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PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Semiconductor Piezoresistance Device

We, TEXAS INSTRUMENTS INCORPORATED of 13500 N. Central Expressway, Dallas, Texas, United States of America, a corporation organized and existing under the Laws of the State of Delaware, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to piezoresistive elements of semiconductor material.

Piezoresistance is the name given to the property exhibited by certain materials wherein the resistivity of the material changes with applied stress. The applied stress may be produced by either tension, shear, or compression forces. Most materials exhibit this property to some degree.

In order to provide an electrical indication of a mechanical force, instruments such as strain gauges, accelerometers, and many other types of transducers utilize materials exhibiting the property of piezoresistance by detecting the change in resistance produced by the application of force in a suitable electrical circuit.

The piezoresistive element that has been most widely used and accepted until comparatively recently is the very thin metallic wire such as is used in wire strain gauges and strain gauge transducers. However, the thin wire transducers cannot provide the sensitivity desired for many applications because the piezoresistance effect in metals is relatively small.

A study of the literature reveals that the piezoresistance effect in certain semiconductor materials is almost two orders of magnitude greater than that of the materials commonly used in wire strain gauges. Because of the great apparent increase in sensitivity that could be obtained if semiconductor strain gauges were utilized, attention was soon given to semiconductor strain gauges, and at the present time several types of silicon strain gauges are commercially available. It is noteworthy that in addition to the high sensitivity available, other characteristics can be designed into transducers based on piezoresistance of semiconductor materials such as small size, low impedance, high dynamic range, and wide frequency response. Also, such devices have an inherent dc response.

In any type of transducer the material must be stressed to near its elastic limit, taking into account an appropriate factor of safety, to achieve a maximum output signal since the piezoresistance effect in a member is proportional to stress. This can be accomplished with applied forces of practical magnitude by reducing the cross-sectional area to as small a dimension as possible and/or by the use of mechanical amplification of the applied forces.

Thus, one type of prior art semiconductor strain gauge utilizes extremely small bars or whiskers of semiconductor material. Although transducers made in this manner exhibit the desired sensitivity and other advantages mentioned above, they are extremely fragile because semiconductor materials are of a crystalline structure and very brittle.

In an effort to increase the ruggedness of the units, but retain the high sensitivity still another form of force-sensitive element has been devised wherein two layers of semiconductor material are cemented on opposite sides of a layer of insulating material. The assembly is supported at one end and the other end is subjected to forces tending to flex the layers so that the opposite surfaces are stressed in opposite directions.

When the layers are incorporated into the respective arms of a bridge circuit having a bias source across one diagonal, a change in voltage is produced across the other diagonal

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of the bridge in response to a change in the applied force. The change in voltage is caused by the change in the resistance of the layers produced by the piezoresistance effect. The resistance of one layer will increase while the resistance of the other layer will decrease.

In this type of force-sensitive element, very small semiconductor elements may be used as the layer of insulating material provides some mechanical support. However, the laminated type arrangement is subject to certain disadvantages in that the strength of the cement used limits the usefulness of the device by its tendency to creep under high stress resulting in hysteresis, and also limits the capability of the unit to operate under extreme temperature conditions.

It is usually desirable that the resistance of the piezoresistance elements be between 100 and 1000 ohm for compatability with the accompanying instrumentation. The literature also indicates that when using semiconductor material for piezoresistance elements, it may be desirable to use very low resistivity material in order that the resistivity of the element and the piezoresistive effect of the element may be made less temperature dependent. To reduce temperature dependence, resistivities of less than 0.01 ohm-centimetres, and preferably in the order of 0.001 ohm-centimetres, are desired. If material of very low resistivity is used, the cross-sectional area and length must be small in order that the desired resistance may be obtained.

Although the use of low resistivity material reduces the temperature dependence of the element, it also reduces the gauge factor. In many applications, either the ambient temperature range may be relatively narrow or temperature compensation may be available, allowing the use of higher resistivity material to achieve maximum sensitivity.

