PROVISIONAL PATENT APPLICATION

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Amplified Compliant Force Pressure Sensors

BACKGROUND OF THE INVENTION

1. Field of the Invention.

The present invention is related to microsensing devices, and, more particularly, to sensing devices with increased sensitivity.

2. Prior Art.

Advances in micromachined sensor technology has developed whole new applications for medical devices, particularly implantable devices, such as for cardiac disease treatment. Engineering on this highly miniaturized scale, with its many unique applications, has also brought with it new challenges.

A number of research groups have reported on different approaches for improving the performance of micromachined sensors. For micromachine pressure sensors, this effort has focused on modifying the dimensions of the various components of the pressure sensors. This work has resulted in improved designs by providing modifications to the sensing membrane components size, shape, and thickness.

Other research approaches to optimization effort have resulted in insights and improvements in the placement of the pressure and the strain-measuring elements on the membrane. The strain-measuring elements on current pressure sensing membrane elements are typically piezo resistors. However, the strain-measuring elements can also be vibrating beam strain sensors.

When designing the geometry of pressure sensor membrane, engineers have several parameters which can be modified in order to achieve the greatest improvement in sensor performance. By example, design considerations can includes modifications in the proportions of the diameter of the sensing element, providing a round, oval, or other shape to this sensing membrane. Researchers will also attempt optimization of sensor function by modifying the membrane thickness. The thickness can be modified in an omnibus manner, or made to vary in different regions of the membrane.

Unfortunately, there are outside physical limitations on how far the pressure sensor designer can change sensor membrane physical parameters to increase the sensitivity. By example, to increase the sensitivity of a pressure sensor, the engineer has the option of providing further thinness to the diaphragm or increasing the diameter of the sensor. These factors can render the membrane unacceptably fragile, and give unwanted larger dimensions to a device which is preferably of a very small size. Also, when the membrane is made larger at the same time membrane thinnest is increased, the burst pressure will be reduced dramatically. All these factors in the pursuit of increased sensitivity can potentially result in a substantially less robust device.

In other areas of micromachining, researches have sought various approaches to improving sensitivity. By example, Pedersen et al have reported the use of amplifier mechanisms for resonant accelerometers (Pedersen et al, J. Micromech. Microeng. 14 (2004) 1281-1293.

It would be a very useful advancement in the art of microsensor technology if the sensitivity of pressure sensing devices could be improved without resort to modifying the dimensions of the sensor membrane component to the extent other strengths of the device are compromised.

SUMMARY OF THE INVENTION

The present invention provides, for the first time, an innovative design which substantially increases the sensitivity of pressure sensors through the inventive used of a beam element in the pressure sensor design. This innovative design approach represents a dramatic advancement over prior art sensitivity methods which have relied on larger, thinner sensor membranes, or bosses. Using the present innovative approach of optimizing compliant force through the use of beam elements in the pressure sensor design provides, for the first time, pressure sensor devices of unprecedented small dimensions and robust character while achieving uniquely fine sensitivity levels.

The inventive devices have special applications in microsensing use, particularly in medical devices. A particularly useful application of the innovative devices is for use in implantable medical devices, most especially cardiac devices. There are many other medical applications for the present inventive pressure sensors, such as detecting pressure in the eye and in spinal fluid.

The invention provides an unprecedented increase in signal output for pressure sensors for a given amount of pressure. In this way, the present invention provides sensing devices which, while constrained in size, are able to provide highly accurate pressure readings at very small changes in pressure. The force amplification of the present invention means and methods increases the capacity for sensitivity of micromachined pressure sensors by about 1-1,000 times preferably about 50-500 times, and most preferably about 150-250 times (see Fig. 5). When combined with other, standard sensitivity design modifications, these sensitivities can reach even higher levels.

The present inventive devices and design methods provide the sensor design engineer a tool by which a which the apparent strain on the sensor membrane can be magnified or amplified. This allows a given membrane deflection due to a pressure difference to be dramatically amplified. With the inventive approach of employing a beam element, the strain-measuring elements will experience a larger strain without distortion. As a result, the electrical sensor signal generated by the sensor will be correspondingly increased.

BRIEF SUMMARY OF THE DRAWINGS

Fig. 1 provides a cross sectional view of a prior art pressure sensing device.

Fig. 2 provides a cross sectional view of the present invention.

Fig. 3 provides a cross sectional view of an alternate embodiment of the present invention.

Fig. 4 is a flow diagram of a simplified inventive fabrication sequence.

Fig. 5 provides a view of an inventive in-plane and mechanical amplification.

Fig. 6 provides a diagrammatic view of one embodiment of the present invention.

Fig. 7 provides a flow diagram of one embodiment of the present inventive fabrication method.

