SEMICONDUCTIVE PIEZORESISTIVE TRANSDUCER HAVING
A GROOVED SUPPORT WITH ELECTRICAL CONTACTS

Filed Dec. 29, 1964 3 Sheets-Sheet 1

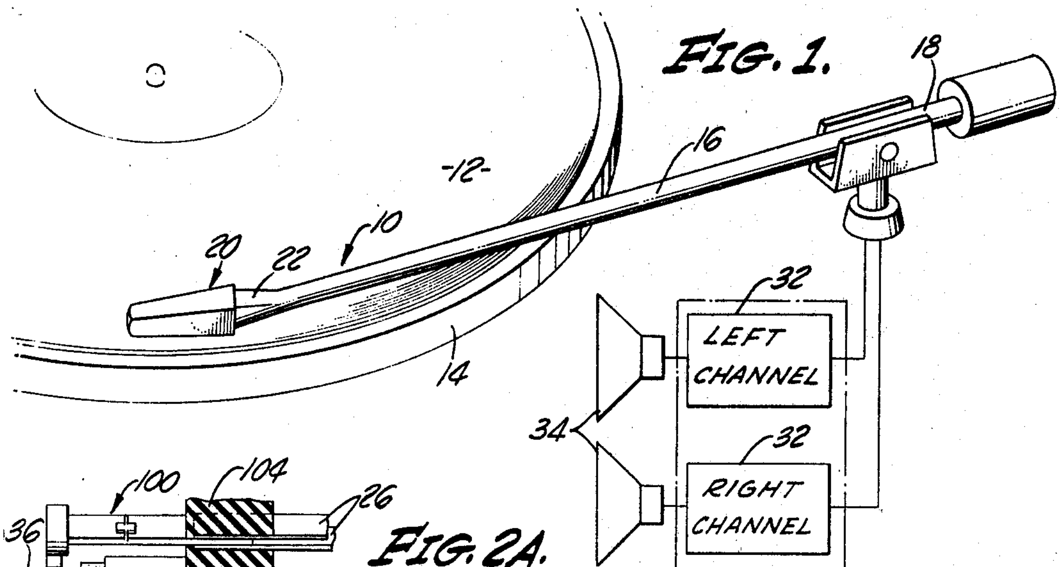


FIG. 1.

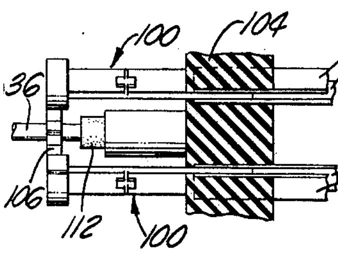


FIG. 2A.

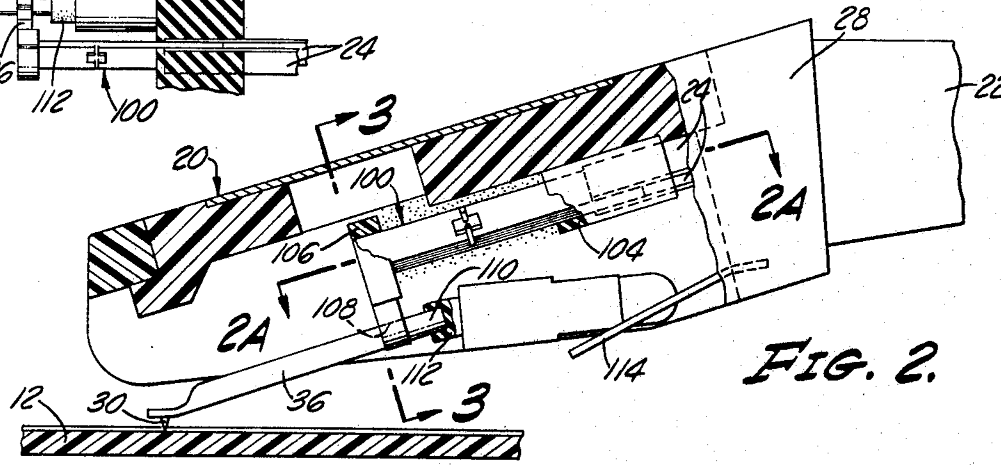
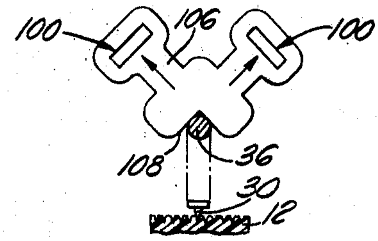


FIG. 2.