As was mentioned before, most materials exhibit the piezoresistance effect to varying degrees. If single crystal semiconductor materials are utilized as the piezoresistive element, not only is the particular semiconductor material important, but also the conductivity type and the crystal plane to which the stress is applied is important. Thus, the gauge factor, usually noted by the symbol π, is a large positive value if p-type silicon is utilized and the stress is in the [111] crystal direction (normal to the (111) plane). On the other hand, if n-type silicon is used, the gauge factor has a negative sign and is the maximum when the stress is in the [100] direction (normal to the (100) plane). The gauge factor is greatest when the stress is applied in the [111] direction in germanium for either type conductivity, and, in this direction, is positive for p-type and negative for n-type materials. The gauge factor may be different in sign as well as magnitude if the element is of another semiconductor material or different conductivity, or if the force is applied in the direction of a different crystal plane. Regarding the above discussion, by positive gauge factor it is meant that the resistivity increases as the tension on the sample increases and by a negative gauge factor it is meant that the resistivity decreases as the tension on the sample increases.

The present invention is an improvement over the prior art devices in that it provides a piezoresistive element in which the ruggedness of elements of large cross-section is obtained while achieving values of maximum stress of the order of those obtained by the prior art devices of extremely small cross-sectional area. This is obtained without the limitations imposed by the prior art devices utilizing cement or other means for bonding the semiconductive elements to a mechanically strong substrate.

The present invention is a piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type, another portion of said member being a long, narrow, thin volume of semiconductor material of different electrical property than the material forming the major portion of the member, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

The present invention is also a piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type and of high resistivity, another portion of said member being a long, narrow, thin volume of semiconductor material of the one conductivity type and low resistivity, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

The present invention is also a piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type, another portion of said member being a long, narrow, thin volume of semiconductor material of opposite conductivity type than the material forming the major portion of the member, means to bias reversely the junction between the major and minor portions of the member, and means to hold the member in a position which is suitable for the application of stress, producing forces to the member.

The present invention is also a piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type, another portion of said member being a long, narrow, thin volume of semiconductor material of different electrical property than the material forming the major portion of the member, and a support rigidly affixed to said semiconductor member at one end, whereby said semicon-

ductor member is in cantilever relationship to said support.

By forming the active force-sensitive regions on opposite sides of the semiconductive substrate in which stresses are obtained by flexing the substrate, a degree of temperature compensation is obtained as the change in resistance for tensional forces is of opposite sign from that for compressional forces. The difference in sign of the changes in resistance contribute to sensitivity as a greater degree of unbalance is obtained. The same effect can be obtained where the element is subjected to pure tension or compression in a further embodiment wherein regions having both positive and negative gauge factors are provided in one element.

It is therefore one object of this invention to provide a very sensitive piezoresistive semiconductor element of rugged construction.

The invention will now be described, by way of example, with reference to the accompanying drawings, wherein like reference numerals denote like parts and in which:—

Fig. 1 is a plan view of a transducer utilizing a piezoresistive element according to the present invention;

Figure 2 is a view in cross-section taken along line 2—2 of Figure 1;

Figure 3 shows a bridge circuit utilizing the piezoresistive elements according to the invention and which can be used to provide an indication of applied force;

Figure 4 is a curve illustrating the manner in which the output the bridge circuit shown in Figure 3 varies responsive to changes in force applied to the piezoresistive element;

Figure 5 illustrates an accelerometer with the cover broken away, using another embodiment of piezoresistive element of this invention;

Figure 6 is a view partially in cross-section taken along line 6—6 of Figure 5;

Figure 7 is a perspective view of a force-sensitive element similar to that shown in Figure 5 that illustrates the manner in which special geometric configurations can be used to achieve particular characteristics;

Figure 8 is a view in cross-section, similar to that of Figure 6, that illustrates another embodiment of the present invention wherein double diffusion techniques are utilized to produce an improved transducer element; and

Figure 9 shows one manner in which the transducer element of Figure 8 can be connected into a bridge circuit to provide an indication of the applied force.