DETAILED DISCRIPTION OF THE INVENTION

The inventive use of beam elements to amplify pressure signals in micromachined sensor devices is a unique and important advancement in the field of micromachining. Following the present inventive teaching, for the first time engineers will be able to substantially increase the sensitivity of pressure sensors through the used of a beam element.

The innovative design approach enjoys a number of advantages over prior art efforts to increase sensitivity of micromachined pressure sensors. Prior art methods relying on larger, thinner sensor membranes, or bosses. By optimizing compliant force through the use of beam elements in the pressure sensor design, the present invention provides for pressure sensor devices of unprecedented small dimensions while providing robust sensitivity.

When designing the geometry of pressure sensor membrane, engineers have previously several parameters to modify in order to achieve the greatest improvement in sensor performance. These can be employed with the advancement of the present invention to further increase the sensitivity of the inventive pressure sensor devices, often with impressive synergistic improvement in sensitivity. By example, design considerations can includes modifications in the proportions of the diameter, providing a round, oval, or other shape to the membrane, and modifying the membrane thickness, which can be made to vary in different regions of the membrane.

However, there are outside limitations on how far the designer can change these physical sensor membrane parameters to increase the sensitivity. By example, to increase the sensitivity of a pressure sensor, the engineer has the option of providing further thinness to the diaphragm. Another option to increase the sensitivity of a pressure sensor would be to increase the diameter of the sensor. Unfortunately, there are physical limitations to both of these optimization approaches. The present invention allows the use of these methods without resorting to extreme measures, with their concomitant risks and disadvantages.

The present invention allows the use of prior art methods without the prior risks incurred in taking them beyond their appropriate physical limits. By example, if the strain for a given amount of pressure exceeds a certain value, typically on the order of 0.01% or 10^{-4}, that the membrane deflection and membrane strain is no longer a linear function of the applied pressure. This nonlinearity that can be accounted for and calculated but complicates the measurement circuit considerably. As a result, previous effective pressure sensor designs required that the device operate within the linear strain versus pressure regime. Prior to the present invention, devices were thus limited by how large and how thin a pressure sensor membrane could be effectively constructed.

Another serious limitation to prior micro pressure sensor designs is the burst pressure that the pressure sensor is required to withstand. In prior art devices, there was typically a safety factor over which the devices operating pressure which will be rated as its burst pressure. As the membrane is designed on a larger scale or where the membrane is made thinner to improve sensitivity, the burst pressure which it can tolerate is reduced dramatically.

The burst pressure would have to be provide that would accommodate the largest possible pressure that the device is likely to experience in the environment in which it would function over a specific required lifecycle. Prior to the present invention, the burst pressure represented a severely limiting factor for the pressure sensor designer.

With the advent of the present invention, these two limitations of linearity and burst pressure no longer represent limits on how large a strain can be generated for a given pressure sensor specification. Because of the much improved sensitivity provided by the inventive beam elements, these standard methods need no longer be taken to inappropriate extremes.

The use of bosses on the pressure sensing membrane represent another prior art method used to maximize the optimizations now achievable by the present inventive beam element. Bosses on the sensor membrane have the effect of concentrating the strain due to pressure applied to the membrane. These currently employed elements have the effect of concentrating the pressure on a few locations on the membrane. The prior art approach of bosses allows the strain-measuring elements to be placed at those locations to optimize sensitivity. The strain for a given applied pressure, accordingly, will be greater if the bosses are placed in the correct location.

The previous use of bosses alone, however, has engineering limitations on how far sensitivity can be optimized. From an electrical measurement standpoint, it is always preferable to have the largest possible strain for a given amount of pressure at the sensor elements. Thus, use of the inventive beam element associated with a boss provides a signal to noise ratio that is as large as possible. Therefore, use of the present invention allows the detect of smaller and smaller differences in pressure. The present invention allows the detection of pressures in the range of about 0.01 to 100,000 mmHg, preferably about 0.1 to 10,000 mmHg, and most preferably 1 to 1000 mmHg.

For a given plate bending, it is possible to calculate the position of the where the center of the curvature. It is also possible to calculate the radius of the curvature of the plate bending. From mechanical texts and from standard engineering analysis, the practioner will be able to locate the strain at any given location within the membrane. This strain is typically equal to the distance of that point from the neutral plane of membrane divided by the radius of curvature.

The beam dimensions in the present invention can range from about 1-1,000μm, preferred about 5-500μm, most preferred about 10-100μm. Additional, in the present invention, multiple inventive beams can be used on a sensor membrane, for instance about 1-100 beams, preferred about 3-50 beams, and most preferred about 4-5 beams.

