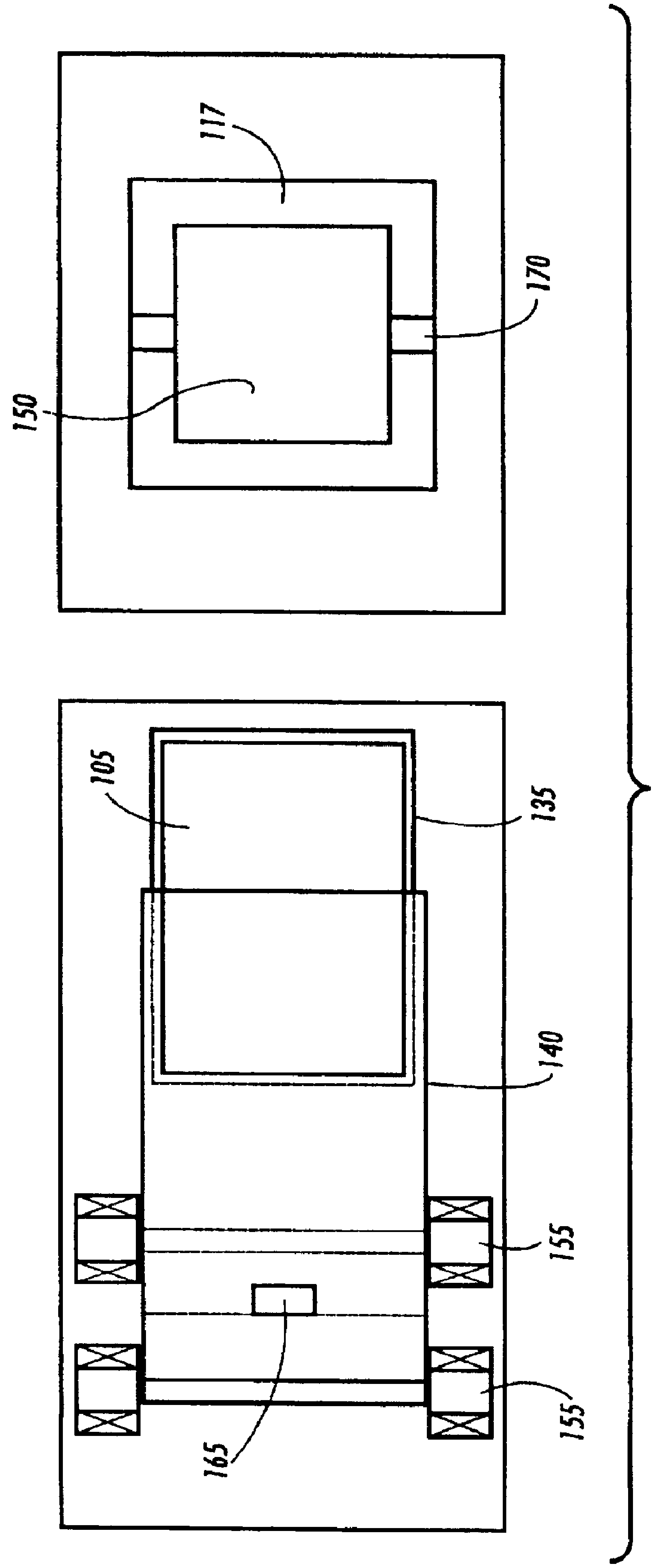


FIG. 2

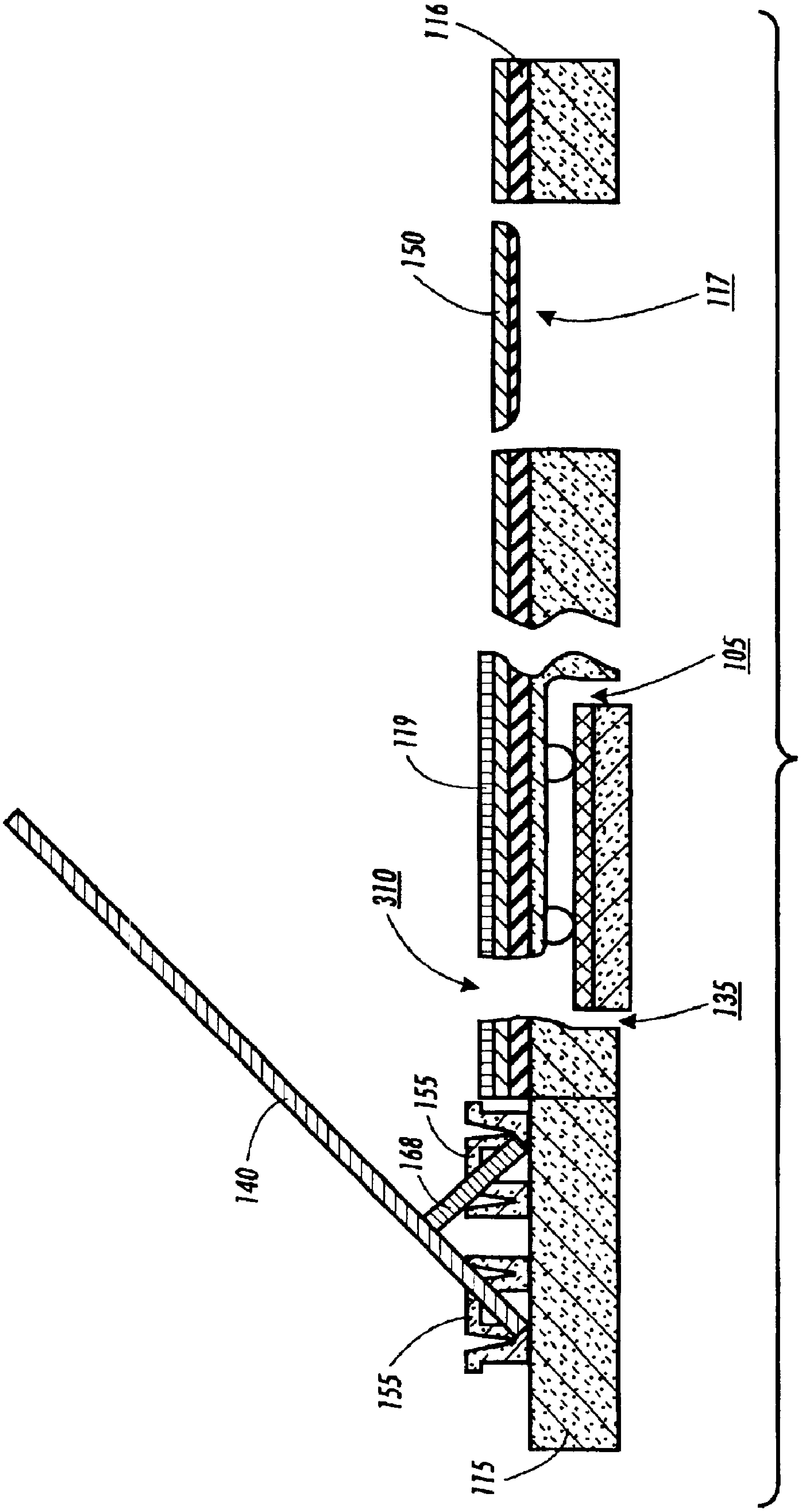
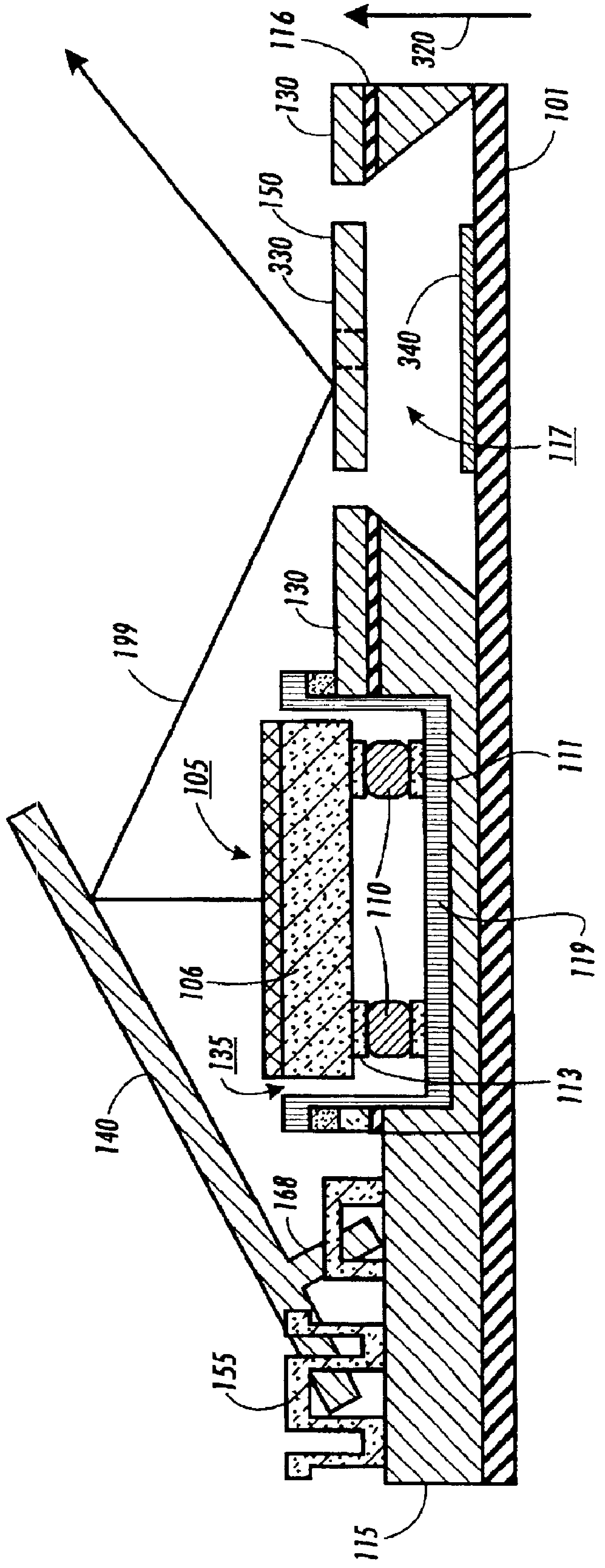