Returning now to the drawings, and more particularly to Figure 1, there is shown a transducer of the cantilever type utilizing two piezoresistive elements as the forcesensitive elements. It comprises a base 1 which can be made of plastic, metal, or any other suitable material capable of supporting the elements and the force producing means. Two piezoresistive elements 2 and 3 are anchored to the base 1. Supported at the other end of the elements 2 and 3 is a mass 4 which may be of brass or any other suitable material. A pair of leads 5 are attached to the upper and lower surfaces of each of the piezoresistive elements.

As can best be seen by reference to Figure 2, the piezoresistive element comprises a bar having main body or main portion 6 of one conductivity type material. Thin diffused layers 7 and 8 are formed in the upper and lower surfaces of the piezoresistive elements 2 and 3, and so form relatively long narrow thin volumes of semiconductor material of different electrical property. If the base 1 or mass 4 are of conductive material means should be provided to prevent shorting the layers 7 and 8 together.

According to one specific example, the bars 2 and 3 were each of p-type conductivity material in which the resistivity varied from 18 to 47 ohm-cm. as the bars were flexed. The bars were 1.3 inches long by 0.045 inches wide by 0.020 inches thick. Each had a diffused layer on the upper and lower surface.

The $\rho\rho$ junction depth was 8.9 microns. The sheet resistance of the diffused layers averaged 60 ohms per square. The calculated surface concentration was 5×10^{18} atoms per cubic cm. Gallium was the diffusant. The bars 2 and 3, the base 1, and the mass 4 were assembled. In this instance the mass weighed 7.09 grams. When assembled, the distance between the mass and the base was 1.00 inch. Contact was made to the diffused layers by leads 5 as shown. The leads 5 were attached approximately 1/16 inch and 1/2inch from the base 1. The resistances of the four active force-sensitive areas 30, 31, 32 and 33 (area 33 is opposite area 32 and not visible) defined by the leads 5 were, respectively, 694 ohms, 700 ohms, 689 ohms, and 689 ohms.

The active force-sensitive areas were then connected to form a bridge circuit as shown in Figure 3. The bridge circuit is biased by the voltage source V_b which is applied across one diagonal of the bridge and the voltage E_o obtained across the other diagonal provides an indication of the force applied to the strained members. The bridge was balanced initially by positioning the transducer so that the elements 2 and 3 are in alignment with the local gravitational field. In this position, the stresses in the diffused regions 7 and 8 should be equal and therefore should not produce any unbalance in the bridge. Using the above described elements, the bridge balanced within 1% without trimming using a bias voltage V_b of 0.503 volts. In some instances it may be necessary to connect variable resistances, not shown, in the arms of

the bridge to obtain an exact electrical balance.

After the bridge was balanced, the transducer was subjected to different acceleration forces. As a result of these forces the mass 4 caused the elements 2 and 3 to flex. Positive accelerations caused the elements to flex downward causing the diffused layer 7 to be in tension and the diffused layer 8 to be in compression. Negative accelerations caused the elements to flex upward producing tension in layer 8 and compression in layer 7. As a result of stresses produced in the force-sensitive areas, the resistance of each of the four elements changed causing the bridge circuit to become unbalanced. The output voltage E_o is indicative of the force applied.

Figure 4 is a curve showing the manner in which the output voltage E_o varied as a result of the application of different forces. It is seen that relatively high output voltages can be obtained as a result of small forces even if the bias voltage is small.

A material which is preferred for use in this embodiment of the present invention is p-type silicon with the longitudinal axis of the beam in the directional normal to the (111) plane as this material has the highest presently known gauge factor when used in this manner. However, factors other than sensitivity may make the use of other materials and crystalline orientations preferable.