The designer of the inventive sensors will readily be able to optimize the structure to achieve as small an arc as is practically possible in order to achieve optimal results. By applying bosses to the sensor membrane and changing the membrane dimensions to reduce to radius of curvature, one must consider that a larger strain will result

Fig. 1 provides a cross-sectional view of a segment of a membrane or plate undergoing a deflection. This diagrammatical representation is of a section of pressure-sensing membrane that is experiencing a pressure difference, causing it to bow.

From the discussion above, the formula which will be employed by the practioner in practice of the present invention will effect the prior art device of **Fig. 1** in the following manner. The largest strains will be when z is the largest. However, since the strain element has to be connected to the plate, the greatest possible z occurs at one or the other surface of the plate.

The present invention is particularly suitable for use in the multiplex systems previously developed by some of the present inventors. This system is described in part in currently pending patent applications US Patent Application No.10/764429 entitled "Method and Apparatus for Enhancing Cardiac Pacing", US Patent Application No.10/764127 entitled "Methods and Systems for Measuring Cardiac Parameters", and US Patent Application No. 10/764125 entitled "Method and System for Remote Hemodynamic Monitoring" all filed 01/23/2004, and US Patent Application No.10/734490 entitled "Method and System for Monitoring and Treating Hemodynamic Parameters" filed 12/11/2003. These applications are herein incorporated into the present application by reference in their entirety.

In **Fig. 1** it can be observed from the top surface of the membrane in the example shown is equal to the thickness divided by 2. On the bottom surface, z is equal to the negative of the thickness divided by 2. This puts a limitation on the maximum strain that the sensor element can experience for a given radius of bending.

Fig. 2 show the effect of the inventive design which serves to displace the strain-measuring elements from the membrane as shown. The section **201** of the pressure-sensing diaphragm is shown in this view bending about the center of radius **202**. Offset elements **203** are provided which serve to displace strain-measuring element **204** from the surface of the membrane.

From this depiction, one can observe that z-prime, the distance of strain-measuring element **204** from the neutral axis **205**, is larger than the thickness divided by 2. In fact, as practiced in the present invention, z-prime can be any arbitrary value. As will be understood by the practioner, z-prime may in some cases be limited by some practical considerations such as fabrication techniques.

Fig. 3 provides an example of an alternate embodiment of the present invention. This figures shows offset elements **303** placed on either side of membrane **301**. In this case, because the offset is below the membrane, the z-prime has a negative value. However, this effect does not affect the engineering principle shown in this case.

In a specific embodiment of the present invention , if one were to take a pressure-sensing membrane with typical dimensions of a thickness of 1.5μm and in the prior art, the maximum z would be half of that, or 0.75μm. If these standoff elements were manufactured using an additional 1.5μm, the z-prime would now be 1.5 + 0.75, or 2.25μm. This engineering modification can be accomplished simply and with ease using known fabrication techniques.

Using the above inventive engineering advances, the inventive devices has effectively increase the sensitivity of this prior art pressure sensor design by 3-fold. This provides a simple exemplification of the present invention. However, using the present inventive techniques, amplification values up to 10 or more times can be easily achieved. The, the present invention increases sensitivity by about 1-100 times, preferably about 10-80 times, and most preferably about 20-40 times.

Fig. 4 provides a flow diagram of a simplified fabrication sequence for making one on the present inventive devices. **Fig. 4a** shows a starting with etch-stop layer **401**, and membrane layer **403**. The etch-stop layer **402** is optional. In a typical device, wafer **401** then will be a silicon. Etched-up layer **402** would typically be silicon dioxide, and membrane layer **403** would also typically be silicon.

In **Fig.4b,** offset layer **404** is deposited on top of wafer **401.** In **Fig.4c** offset layer **404** is patterned to make openings or features **405** in offset layer **404**. In **Fig.4b** a strain-sensing material **406** is deposited on top of the offset layer **404**. Strain-sensing material **406** can be a piezo resistive metal such as platinum. Alternatively, strain-sensing material **406** can be an diffused resister into a silicon layer. In **Fig.4e,** a hole is etched through the back of chip **407** to define the sensing membrane. **Figs. 4f, 4g, and 4h** provide planer views of the constructs illustrated in **Figs. 4a, 4b, and 4c**, respectively.

Practical considerations limit the amplification factor using this simpler embodiment of the inventive technique to amplifications of about 10. However, as shown in **Fig. 5**, by extending the inventive concept further, in a more advanced, sophisticated embodiment using in-plane amplification, much larger amplification ratios of the strain are possible. In this case, 100 or several hundred fold increase is available using the present inventive approaches.