FIG. 3A


116
320
130
101
150
330
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117
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111
110
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135
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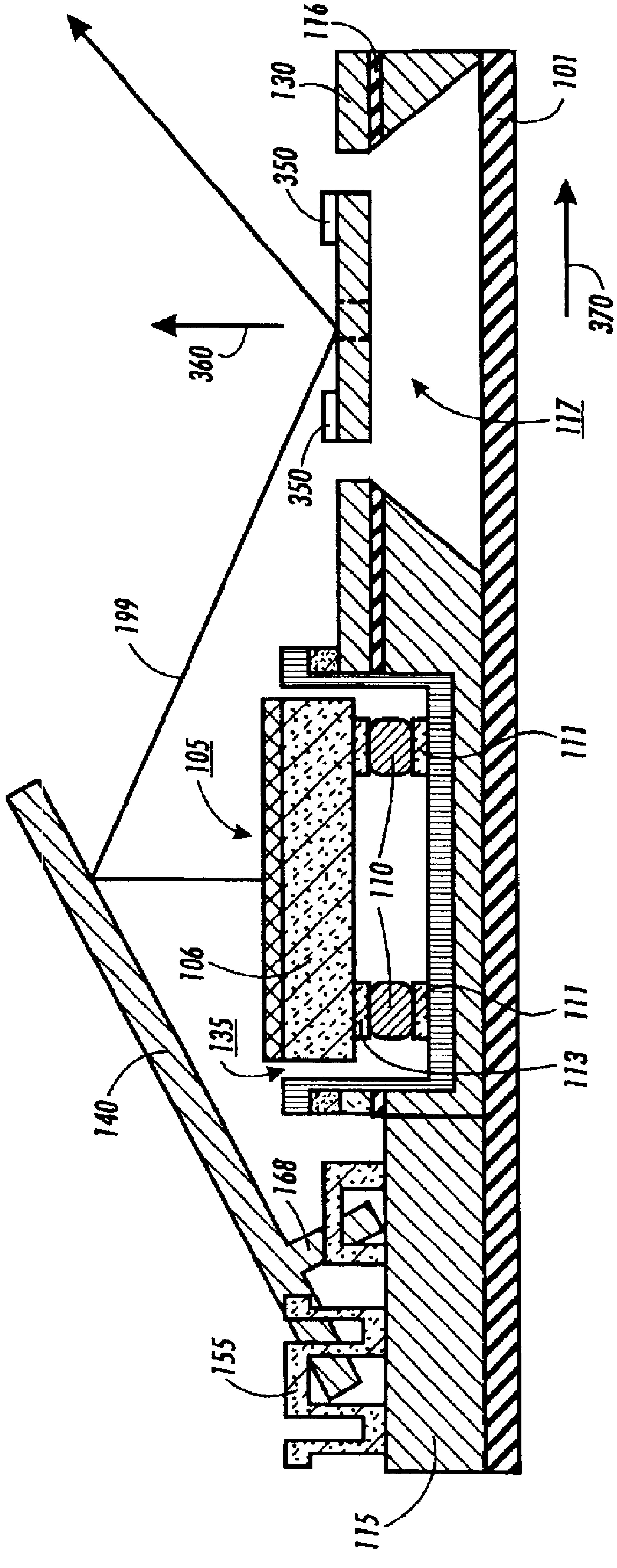
168
155
115