FIG. 3.



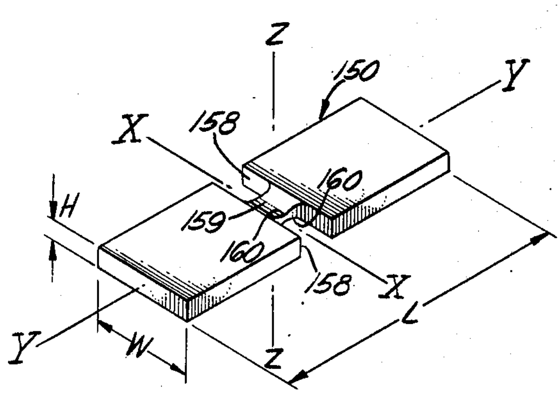


FIG. 4.

LESLIE B. WILNER
INVENTOR.

BY Reed C. Lawlor
ATTORNEY

FIG. 5.

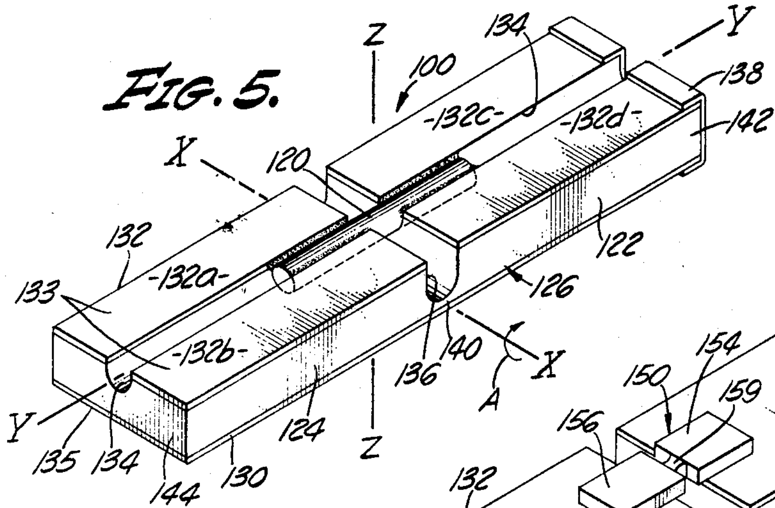


FIG. 6.

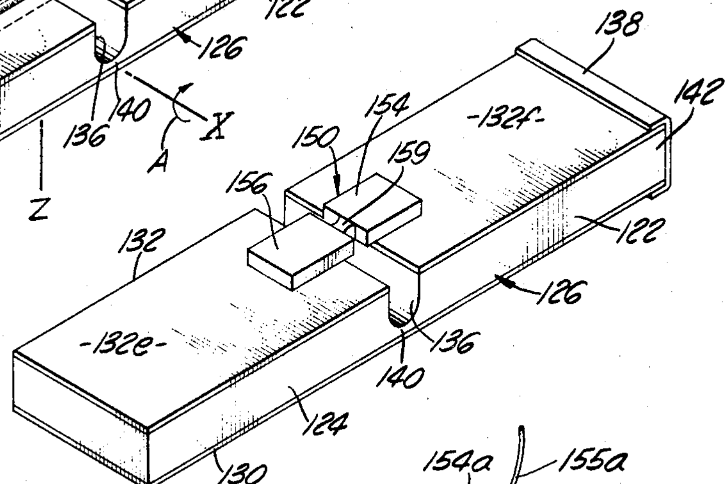
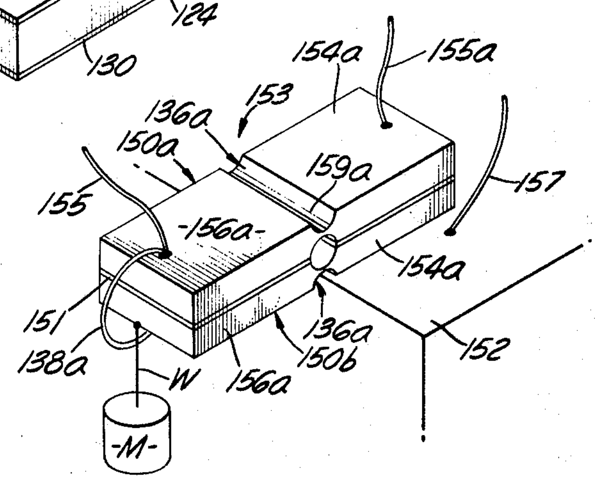


FIG. 8.