Fig. 5 provides a planer view of pressure sensor chip **501**, with a pressure sensor membrane **502**. Amplifying structures **503** and **504** are deposited on the pressure sensor chip surface. **Figs. 5b and 5c** provide cross-sections through this device at different locations marked by the A and A-prime and B and B-prime. As shown in **Figs. 5a, 5b and 5c, the** force-amplifying structures contact the surface of the chip in some locations but do not contact it in others, that is are freestanding above the surface in those locations.

An example of an inventive force amplification structure is provided in additional detail in **Fig 6**. Pad **601** is a location that is attached to one part of the pressure sensor membrane and pad **602** is attached to a second part of the pressure sensor membrane. Using the method of the present invention, these locations will be chosen such that there are locations that experience a large displacement when membrane deflects due to an applied pressure.

Using the example of beam **603**, if location **601** were to move away from location **602** when a positive pressure was applied, beam **603** would get pulled toward pad **601**. This movement would cause a rotation of beam **604** whose one end is anchored to pad **602**. However, a mid-point is attached to beam **603**. That rotation would cause a tension on beam **605** which is then attached to a fixed pad **606**. Fixed pad **606** is attached to some portion of the chip that would not move. This stationary portion of the chip can be, by example, in the periphery of the membrane.

Beam **604** is provide with a segment **607**. Comparing the length of segment **607** to the length of the segment **608**, if these lengths are unequal, it will result in either magnification or a reduction in the amplitude of the relative motion of pad **601** or pad **602**. For instance, if segment **607** were 10μm long and segment **608** were 100μm long, then the end of beam **604** would move 10 times as much as the displacement between pad **601** and pad **602.** This inventive design provides a 10-fold multiplication in the amplitude of the motion. This improvement translates to a 10-fold increase in the strain in beam **605** and a 10-fold increase in the electrical output of the sensor for a given amount of pressure.

As an example, this particular structure is provided with a mirrored structure. As such, pad **606** has its mirror image in pad **609**. This inventive design is a convenient approach to fabrication. It also meets standards of good mechanical practice by providing symmetry. This inventive embodiment has the additional advantage that if, for instance, a strain measuring element **605**, was a piezo resister, the resistance between pad **606** and pad **609** can be measured. By observing the change in the resistance, a measure of the strain is provide in those elements, and hence a measure of the pressure.

The above provides one example of using the inventive lever principle to amplify the force. It will be appreciated by the ordinary skilled artisan that there are many variations on a lever. Equally, how to make levers has been provided in at a previously unavailable level of sophistication by computer methods for determining the optimum shape of levers for micromachine structures. In the prior art, such approaches have been applied to applications like accelerometers and to sort of the micromachine equivalent of a Pantograph. In the latter example, the motivation is to apply a large displacement and cause a very precise motion.

Otherwise, the device is employing a force generator that has only a very small displacement which must be amplified.

Fig. 7 is a flow diagram depiction of one embodiment of the present inventive fabrication method to make the inventive in-plane lever structure. In **Fig.7a,** the fabrication begins with wafer **701**. Wafer **701** is preferably a silicon wafer. Deposited on wafer **701** is etch-stop **702**. Etch-stop **702** can be silicon dioxide. Etch-stop **702** is surfaced with membrane layer **703**. Toping these layers is sacrificial layer **704.** In **Fig. 7b** sacrificial layer **704** is patterned to form a series of features **705**.

The features **705** in the sacrificial layer **704** represent areas where mechanical structure of the inventive device will not touch the underlying membrane. The holes **706** in the sacrificial layer **704** are positioned in places where the lever layer **707** will be attached to the membrane. In **Fig. 7c**, lever layer **707** is deposited. Lever layer **707** preferably is constructed of polycrystalline silicon.

In **Fig. 7d** the intermediate chip is patterned into structures **708.** Structures **708** represent the various lever arms and anchor pads described in the previous figure. In **Fig. 7e**, the sacrificial layer **704** is etched away. If, by example, silicon dioxide is used as the sacrificial layer **704**, it can be etched away with hydrofluoric acid. In whatever manner sacrificial layer **704** is etched, freestanding lever structures **708** are produced.

Fig. 7f describes the last step in this embodiment of the present inventive fabrication method. In the backside of the chip **hole 709** is etched to define the membrane area.

Amplified Compliant Force Pressure Sensors

CLAIMS

Claim 1. An amplified compliant force pressure sensor comprising a pressure sensor membrane with one or more beam features.

Claim 2. The amplified compliant force pressure sensor of Claim 1 wherein said beam features have dimensions from about 1-1,000μm.

Claim 3. The amplified compliant force pressure sensor of Claim 2 wherein said beam features have dimensions from about 5-500μm.

Claim 4. The amplified compliant force pressure sensor of Claim 3 wherein said beam features have dimensions from about 10-100μm.