FIG. 3B


116
130
101
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155
115

FIG. 3C

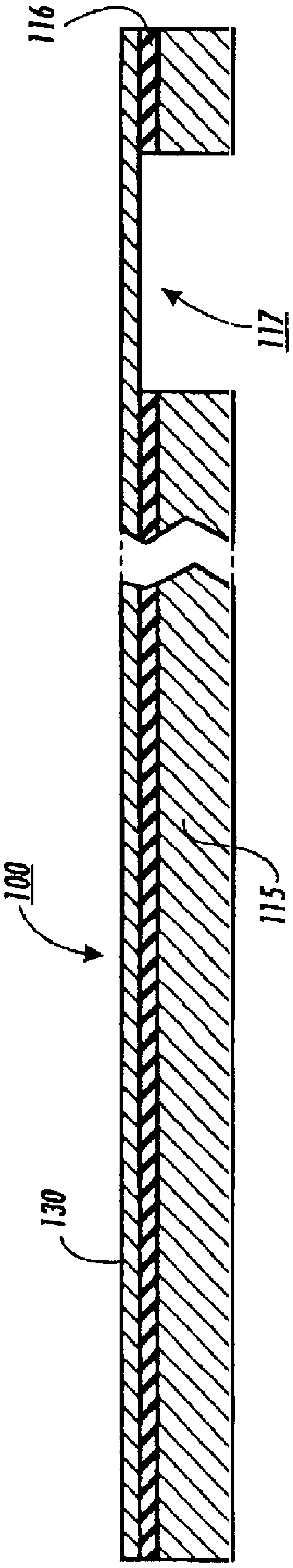

FIG. 4A

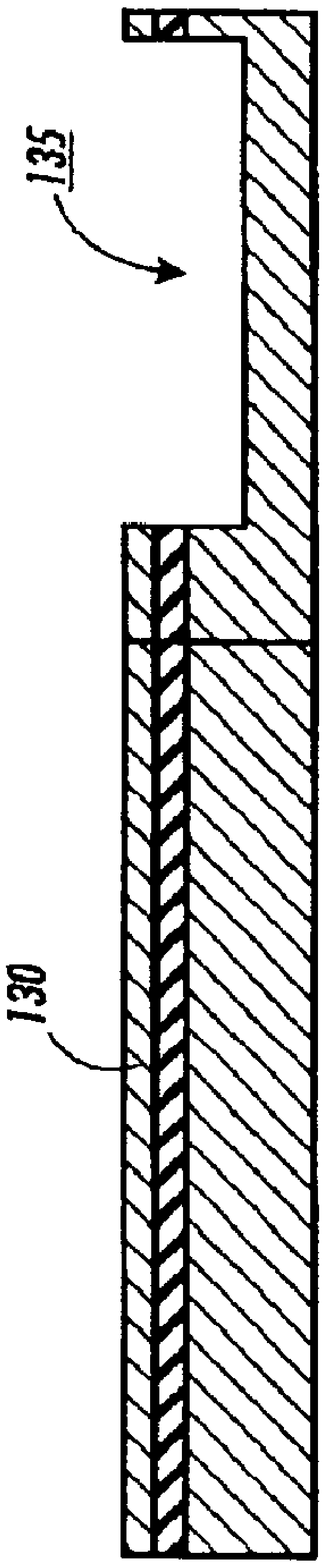

FIG. 4B

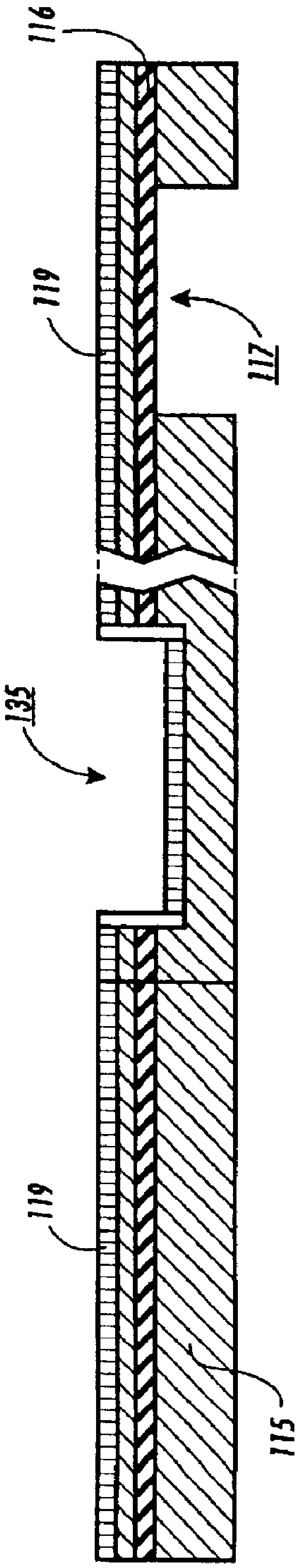

FIG. 4C

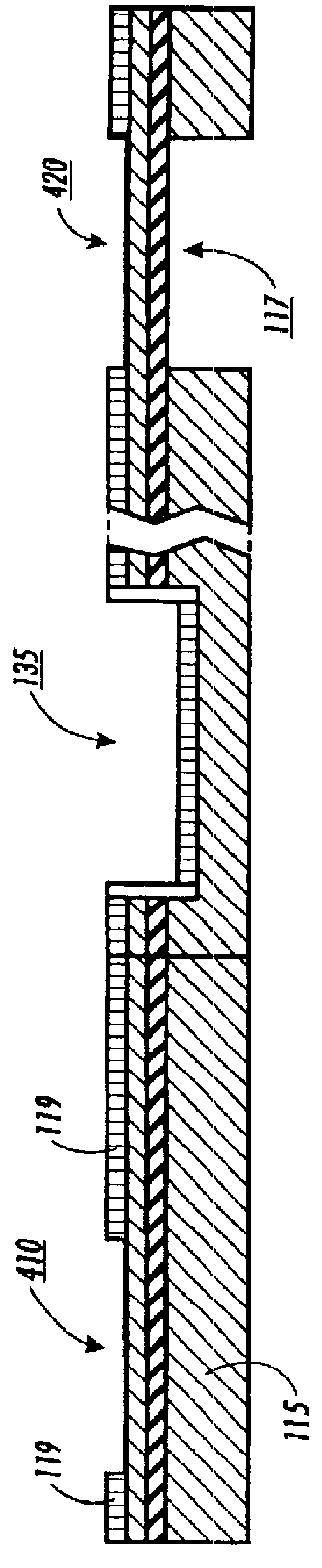

FIG. 4D

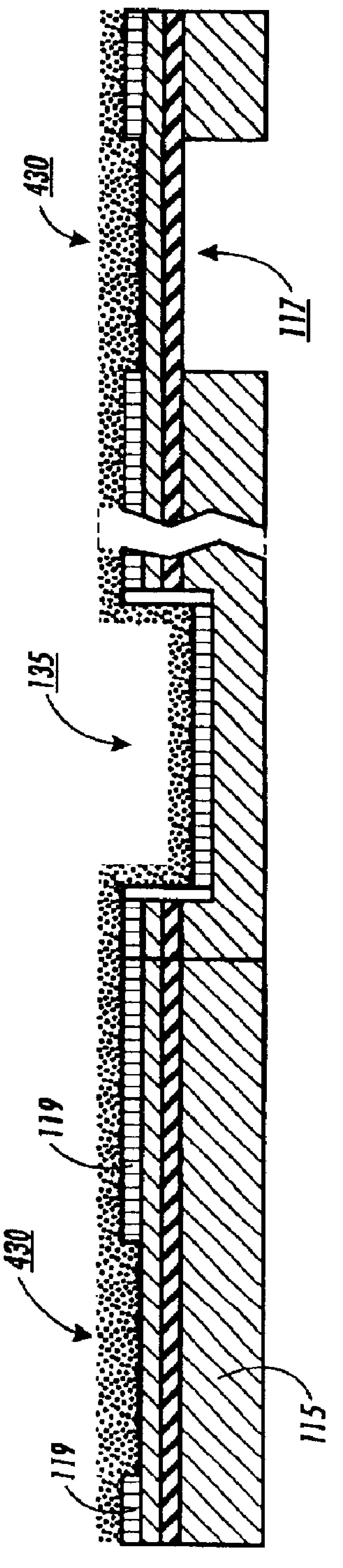

FIG. 4E

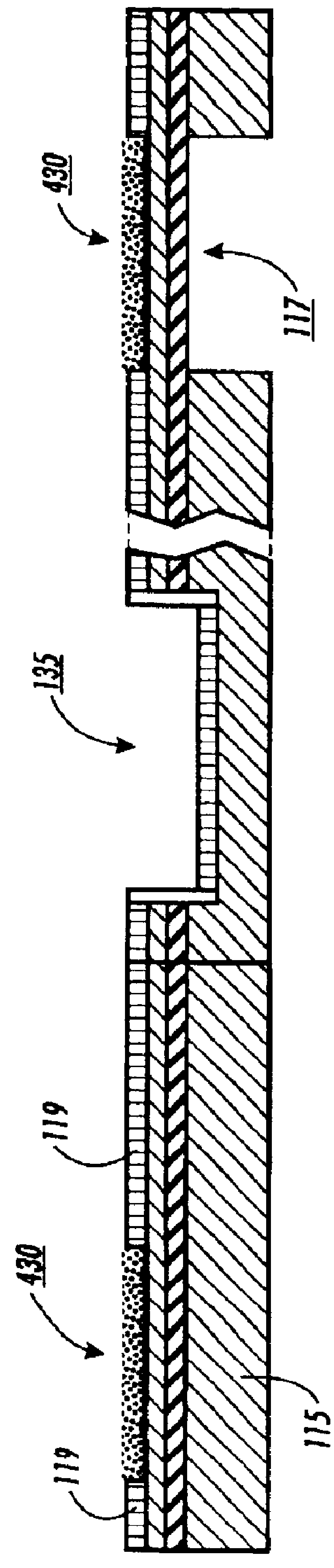

FIG. 4F

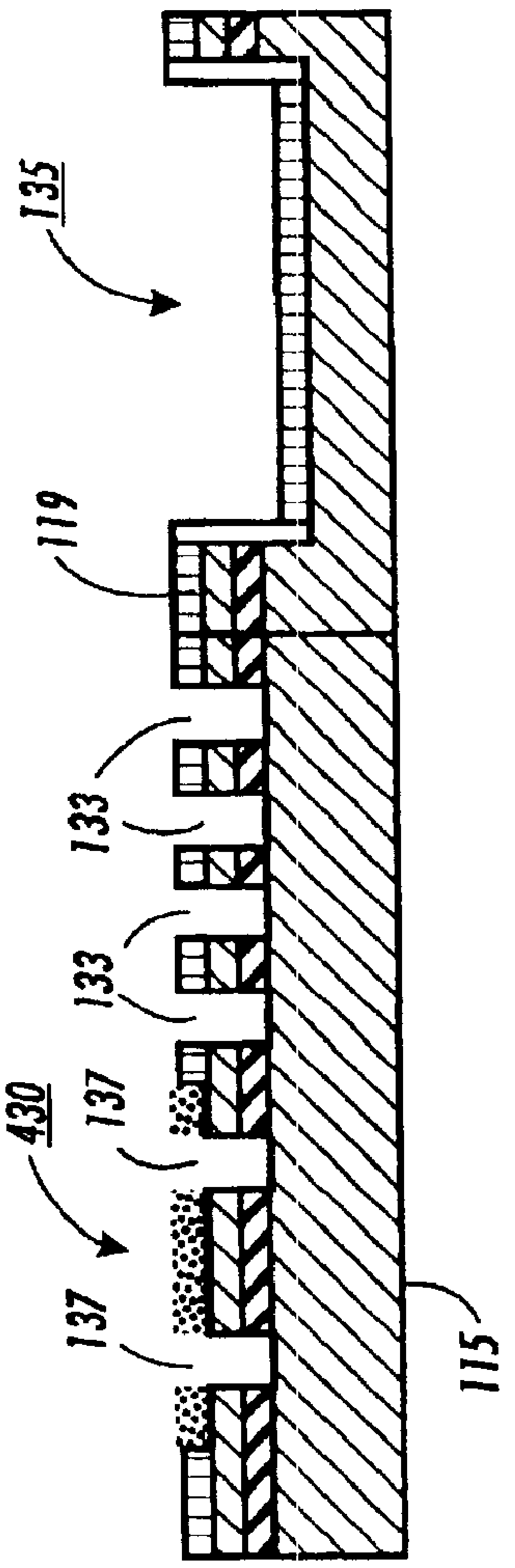

FIG. 4G

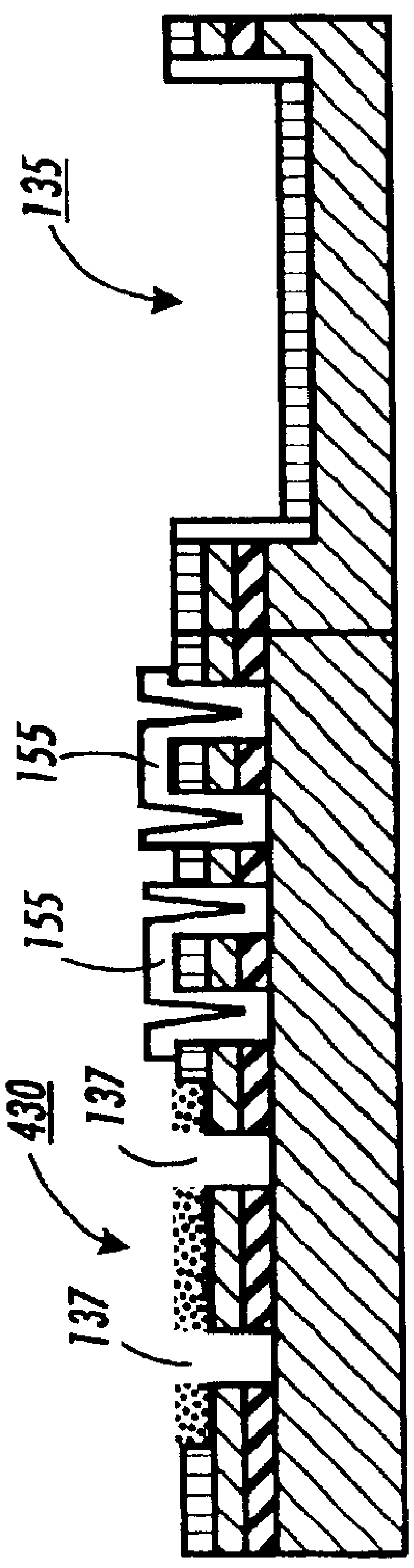

FIG. 4H

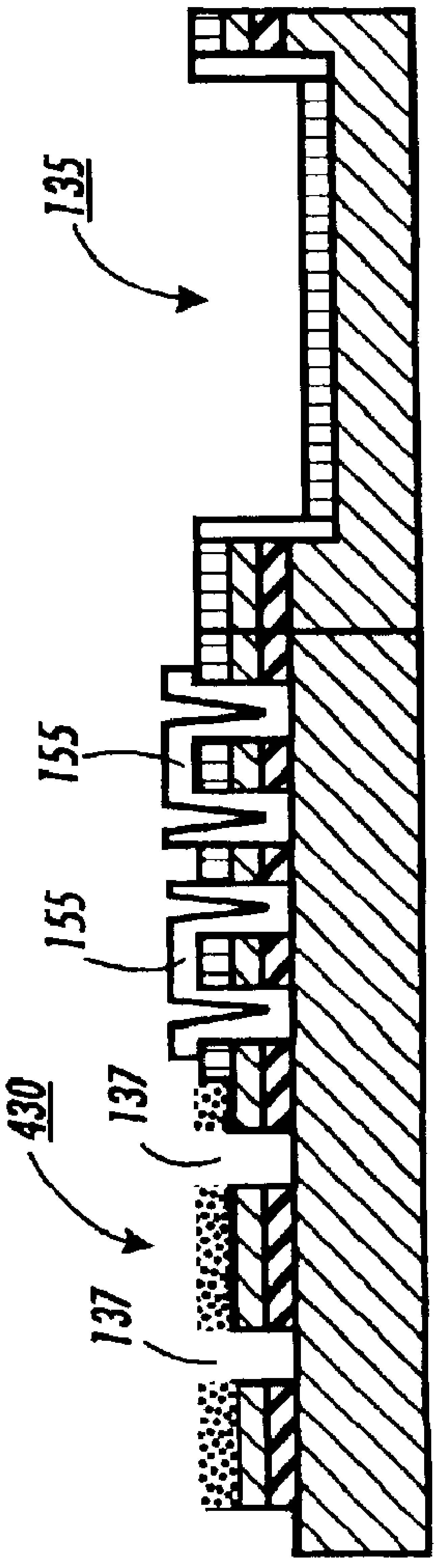

FIG. 4I

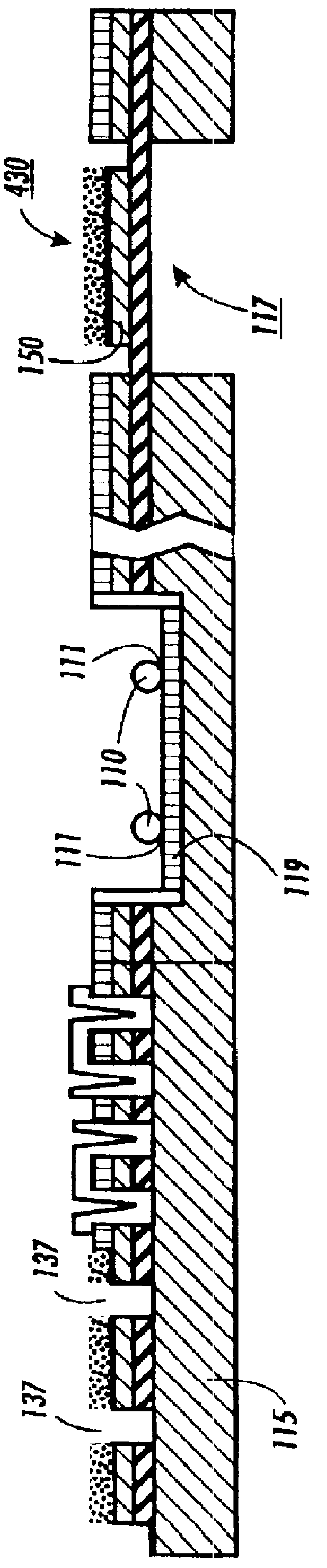

FIG. 4J

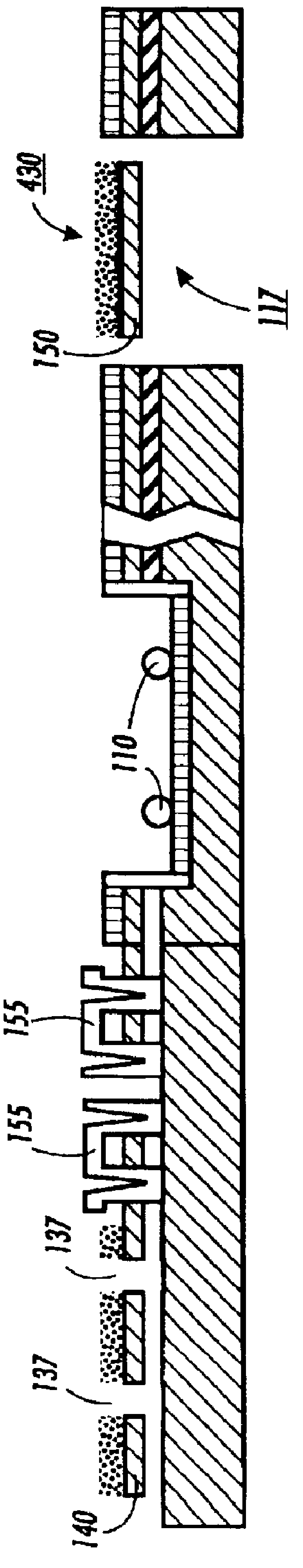

FIG. 4K

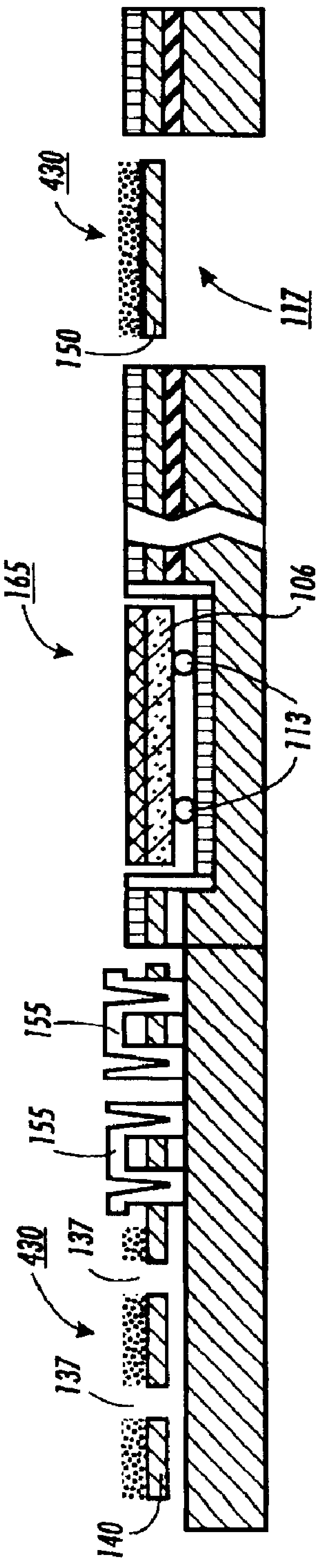

FIG. 4I

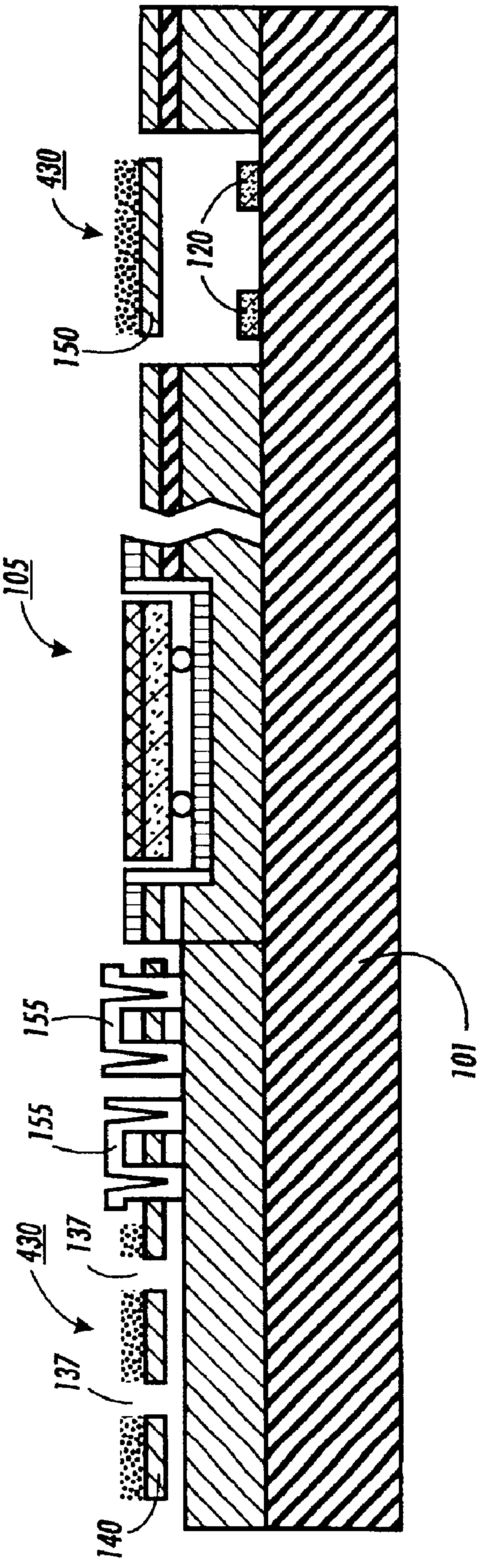

FIG. 4M

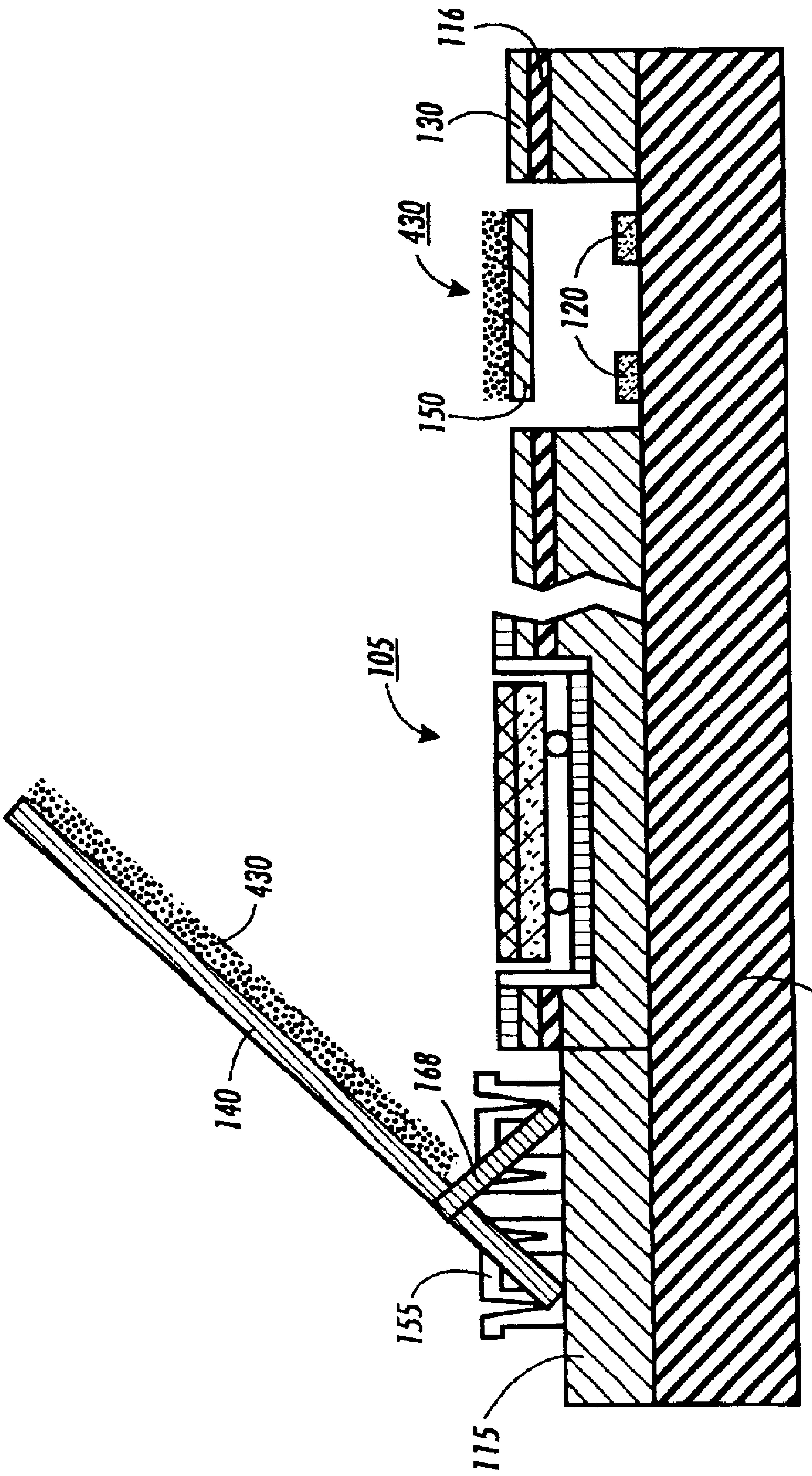

FIG. 4N

METHOD AND APPARATUS FOR AN INTEGRATED LASER BEAM SCANNER

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

CROSS-REFERENCE TO RELATED APPLICATIONS

The present invention is related to "METHOD AND APPARATUS FOR AN INTEGRATED LASER BEAM SCANNER USING A CARRIER SUBSTRATE" by Floyd, Sun and Kubby (Attorney Docket No. D/98707), Ser. No. 09/203,442, filed on the same day and assigned to the same assignee which is hereby incorporated by reference in its entirety.

BACKGROUND AND SUMMARY OF INVENTION

The present invention relates generally to the field of laser beam scanning systems, and more particularly to micro-electro-mechanical systems (MEMS) for laser beam scanning. Miniature laser beam scanning systems are important for applications such as barcode scanning, machine vision and, most importantly, xerographic printing. The use of MEMS to replace standard raster output scanning (ROS) in xerographic print engines allows simplification of printing systems by eliminating macroscopic mechanical components and replacing them with large arrays of scanning elements. Advanced computation and control algorithms are used in managing the large arrays of scanning elements.