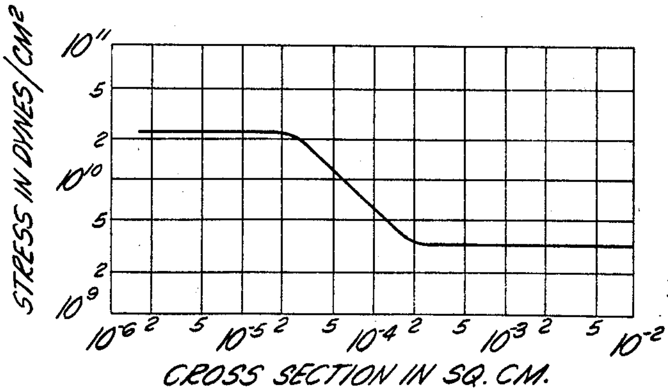


FIG. 13.

LESLIE B. WILNER
INVENTOR.

BY Reed C. Lawlor
ATTORNEY

March 17, 1970 L. B. WILNER 3,501,732
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FIG. 7.

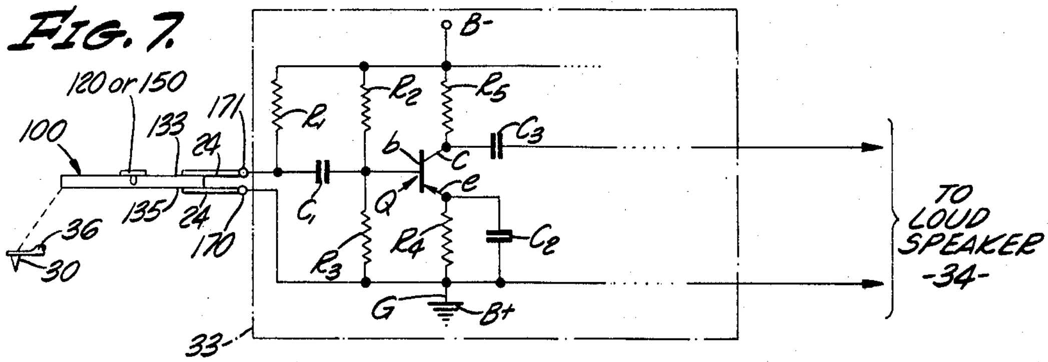


FIG. 9.

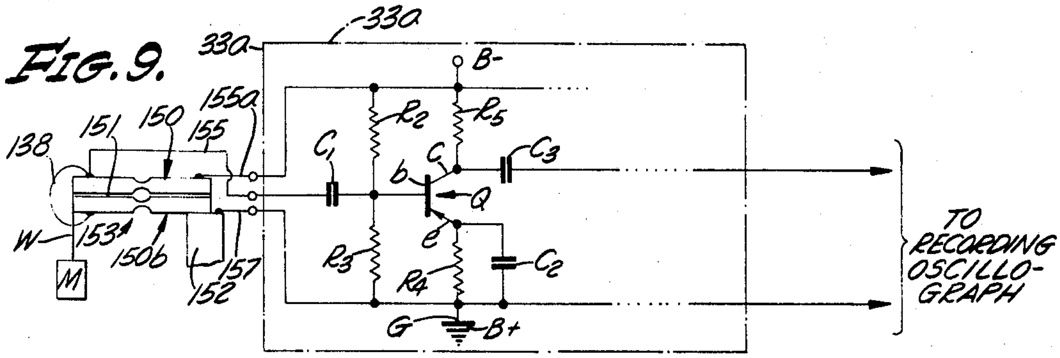


FIG. 10.