Claim 5. An amplified compliant force pressure sensor comprising a pressure sensor membrane with multiple inventive beam features.

Claim 6. The amplified compliant force pressure sensor of Claim 5, wherein said pressure sensor membrane is provided with about 1-100 beams.

Claim 7. The amplified compliant force pressure sensor of Claim 6, wherein said pressure sensor membrane is provided with about 3-50 beams.

Claim 8. The amplified compliant force pressure sensor of Claim 7, wherein said pressure sensor membrane is provided with and most preferred about 4-5 beams.

Claim 9. A micromachined pressure sensor which can detect pressures in the range of about 0.01 to 100,000 mmHg.

Claim 10. The micromachined pressure sensor of Claim 10 which can detect pressures in the range of about 0.1 to 10,000 mmHg.

Claim 11. The micromachined pressure sensor of Claim 10 which can detect pressures in the range of about 1 to 1000 mmHg.

Claim 12. A amplified compliant force pressure sensor with an increase in sensitivity over planer micromachined pressure sensors in of about 1-100 times.

Claim 13. The amplified compliant force pressure sensor of Claim 12, where the increase in sensitivity is about 10-80 times.

Claim 14. The amplified compliant force pressure sensor of Claim 13, where the increase in sensitivity about 20-40 times.

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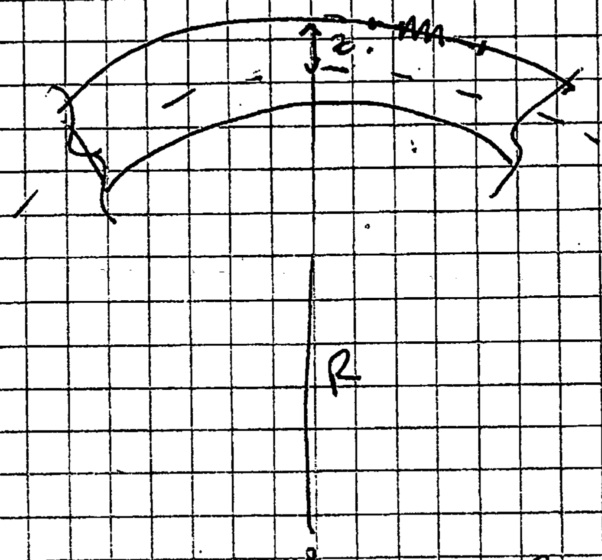
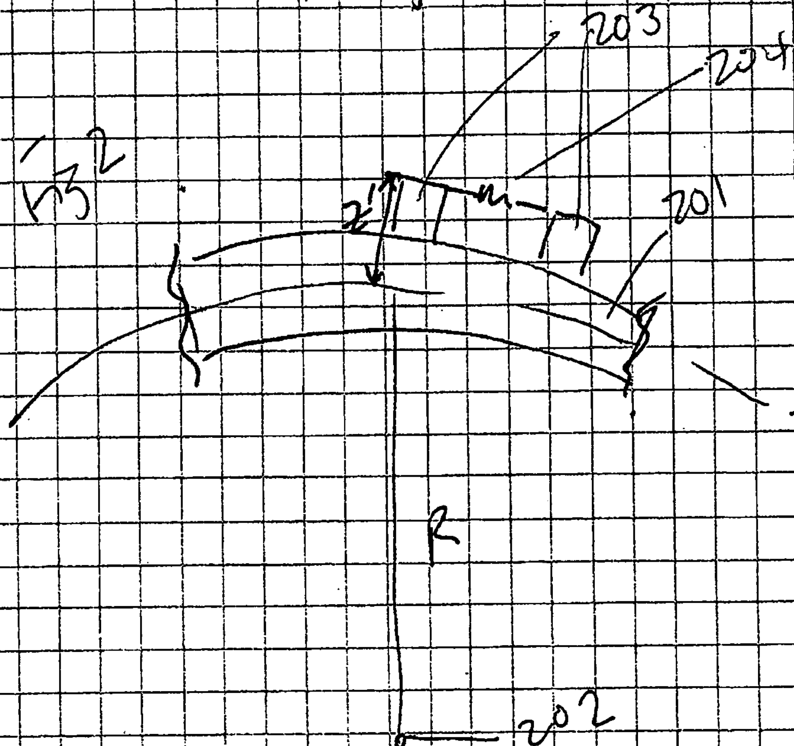
Fig 1