Such MEMS based printing systems are entirely solid state, reducing complexity, and allowing increased functionality, including compensation of errors or failures in the scanner elements. An important step in constructing solid state scanning systems is integrating the semiconductor light emitter directly with MEMS actuators to gain the desired optical system simplification. Integrated scanners, which have lasers and scanning mirrors in the same structure, have been demonstrated using manual placement of laser chips onto MEMS wafers with micromachined alignment parts and adhesives by L. Y. Lin et al in Applied Physics Letters, 66, p. 2946, 1995 and by M. J. Daneman et al in Photonics Technology Letters, 8(3), p. 396, 1996. However, current techniques do not allow wafer-scale integration of the light-emitter and MEMS device.

In accordance with the present invention a laser beam scanner consisting of a single crystal silicon (SCS) deflection and scanning mirror is integrated with a laser diode or light emitting diode. By combining methods of deep reactive ion etching (deep RIE) of silicon with solder bump bonding methods, completed and tested laser diodes are integrated with silicon (Si) or silicon on insulator (SOI) substrates supporting MEMS layers. Details of creating a torsional mirror and actuating it magnetically or electrostatically are detailed in U.S. Pat. No. 5,629,790 by Neukermans and Slater which is incorporated herein by reference in its entirety.

Using solder bump bonding methods, completed and tested laser diodes are bonded to silicon MEMS built using a typical surface and bulk micromachining processes. Because of the deep RIE recesses, the laser diode solder bumps can be passively aligned to those on the host substrate. In addition, the deep RIE recesses allow nearly coplanar laser chip and Si surfaces to be made. The use of the SCS layer of an SOI wafer, rather than the polysilicon film provides for the introduction of very flat and smooth mirrors and high reliability torsion bars. The device is easily scalable to arrays of lasers and scanning mirrors on a single wafer.