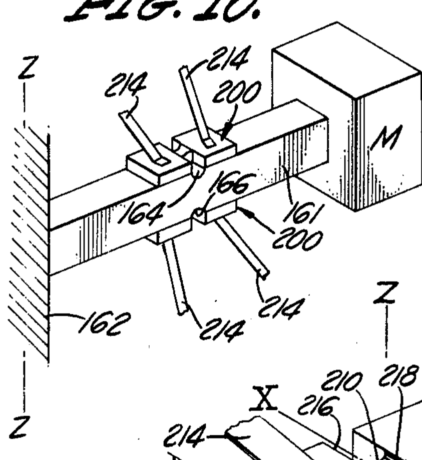
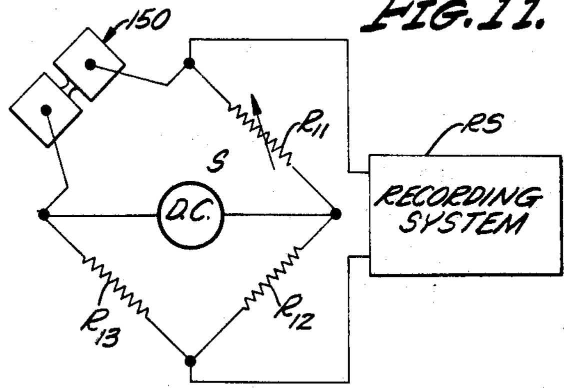


FIG. 11.



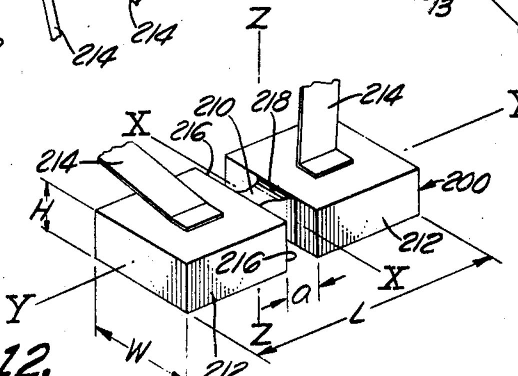


FIG. 12.

LESLIE B. WILNER
INVENTOR.

BY Reed C. Lawlor
ATTORNEY

United States Patent Office 3,501,732
Patented Mar. 17, 1970

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3,501,732 SEMICONDUCTIVE PIEZORESISTIVE TRANSDUCER HAVING A GROOVED SUPPORT WITH ELECTRICAL CONTACTS

Leslie B. Wilner, Palo Alto, Calif., assignor to Endevco Corporation, Pasadena, Calif., a corporation of California

Continuation-in-part of application Ser. No. 364,673, May 4, 1964. This application Dec. 29, 1964, Ser. No. 421,869
Int. Cl. G01l *1/22;* G04r *21/04*
U.S. Cl. 338—2 12 Claims

ABSTRACT OF THE DISCLOSURE

An electromechanical transducer is provided in which a piezoresistive element is mounted across the gap formed by two support members connected by a leaf spring that serves as a hinge. The ends of the support members are enlarged while the neck is reduced in size providing concentration of motion in the neck, where the electrical resistance per unit length is highest but the mechanical strain per unit angular displacement of the hinged elements is greatest.

This application is a continuation-in-part of my prior patent application Ser. No. 364,673, that was filed May 4, 1964, which is now Patent No. 3,351,880.

This invention relates to improvements in electromechanical transducers and more particularly to transducers employing a piezoresistive element for converting vibrations into electrical signals. The invention is particularly applicable to phonograph record pickups, microphones, and accelerometers. Because of the importance of its application to phonographs, that is, record players, the invention will be described primarily in connection therewith.

At the present time phonograph record pickups generally employ electromechanical transducers that are based upon piezoelectric effects and electromagnetic effects. In piezoelectric transducers, movement of the needle in a phonograph record groove causes pressure to be applied to a piezoelectric element which generates an electric signal that varies in amplitude and frequency in accordance with the changes in shape of the waves or undulations in the surface of the record groove. With electromagnetic pickups, similar signals are produced by movement of a ferromagnetic element, usually one of "soft" ferromagnetic properties, thus changing the reluctance in a magnetic path. Piezoelectric transducer elements form high-impedance capacitive elements. For this reason, they are best suited for use with vacuum tube circuits. Electromagnetic pickups have best response when feeding signals into a high-impedance load. For this reason, they too are most suitably used with vacuum tube circuits. Their response, however, is notoriously low and their frequency responses erratic. For best effects, both of these types of transducers commonly employ a preamplifier both to amplify the small signal generated and to provide an electrical impedance match between the pickup or transducer element and the electrical amplifier which is employed to drive a loudspeaker for producing the sound originally recorded in the groove of the record.