$\epsilon = \frac{z}{R}$

where $z = t/2$

Fig 2



$\epsilon' = \frac{z'}{R}$

$z' > t/2$

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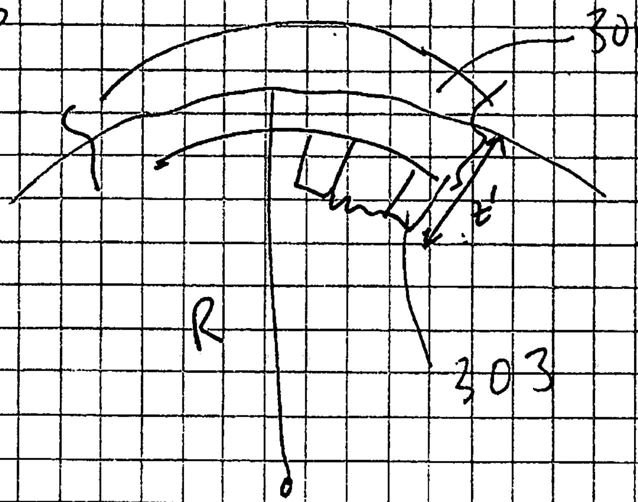
Fig 3



$\epsilon' = \frac{z'}{R}$ where $z' < 0$

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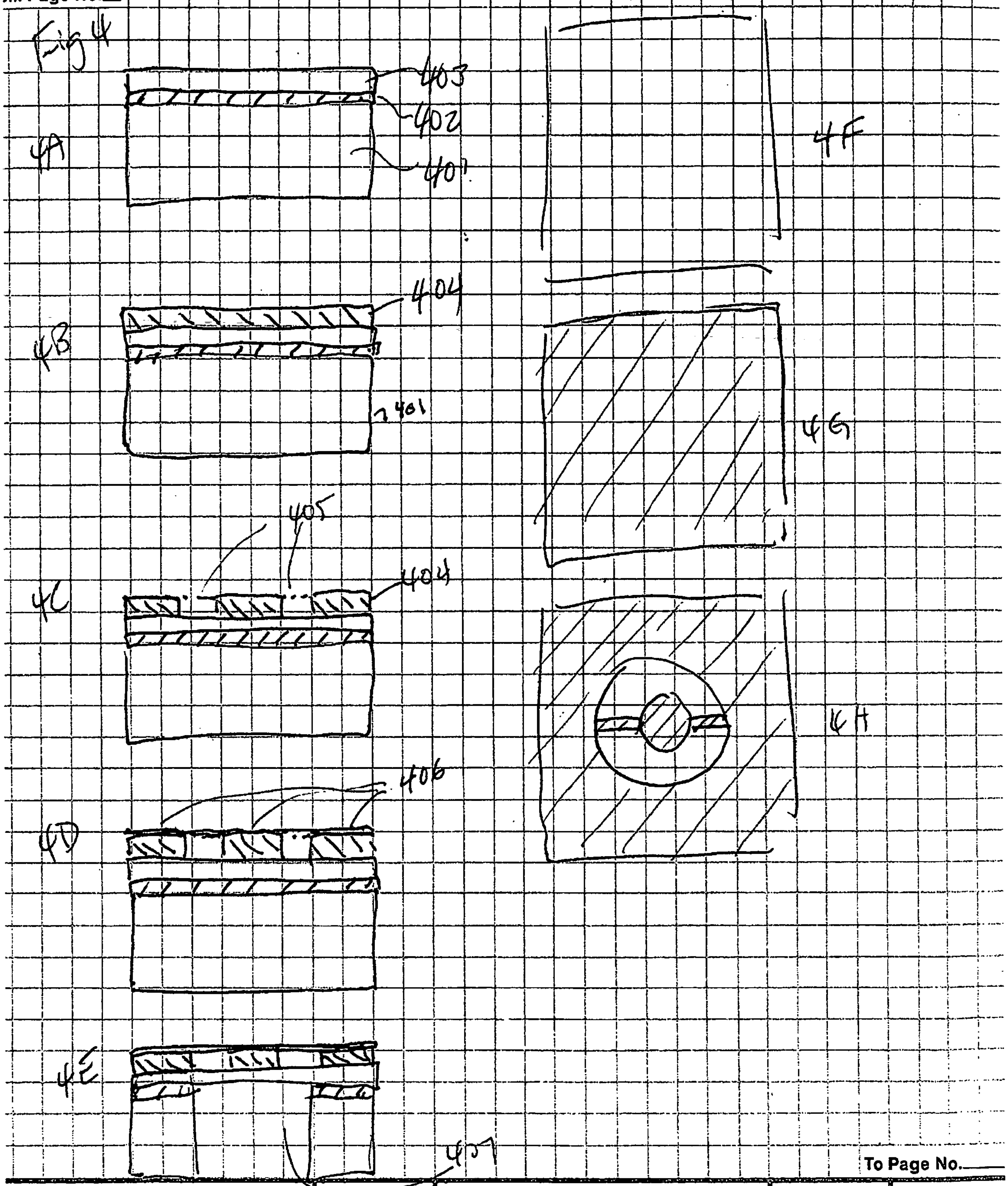