Integration of the scanner and light source eliminates the need for external, manual positioning of light sources and scanning mirrors. Simplified and more cost effective post-processing steps such as interconnect metallization can be realized because the use of an etched recess results in nearly planar surfaces. In addition, pick and place technologies commonly used for multi-chip module assembly can be adapted for wafer scale assembly and bonding of light sources to the carrier substrate. With such commercial systems, bare die can be placed with accuracy better than ±30 μm.

Thus, the present invention allows the integration of completed and tested light emitting devices directly with the MEMS actuators to gain the desired simplification of the optical system needed to realize solid state scanning systems.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained and understood by referring to the following detailed description and the accompanying drawings in which like reference numerals denote like elements as between the various drawings. The drawings, briefly described below, are not to scale.

FIG. **1** shows an embodiment in accordance with this invention of an integrated solid state scanner and laser.

FIG. **2** shows a top view of an embodiment in accordance with this invention.

FIGS. **3**a–**3**c show alternative embodiments in accordance with this invention of an integrated solid state scanner and laser.

FIGS. **4**a–**4**n show the processing steps for constructing an embodiment in accordance with this invention.

DETAILED DESCRIPTION

An embodiment in accordance with this invention is shown in FIG. **1**. A laser beam scanner consisting of a single crystal silicon (SCS) deflecting mirror **140** and torsional mirror **150** is integrated with laser diode or light emitting diode **105**. By combining methods of deep reactive ion etching (deep RIE) of silicon with solder bump bonding methods, completed and tested laser diodes **105** are integrated with silicon (Si) or silicon on insulator (SOI) substrates **100** supporting MEMS layers. For example, completed GaAs-based lasers may be joined to Si MEMS to make laser beam scanners in accordance with this invention.

Electrical contact to laser **105** can be made in a variety of ways. Contact can be made by planar surface metallization, by wire bonding to the laser, through the polysilicon layer with solder bumps or some combination of each. Using solder bump bonding methods, completed and tested lasers **105** are bonded to layer phosphorus-doped glass (PSG) layer **119** in recess **135**. Deep RIE etching may be used to define recess **135** in the MEMS surface layers **130** and Si substrate **115** for subsequent laser chip **105** placement. Because of deep RIE recess **135**, laser diode solder bumps **110** can be passively aligned to wettable metal bonding pads **111** on substrate **115**. In addition, deep RIE recess **135** allows for nearly coplanar laser chip **105** and Si surfaces. This allows simplification of the subsequent metallization steps and laser chip **105** does not interfere with the space used for the optical path. The use of SCS layer **130** of SOI wafer **100** for the mirror material, rather than polysilicon film provides for the introduction of very flat and smooth mirrors **140** and **150** and high reliability torsion bars **170**. The device is easily scalable to arrays of lasers and scanning mirrors. The reflective surface of deflecting mirror **140** and torsional mirror **150** is typically coated with aluminum **430** (see FIGS. **4**e–**4**m).