Both types of pickups now commonly used, that is, both piezoelectric pickups and electromagnetic pickups, suffer from the disadvantage that they possess low sensitivity at low frequencies. This requires base-compensation in the amplifier that is employed between the pickup and the loudspeaker. Both also suffer from the disadvantage that the preamplifiers which are ordinarily employed by them introduce noise, in addition to whatever noise is produced by the phonograph record itself or by the transducer element.

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Furthermore, in both systems the electrical power generated by the action of the record on the pickup is limited by the capability of the piezoelectric element or the electromagnetic element to generate electrical signals in response to mechanical movements of parts thereof.

Accordingly, it is an object of the present invention to provide an improved transducer element for phonograph record reproduction which is capable of producing at the pickup itself a greater amount of electrical power than is attainable with piezoelectric pickups and electromagnetic pickups that are commonly in use.

It is also an object of the present invention to provide a pickup which has a high response at low frequencies as well as at high frequencies, thus making it possible to reduce the need for base amplification to compensate for inherently poor low-frequency response of the pickup.

It is also an object of the present invention to provide a phonograph pickup which makes it possible to eliminate the need for preamplifiers.

Another object of the invention is to provide a phonograph pickup which is of low cost so that the combined cost of a phonograph pickup and amplifier of a phonograph is reduced.

Still another object of the invention is to provide a phonograph pickup that has a low electrical impedance so that it may be connected directly to an amplifier having a low input impedance.

In the transducer of this invention, an electrosensitive, or piezosensitive, unit is provided that employs a stiff piezoresistive element bonded to two support arms which are hinged together to provide a mechanical advantage so that a force applied to the end of one arm produces an amplified force on the piezoresistive element, thus increasing the strain of the piezoresistive element. In the application the term electrosensitive or piezosensitive element means one which has a measurable or detectable electrical property which is modified in magnitude in accordance with the stress applied to the stress to which the element is subjected. One of the arms rotates about the other about a hinge joining the arms. Thus a base member is provided that employs two hinged arms which are angularly displaceable or deflectable relative to each other about the hinge to apply a strain to the piezoresistive element having ends that are rigidly secured to the respective arms. In this transducer an electric current flows through the piezoresistive element to provide a source of energy thus making it unnecessary to rely entirely on the mechanical energy supplied by a moving record to provide the electric energy at the output of the transducer. The magnitude or amplitude of this current is modified in accordance with the strain of the piezoresistive element and hence in accordance with the movement of the end of the arm to which the driving force is applied. Such a transducer element may be made very small and is, therefore, easily installed in a phonograph cartridge. The electrosensitive element is so constructed that the hinge portion thereof has such a low torsion constant relative to that associated with the piezoresistive element that the torsion constant thus introduced by the hinge does not substantially reduce the strain produced in the piezoresistive element when the base is bent about the hinge.

Numerous other features are embodied in the electrosensitive element of this invention to maintain light weight, small size, low manufacturing cost, and high reliability, all set forth hereinafter.

This invention is applicable not only to phonograph pickups, but also to other types of devices which are employed for detecting and measuring displacements, movements, and forces of all kinds.

The foregoing and other objects, features, and advantages of the invention will be understood more fully from the following specification describing several embodiments of the invention taken in connection with the accompanying drawings wherein:

In the drawings:

FIGURE 1 is principally a perspective view of a record player with a phonograph pickup unit connected diagrammatically with amplifiers and loudspeakers;

FIG. 2 is a vertical sectional view through the pickup head of FIG. 1;

FIG. 2A is a fragmentary sectional detail taken on the line 2A—2A of FIG. 2;

FIG. 3 is a detailed elevational view principally on the line 3—3 of FIG. 2 indicating the location of two electrosensitive units employed relative to the phonograph needle;

FIG. 4 is a detailed perspective view of a piezoresistive element of this invention;

FIG. 5 is a perspective view showing an electrosensitive unit employing a piezoresistive filament;

FIG. 6 is a view similar to that of FIG. 5 wherein the piezoresistive element is in the form of two spaced pads integrally connected by an Euler column;

FIG. 7 is a wiring diagram showing electrical connections of the unit of FIG. 5 into the circuit of a phonograph pickup and an amplifier;

FIG. 8 is a perspective view showing two connected piezoresistive elements similar to that of FIG. 5 connected back-to-back for use in an accelerometer;

FIG. 9 is a wiring diagram showing the connection of the unit of FIG. 8 into an accelerometer circuit with an amplifier;

FIG. 10 is a perspective view showing another accelerometer using this invention;

FIG. 11 is a wiring diagram of a recording system for the device of FIG. 10;

FIG. 12 is a perspective detail showing of a piezoresistive element of FIG. 10; and

FIG. 13 is a graph representing the variation of yield strength with cross-sectional area of a thin silicon rod.