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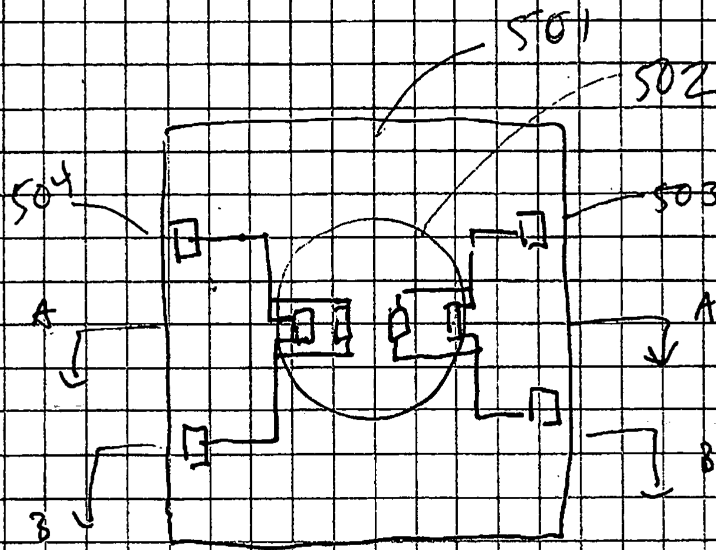
Fig 5



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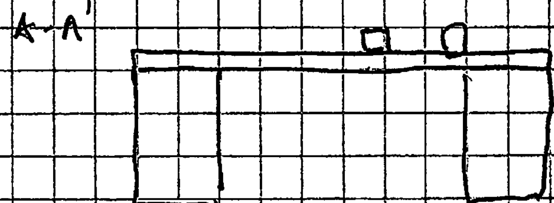

5C

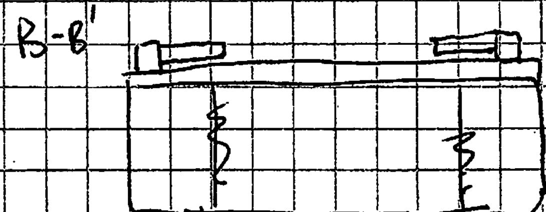

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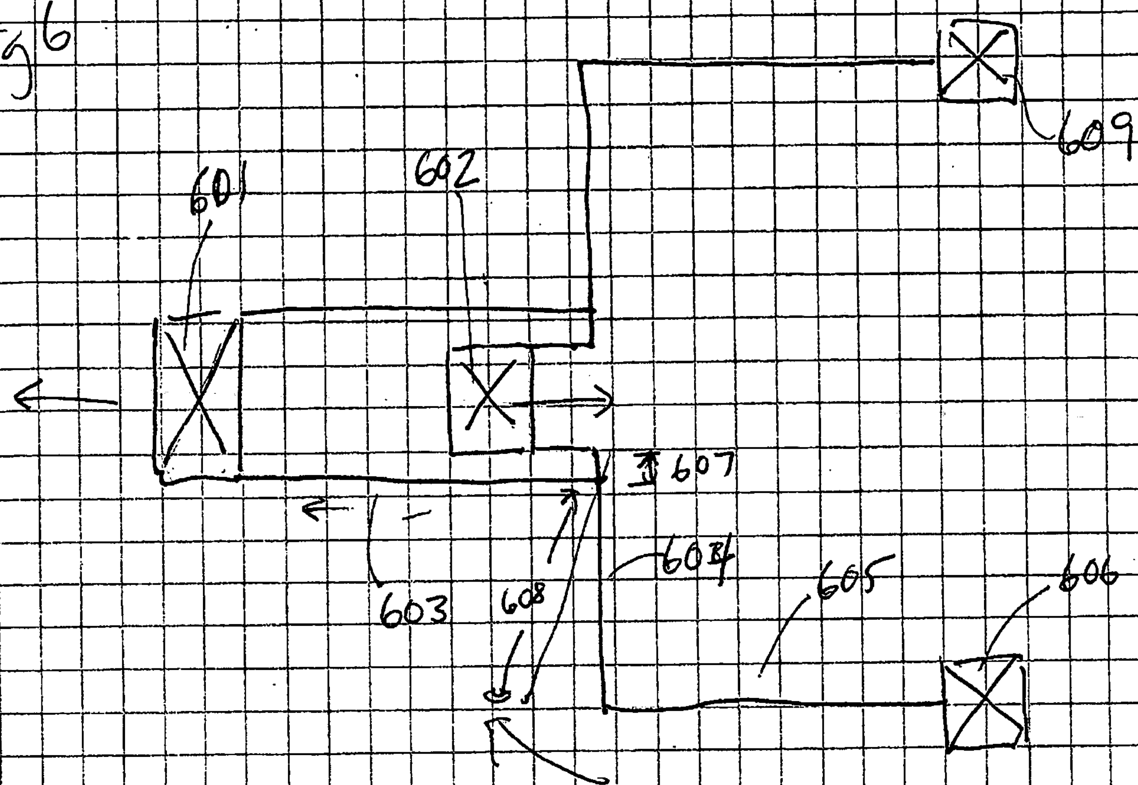
Fig 6