In FIG. **1**, MEMS components such as single crystalline silicon (SCS) mirror **140** and torsional mirror **150** are formed in SCS layer **130** by using a combination of well-known surface and bulk micro-machining techniques. VCSEL (vertical cavity surface emitting laser) **105** is solder bump **110** bonded to wettable metal bonding pads **111** residing on phosphorus-doped glass (PSG) layer **119**. Additionally, actuation electrodes **120** are formed on glass or SiO_2 coated silicon substrate **101** which is bonded to SCS substrate **115** after etching hole **117** (see FIG. **4**a). Typical thicknesses are 0.5 mm for SCS substrate **115** and glass or dielectric-coated (typically SiO_2 or SiN_x) Si substrate **101**. SCS substrate **115** has deep RIE and/or wet etched recess **135** for alignment and placement of VCSEL **105** on SCS layer **130**. VCSEL **105** typically has a divergence angle of about 14 degrees. Emitted light **199** then passes onto deflecting mirror **140** which reflects emitted light **199** onto torsional mirror **150**. SCS layer **130** is typically about 2–20 μm thick. The spot diameter of emitted light **199** at deflecting mirror **140** is typically about 234 μm and the spot diameter at torsional mirror **150** is typically about 480 μm.

Polysilicon hinge **155** is micromachined from a deposited polysilicon layer and attaches deflecting mirror **140** to SOI substrate **115**. Polysilicon hinge **155** allows deflecting mirror **140** to rotate clockwise about an axis perpendicular to the plane of FIG. **1**, out of SCS layer **130** to a typical angle of about 30 degrees above recess **135** as shown in FIG. **1**. The distance between polysilicon hinge **155** and torsional mirror **150** is typically on the order of 1.1 mm. A typical length for deflecting mirror **140** is about 1 mm. Deflecting mirror **140** can be supported by support latch **168** controlled by a spring and latch assembly (not shown) in the manner described by Lin et al. in Photonics Technology Letters, 6(12), p. 1445, 1994 and incorporated herein by reference in its entirety. Typically, the length of support latch **168** is 100 μm. Controlling the position and length of support latch **168** allows the angle of deflecting mirror **140** with respect to SCS layer **130** to be precisely fixed, at for example, 30 degrees in the embodiment shown in FIG. **1**. Torsional mirror **150** is electrostatically actuated by actuation electrodes **120** to perform, for example, an optical scan.

FIG. **2** shows a top view of one embodiment deflection mirror/torsional mirror solid state element. Hinge **155** and deflecting mirror **140** is shown along with hole **165** to receive the tab (not shown) on support latch **168**. The layout of torsional mirror **150** supported by torsion bar **170** with respect to hole **117** is also shown.

FIG. **3**a shows an alternative embodiment in accordance with the present invention which requires via **310** for laser beam **199**. Via **310** has a cross-sectional area much smaller than that of VCSEL **105**. This preserves SCS layer **130** and other MEMS layers opposite VCSEL **105** for potential use in forming MEMS devices. In the embodiment in FIG. **3**a, alignment recess **135** is on the back side of wafer **100**, opposite the surface MEMS layers. VCSEL chip **105** is solder bump bonded to wettable metal bonding pads **111** on PSG layer **119** on wafer **115**. Light passes through aperture **310** formed by wet etching and/or deep RIE. Torsional mirror **150** is electrostatically actuated by actuation electrodes **120** to perform, for example, an optical scan.

FIG. **3**b shows an alternative embodiment in accordance with the present invention similar to that shown in FIG. **1**. However, the embodiment shown in FIG. **3**b has ferromagnetic thin film **330** deposited on torsional mirror **150** and thin film coil **340** deposited on glass or SiO_2 coated Si substrate **101**. Magnetization of ferromagnetic thin film **330** is in the plane of torsional mirror **150** so that magnetic field **320** generated by thin film coil **340** will actuate torsional mirror **150**.

FIG. **3**c shows an alternative embodiment in accordance with the present invention similar to that shown in FIG. **1**. However, the embodiment shown in FIG. **3**c has microfabricated metal thin film coil **350** with a diameter approximately that of torsional mirror **150** deposited on torsional mirror **150**. Metal thin film coil **350** generates magnetic field **360** (shown for counterclockwise current flow in thin film coil **350**) perpendicular to torsional mirror **150** when current is passed through thin film coil **350**. Additionally, external magnetic field **370** parallel to torsional mirror **150** is present. Depending on the direction of the current flow in thin film coil **350**, torsional mirror **150** will rotate to the left or to the right in FIG. **3**c to minimize the misalignment between magnetic field **360** and magnetic field **370**.

Steps for fabricating deflecting mirror, supporting latch and VCSEL in accordance with this invention are shown in FIGS. **4**a–**4**j. The starting material used as a substrate is typically a silicon on insulator (SOI) wafer. Such silicon wafers are commercially available from several manufactures such as Bondtronix, Inc. of Alamo, Calif. and Ibis Technology Corporation of Danvers, Mass. Typically, the thickness of SCS layer **130** is chosen to be 2–20 μm depending on the stiffness that is required of the torsional spring elements and the mirror surfaces to be constructed from MEMS layer **130**. Other mechanical layers are deposited on top of SOI wafer **100** by well-known methods such as Low Pressure Chemical Vapor Deposition (LPCVD). The deposited layer are mechanical layers of polycrystalline silicon (poly) and a sacrificial oxide layer that is phosphorus-doped glass (PSG). Aluminum can be deposited by sputtering or thermal evaporation. FIG. **4**c shows PSG layer **119** of 1–2 μm thickness directly on top of MEMS layer **130** of SOI wafer **100**.

FIGS. **4**a–n show the processing steps used to fabricate deflecting mirror **140**, supporting latch **168** and VCSEL **105** in an embodiment in accordance with this invention. Supporting latch **168** has a tab (not shown) which inserts into corresponding hole **165** (see FIG. **2**) in deflecting mirror **140**. Deflecting mirror **140** and supporting latch **168** are defined by reactive ion etching (RIE) using CF_4 with 4–10 percent O_2 during the etching steps. The completed deflecting mirror **140** and supporting latch **168** configuration is shown in FIG. **4**n. The typical size of deflecting mirror **140** is in the range of 0.5–1.0 mm square.

FIG. **4**a has SiN_x layer (not shown) deposited on SOI wafer **100** by LPCVD. SiN_x layer is patterned using CF_4/O_2 RIE with a photoresist mask to form a mask for KOH (potassium hydroxide) etching of Si. KOH etching is used to etch hole **117** from the bottom of SOI wafer **100**, stopping on insulator layer **116** of SOI wafer **100**. The dimensions of etched hole **117** will be comparable to that of torsional mirror **150** to allow free rotation of torsional mirror **150**. Alternatively etched hole **117** may be defined by deep RIE using C_4F_8 and SF_6 with a SiN_x or photoresist mask.

FIG. **4**b shows SOI wafer **100** with recess **135** (200–250 μm deep) etched into SOI wafer **100** using a combination of CF_4/O_2 RIE for MEMS layer **130** and insulator layer **116** and deep RIE using C_4F_8 and SF_6 in substrate **115**.

FIG. **4**c shows chemical vapor deposition (CVD) of phosphorus-doped glass (PSG) **119**.

FIG. **4**d shows a wet etch using hydrofluoric acid of windows **410** and **420** in PSG layer **119**.

FIG. **4**e shows deposition of aluminum film **430** (0.1–0.2 μm) as a high reflectivity layer.

FIG. **4**f shows a wet etch (typically a mixture of phosphoric and nitric acid) Al to leave Al in mirror regions.

FIG. **4**g shows etching of vias **133** to Si substrate **115** using CF_4/O_2 RIE with a photoresist mask.