If the beams 2 and 3 are of very high resistivity material, some degree of electrical isolation between the active areas on each beam can be achieved at low temperatures by making the diffused layers 7 and 8 of very low resistivity, such as by diffusion of the same conductivity type material.

Greatly improved isolation can be obtained if the active force-sensitive regions are of opposite conductivity-type material thereby forming a p—n junction which electrically isolates the active force-sensitive regions from the main bulk of the beam. If p—n junctions are used for electrical isolation, the bulk material may be of either high or low resistivity although the high resistivity bulk material will provide better isolation. In any event, the best isolation is provided by a p—n junction that is back-biased in a manner well known in the art.

The beam may be of constant cross-sectional area as shown or a constant strength beam can be used. Although a constant cross-sectional area beam is easier to fabricate, the average stress obtainable in the active or sensitive areas is less than can be obtained using a constant strength beam.

The accelerometer shown in Figure 5 utilizes such a constant strength beam. It comprises a rigid hollow casing of metal or plastic having a top wall 11 and a bottom wall 12 connected at one end by a thick wall member 13. The front wall of the casing is slotted to provide upper and lower spaced flange portions 14 and 15 extending toward each other. The inner surface of the rear wall 13 is provided with a transversely extending groove 16 in alignment with the transverse opening in the front wall formed by the spaced flanges 14 and 15, the groove having a smaller height dimension than the front wall opening and being centrally positioned with respect thereto.

The piezoresistance element depicted in Figure 5 comprises a substrate 17 of semiconductor material in the form of a flat bar or slab that is formed to define a constant strength beam in which the stress at any point in a plane parallel to the upper and lower surfaces is the same. The substrate 17 forms the major portion of a semiconductor member. The substrate is firmly secured in the groove 16 of the rear wall 13 by cement or is otherwise firmly clamped therein. The free end of the substrate 17 may be provided with a mass 18 and extends into the space between the opposing flanges 14 and 15 which are spaced apart sufficiently to allow vertical movement of the substrate and its mass and form stops to prevent movement thereof beyond its elastic limit.

Regions 20 and 21, of which only 20 is shown in Figure 5, are formed in the upper and lower surfaces of the substrate 17. The regions 20 and 21 define the active force-sensitive areas in the piezoresistive element, and form other portions of the semiconductor member. These regions may be better seen by reference to Figure 6, and comprise relatively long, narrow, thin volumes of semiconductor material of different electrical property. Leads 22 and 24 are connected to the regions 20 and 21, respectively, and provide a means for monitoring the changes in resistance of the active force-sensitive areas produced by flexing of the beam 17. Thus, for example, when the beam 17 is subjected to a force causing it to flex downward, the active force sensitive area 20 is subjected to tension and the active force sensitive area 21 is subjected to compression. Assuming that the semiconductor material being used has a positive gauge factor, the resistivity of the region 10 would increase while the resistivity of the region 11 would decrease.

The resistance of the active regions can be controlled over a wide range, even though the regions are of extremely low resistivity, without resort to the use of long filaments of very small cross-sectional area with the inherent disadvantages of brittleness and easy fracture under relatively low magnitudes of force. This can be effected by using very thin regions and shaping the regions by using well known masking and/or etching techniques. The active area may be of many configurations, such as is illustrated in Figure

7, to increase the resistance or obtain special characteristics.

Figure 8 of the drawings illustrates still another embodiment of the invention wherein four active strain-sensitive regions are formed in one semiconductive substrate. According to this embodiment, a preferred material for the substrate is p-type conductivity germanium with the longitudinal axis of the substrate in the [111] direction. Regions 42 and 44 are formed by the diffusion of n-type impurity materials into the p-type substrate 40. The regions 46 and 48 are then formed by the diffusion of p-type impurities into the n-type regions 42 and 44. Suitable leads may then be attached for making ohmic contact to the regions as required.