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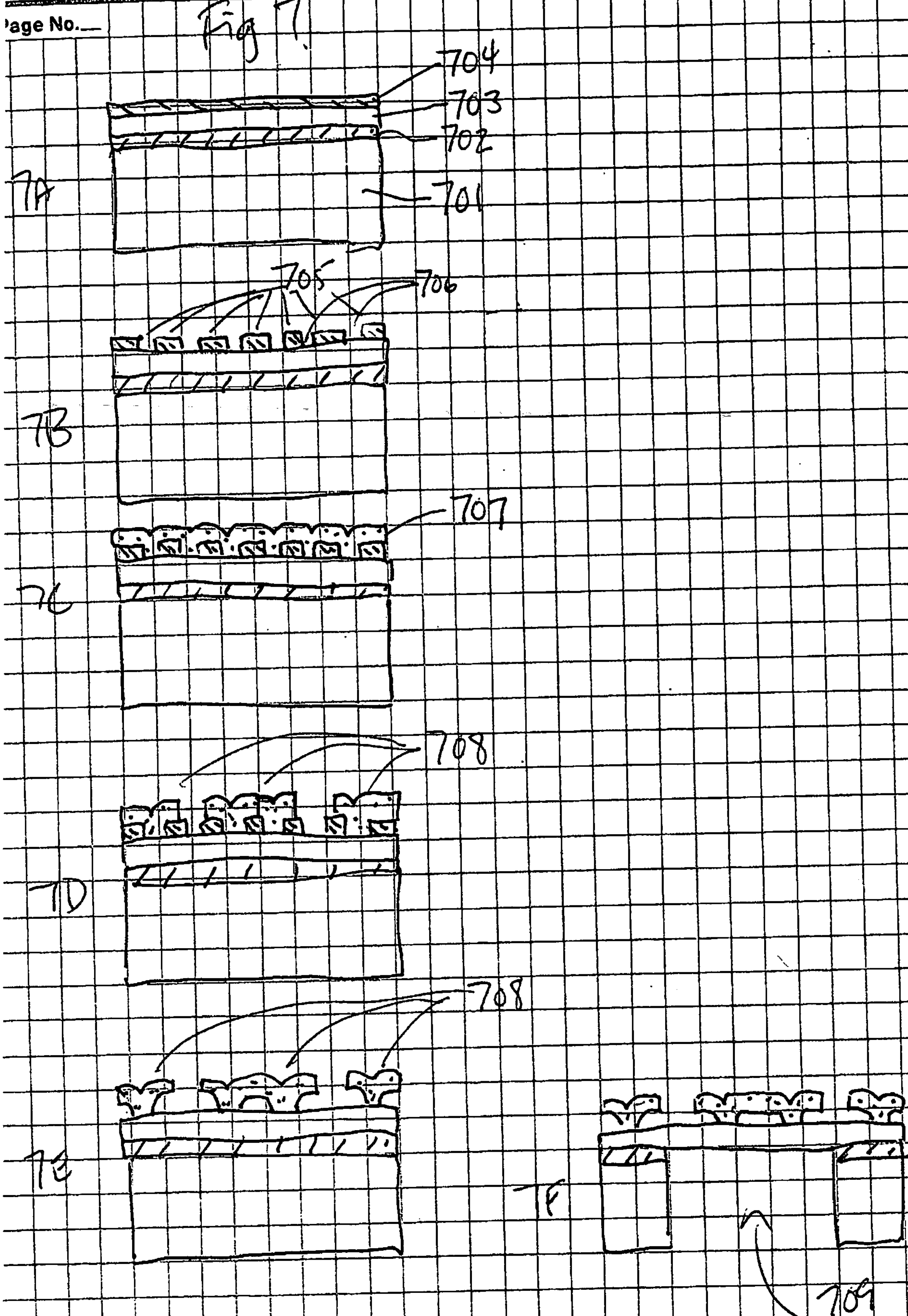

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