FIG. **4**h shows the deposited polysilicon layer of 1–2 μm thickness after being patterned to form hinge **155** for deflecting mirror **140**. Patterning of polysilicon hinges **155** is described in Wu, "Micromachining for Optical and Optoelectronic Systems", Proceedings of IEEE, vol. 85, p.1833, 1997 and Pister et al., "Microfabricated hinges", Sensors and Actuators, A: Physica v 33 n 3 p. 249–256, 1992 which are hereby incorporated by reference in their entirety. If the RIE etching step is done before deposition of the polysilicon layer, the polysilicon can be deposited in etched recess **135** to reduce surface roughness due to the etching.

FIG. **4**i shows the etch of PSG layer **119** and SCS layer **130** to pattern deflecting mirror **140**, hinge **155** and access holes **137**. Holes **137** allow for the etchant used to release deflecting mirror **140** to reach insulating layer **116**. A typical size for holes **137** is 10 μm by 10 μm. Torsional mirror **150** is also defined in this step. Typical size for torsional mirror **150** in accordance with this invention is in the range of 1–2 mm square.

FIG. **4**j shows the Ti—Au deposition of wettable metal bonding pads **111** and solder for solder bumps **110**. Solder is reflowed into solder bumps **110** by heating at temperatures<310° C. This leaves the finished, unreleased MEMS parts, along with precisely defined recess **135**, ready for the GaAs bonding step in FIG. **4**.

FIG. **4**k shows release of deflecting mirror **140** and hinge **155** by etching PSG layer **119** and insulator layer **116** by using a hydrofluoric (HF) based etch.

FIG. **4**l shows placement of VCSEL **105** (thickness from 100–125 μm) into recess **135** for the GaAs bonding step. Solder bumps **110** can be defined on VCSEL **105** and VCSEL **105** is placed into recess **135** which approximately aligns the bumps to wettable metal bonding pads **111** and **113** due to the coordinated geometry of VCSEL **105**, recess **135**, wettable metal bonding pad **111** and solder bump **110** positions. Si Substrate **115** and VCSEL substrate **106** are heated to allow solder to flow and contact wettable metal bonding pads **113** on the bottom of VCSEL substrate **106**.

FIG. **4**m shows hinges **155**, deflecting mirror **140**, torsional mirror **150** and VCSEL **105** bonded to glass substrate **101** or to SiN_x-coated or SiO_2-coated Si substrate **101**. Substrate **101** supports actuation electrodes **120** for torsional mirror **150**.

FIG. **4**n shows raised deflecting mirror **140** locked with latch **168**. Angle of deflecting mirror **140** is fixed by the length of latch **168** and position of hole **165** at base of deflecting mirror **140**.

Linear arrays of lasers can be bonded in a similar way; the extent of the array being perpendicular to the cross section shown in FIGS. **3**a and **3**b.

While the invention has been described in conjunction with specific embodiments, it is evident to those skilled in the art that many alternatives, modifications, and variations will be apparent in light of the foregoing description. Accordingly, the invention is intended to embrace all other such alternatives, modifications, and variations that fall within the spirit and scope of the appended claims.

What is claimed is:

1. An integrated laser beam scanning structure comprising:

a wafer having a recess on a side;

a layer having a first region and a second region, said layer being attached to said side of said wafer having said recess;

a deflecting mirror fashioned from said first region of said layer;

a torsional mirror fashioned from said second region of said layer, said torsional mirror having a first side; and

a semiconductor light emitter mounted in said recess whereby a light beam emitted from said semiconductor light emitter is deflected by said deflecting mirror onto said first side of said torsional mirror.

2. The structure of claim **1** wherein said wafer is a silicon on oxide wafer.

3. The structure of claim **1** wherein said layer is a single crystal silicon layer.

4. The structure of claim **1** wherein said semiconductor light emitter is mounted in said recess using solder bumps.

5. The structure of claim **1** wherein said semiconductor light emitter is a VCSEL chip.

6. The structure of claim **1** wherein said recess is deep reactive ion etched.

7. The structure of claim **1** wherein said torsional mirror is actuated by a pair of electrodes.

8. The structure of claim **1** wherein a ferromagnetic thin film is attached to said first side of said torsional mirror.

9. The structure of claim **8** wherein said torsional mirror is actuated by a thin film coil.

10. The structure of claim **1** wherein a thin film coil is attached to said first side of said torsional mirror.

11. A method for making an integrated laser beam scanner comprising the steps of:

providing a wafer having a recess on a side;

attaching a layer having a first region and a second region to said side of said wafer having said recess;

fashioning a deflecting mirror from said first region of said layer;

fashioning a torsional mirror from said second region of said layer, said torsional mirror having a first side; and

mounting a semiconductor light emitter in said recess such that a light beam emitted from said semiconductor light emitter is deflected by said deflecting mirror onto said first side of said torsional mirror.

12. The method of claim **11** wherein said wafer is a silicon on oxide wafer.

13. The method of claim **11** wherein said layer is a single crystalline silicon layer.

14. The method of claim **11** wherein said semiconductor light emitter is mounted in said recess using solder bumps.

15. The method of claim **11** wherein said semiconductor light emitter is a VCSEL chip.

16. The method of claim **11** wherein said recess is deep reactive ion etched.

17. The method of claim **11** wherein said torsional mirror is actuated by a pair of electrodes.

18. The method of claim **11** wherein said torsional mirror is actuated by a thin film coil and an external magnetic field.

19. The method of claim **11** wherein a ferromagnetic thin film is attached to said first side of said torsional mirror.

20. The method of claim **11** wherein a thin film coil is attached to said first side of said torsional mirror.

21. A MEMS formation method including:

providing a SOI wafer including a single crystal silicon layer attached to an insulator layer;

forming at least one first MEMS component by paterning the single crystal silicon layer;

depositing at least one layer of polysilicon on the patterned single crystal silicon; and

forming at least one second MEMS component by patterning the polysilicon.

22. The method of claim 21 wherein the at least one second MEMS component is a hinge.

23. The method of claim 22 wherein the at least one first MEMS component is a mirror retained by the hinge.

24. The method of claim 21 wherein depositing at least one layer of polysilicon includes chemical vapor deposition.

25. The method of claim 24 wherein depositing at least one layer of polysilicon includes low pressure chemical vapor deposition.

26. A MEMS formation method including:

providing a SOI wafer including a single crystal silicon layer attached to an insulated layer;

forming at least one first MEMS component by patterning the single crystal silicon layer;

depositing at least one layer of polysilicon on the patterned single crystal silicon; wherein forming at least one first MEMS component includes forming a deflecting mirror, and forming at least one second MEMS component by patterning the polysilicon, the at least one second MEMS component including a hinge retaining the deflecting mirror.

27. The method of claim 26 wherein forming at least one first MEMS component further includes forming a torsional mirror, and the method further comprises forming a recess in the SOI wafer and mounting a light emitter in the recess so that it will emit light at the deflecting mirror, which deflects light to the torsional mirror.

28. A MEMS device comprising:

at least one single crystal silicon component bonded to an insulator that rests on a handle wafer; and

a polysilicon hinge derived from a layer of polysilicon applied over the at least one single crystalline component.

29. The MEMS device of claim 28 wherein the at least one single crystal silicon component comprises a deflecting mirror retained by the hinge.

30. The MEMS device of claim 28 wherein the at least one single crystal silicon component comprises a torsional mirror.

31. A MEMS device comprising:

at least one single crystal silicon component bonded to an insulator that rests on a handle wafer; and

at least one polysilicon component derived from a layer of polysilicon applied over the at least one single crystalline silicon component;

a recess in the handle wafer aligned with the at least one single crystal silicon component; and

a semiconductor light emitter mounted in the recess to emit a light beam at the single crystal silicon component.

32. The MEMS device of claim 31 wherein the at least one single crystal silicon component comprises a deflecting mirror at which the light beam is directed and a torsional mirror to which the deflecting mirror deflects the light beam, and the at least one polysilicon component comprises a hinge retaining the deflecting mirror.

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