The diffused regions 42, 44, 46, and 48 can then be connected to form the four branches of a bridge circuit as shown in Figure 9. As is mentioned previously the n-type germanium has a negative gauge factor and the p-type germanium has a positive gauge factor. Thus, when the p-type region 46 and n-type region 42 are subjected to tension, the resistance of the p-type region 46 will increase whereas the resistance of the n-type region 42 will decrease. Conversely, when the n-type region 44 and p-type region 48 are subjected to compression, the resistance of the n-type region 44 will increase whereas the resistance of the p-type region 48 will decrease. The result of the change in resistance of the strain-sensitive areas is to produce unbalance in the bridge circuit. The bridge circuit of Figure 5 is biased with a bias-potential V_b and the amount of unbalance is indicated by the meter 50. Obviously the meter 50 may be calibrated to give a direct indication of the amount of force applied to the member 40. This type element is especially useful in those applications where the element is subjected to forces that produce only tension or compression.

The invention has been described with regard to certain specific embodiments, but many modifications would be obvious to one skilled in the art. For example, materials other than germanium or silicon could be used. Many circuits other than the one shown may be used for detecting changes in resistivity. The diffusion steps mentioned in regard to the embodiment shown in Figure 8 could be performed separately or simultaneous diffusion of two impurities could be utilized. Although the strain-sensitive areas as described have been produced by diffusion of appropriate impurity materials other means such as epitaxial growth could be used for producing the active strain sensitive areas. Rod type elements in which shear type stresses are produced by torsional forces may be used. Thus, other materials for providing piezoresistive elements in accordance with the teaching of this invention and modifications in the structure of such elements may occur to persons skilled in the art without departing from the scope of the invention which is defined in the appended claims.

WHAT WE CLAIM IS:—

1. A piezoresistance element comprising a semi-conductor member, the major portion of said member being of one conductivity type, another portion of said member being a long, narrow, thin volume of semiconductor material of different electrical property than the material forming the major portion of the member, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

2. A piezoresistance element according to claim 1, in which said different electrical property is manifest by an opposite conductivity type for the material of the long, narrow, thin volume.

3. A piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type and of high resistivity, another portion of said member being a long, narrow, thin volume of semiconductr material of the one conductivity type and low resistivity, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

4. A piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type, another portion of said member being a long, narrow, thin volume of semiconductor material of opposite conductivity type than the material forming the major portion of the member, means to bias reversely the junction between the major and minor portions of the member, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

5. A piezoresistance element according to any of the preceding claims, in which the electrical conductivity type and resistivity of the long, narrow, thin volume are substantially determined by impurities diffused therein.

6. A piezoresistance element according to any of the preceding claims, including ohmic connections to the long, narrow, thin volume at or near the extremities of the length thereof.

7. A piezoresistance element according to any of the preceding claims in which there is included a second long, narrow, thin volume of semiconductor material.

8. A piezoresistance element according to claim 7 in which said second volume is complementary to the other or first volume and is positioned in said member such that when said member is flexed in a predetermined direction, the resistance of one of the volumes increases while the other decreases.

7, to increase the resistance or obtain special characteristics.

Figure 8 of the drawings illustrates still another embodiment of the invention wherein four active strain-sensitive regions are formed in one semiconductive substrate. According to this embodiment, a preferred material for the substrate is p-type conductivity germanium with the longitudinal axis of the substrate in the [111] direction. Regions 42 and 44 are formed by the diffusion of n-type impurity materials into the p-type substrate 40. The regions 46 and 48 are then formed by the diffusion of p-type impurities into the n-type regions 42 and 44. Suitable leads may then be attached for making ohmic contact to the regions as required.

The diffused regions 42, 44, 46, and 48 can then be connected to form the four branches of a bridge circuit as shown in Figure 9. As is mentioned previously the n-type germanium has a negative gauge factor and the p-type germanium has a positive gauge factor. Thus, when the p-type region 46 and n-type region 42 are subjected to tension, the resistance of the p-type region 46 will increase whereas the resistance of the n-type region 42 will decrease. Conversely, when the n-type region 44 and p-type region 48 are subjected to compression, the resistance of the n-type region 44 will increase whereas the resistance of the p-type region 48 will decrease. The result of the change in resistance of the strain-sensitive areas is to produce unbalance in the bridge circuit. The bridge circuit of Figure 5 is biased with a bias-potential V_b and the amount of unbalance is indicated by the meter 50. Obviously the meter 50 may be calibrated to give a direct indication of the amount of force applied to the member 40. This type element is especially useful in those applications where the element is subjected to forces that produce only tension or compression.

The invention has been described with regard to certain specific embodiments, but many modifications would be obvious to one skilled in the art. For example, materials other than germanium or silicon could be used. Many circuits other than the one shown may be used for detecting changes in resistivity. The diffusion steps mentioned in regard to the embodiment shown in Figure 8 could be performed separately or simultaneous diffusion of two impurities could be utilized. Although the strain-sensitive areas as described have been produced by diffusion of appropriate impurity materials other means such as epitaxial growth could be used for producing the active strain sensitive areas. Rod type elements in which shear type stresses are produced by torsional forces may be used. Thus, other materials for providing piezoresistive elements in accordance with the teaching of this invention and modifications in the structure of such elements may occur to persons skilled in the art without departing from the scope of the invention which is defined in the appended claims.

WHAT WE CLAIM IS:—

1. A piezoresistance element comprising a semi-conductor member, the major portion of said member being of one conductivity type, another portion of said member being a long, narrow, thin volume of semiconductor material of different electrical property than the material forming the major portion of the member, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

2. A piezoresistance element according to claim 1, in which said different electrical property is manifest by an opposite conductivity type for the material of the long, narrow, thin volume.

3. A piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type and of high resistivity, another portion of said member being a long, narrow, thin volume of semiconductr material of the one conductivity type and low resistivity, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

4. A piezoresistance element comprising a semiconductor member, the major portion of said member being of one conductivity type, another portion of said member being a long, narrow, thin volume of semiconductor material of opposite conductivity type than the material forming the major portion of the member, means to bias reversely the junction between the major and minor portions of the member, and means to hold the member in a position which is suitable for the application of stress-producing forces to the member.

5. A piezoresistance element according to any of the preceding claims, in which the electrical conductivity type and resistivity of the long, narrow, thin volume are substantially determined by impurities diffused therein.

6. A piezoresistance element according to any of the preceding claims, including ohmic connections to the long, narrow, thin volume at or near the extremities of the length thereof.

7. A piezoresistance element according to any of the preceding claims in which there is included a second long, narrow, thin volume of semiconductor material.

8. A piezoresistance element according to claim 7 in which said second volume is complementary to the other or first volume and is positioned in said member such that when said member is flexed in a predetermined direction, the resistance of one of the volumes increases while the other decreases.

* C L M S *

9. A piezoresistance element according to any of the preceding claims in which the means to hold the member is a support rigidly affixed to said member at one end, whereby said member is in cantilever relationship to said support.

10. A piezoresistance element according to any of the preceding claims in which said semiconductor member is essentially rectangular in shape, with its length substantially greater than its width or thickness.

11. A piezoresistance element according to claims 9, in which the width of the member diminishes along its length in such manner that when a flexing load is applied to the non-supported end, the stress within said member is substantially constant along its length.

12. A piezoresistance element according to any of the preceding claims in which said semiconductor member is of silicon.

13. A piezoresistance element according to any of claims 1 to 11, in which said semiconductor member is of germanium.

14. A piezoresistance element substantially as hereinbefore described in conjunction with Figs. 1 and 2, Figs. 5 and 6, Fig. 7, or Fig. 8 of the accompanying drawings.

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