By way of background there is shown in FIGS. 1 and 2 a record player having a phonograph pickup unit **10** for reproducing signals that have been recorded as mechanical waves or undulations in the spiral groove of a phonograph record **12**. To reproduce those sounds, the record **12** is rotated beneath the pickup unit by a motor-driven turntable **14**. The pickup **10** includes a tone arm **16** which is pivoted at one end **18** and which carries a transducer cartridge **20** at the other end **22**. The cartridge includes a pair of electromechanical transducer units as described below for converting the undulations or waves in the surface of the groove into electrical undulations or waves representative of the sound originally recorded on the record.

As indicated in FIG. 2 the cartridge **20** is provided with a plurality, in this case, four, electrical terminals **24, 24** and **26, 26** at one end thereof for insertion into a connector plug **28** mounted on the free end **22** of the tone arm **10**. A phonograph needle **30** is resiliently mounted on the cartridge **20** and is adapted to respond to the mechanical undulations in the groove of the phonograph record to generate electric signals which are applied through the two pairs of terminals **24, 24** and **26, 26** and thence through the tone arm **10** to electrical circuits **32, 32** and loudspeakers **34, 34**. For purposes of illustration, a phonograph cartridge **20** is employed that is adapted to reproduce sound in two channels from a stereophonic type record is illustrated, namely a right channel and a left channel.

The cartridge **20** is similar to one of a standard commercial construction now on the market. It includes a pair of electrosensitive units **100, 100** coupled to the

needle **30** in such a way that electrical signals are produced by these elements **100, 100** in response to movement of the photograph needle. The electric signals that are generated, appear at pairs of the cartridge terminals **24, 24** and **26, 26** as indicated in FIGS. 1 and 2. More particularly, the two electrosensitive units **100, 100** are in the form of flat bar-shaped elements which are arranged in planes at 90° with respect to each other and forming angles of 45° with the vertical plane, which in turn is perpendicular to the horizontal plane in which the phonograph record rotates beneath the cartridge. This arrangement is provided so that one of the electrosensitive units generates signals corresponding to mechanical undulations recorded on one sloping side of the record groove and the other electrosensitive unit generates signals corresponding to mechanical undulations recorded on the other sloping side of the record groove. The one reproduces sounds from one area or position, and the other sounds from another area or position.

The two electrosensitive units **100, 100** are snugly mounted in slots **102, 102** arranged at 90° relative to each other within two embedment blocks **104, 104** suitably supported in the cartridge. One pair of the electric terminals **24, 24** make connection with electrodes to be described later on opposite faces of one of the electrosensitive nuits and the remaining pair of electric terminals **26, 26** make connection with electrodes to be described later on opposite faces of the other electrosensitive unit. The ends of the electrosensitive units so embedded are relatively stationary, thus being, in effect, pivoted in the embedment blocks.

The remaining ends of the electrosensitive units snugly fit within slots in a rubber yoke or saddle **106**. The yoke **106** is provided with an inclined groove **108** on the lower side thereof.

The phonograph needle **30** itself is mounted at the distal end of a needle arm **36** of circular configuration which snugly fits within the groove **108** of the yoke **107**. The end **110** of the needle arm remote from the needle **30** is embedded within a resilient rubber support **112** which forms a universal joint about which the needle arm can rotate under the influence of the undulations of the groove as the groove is advanced beneath the needle.

The subassembly that includes the needle arm **36**, the yoke **107**, and the joint **112** is held in place within the cartridge by means of a clamp **114**.

In accordance with this invention, an improved electrosensitive transducer, employing a piezoresistive element, is provided which makes it possible to employ simpler less expensive amplifiers than are currently in use and which also improves the operation of a record player in other ways.

One form of the electrosensitive unit **100**, as shown in FIG. 5 employs a piezoresistive filament **120**, which in this case is of uniform circular cross section and which is anchored to separate arms **122, 124** of a notched support member **126**. The width of the gap or cross slot **136** between the arms **122** and **124** and hence the length of the filament **120** between the arms is sufficiently short so that, in the range of movement involved, the filament can be extended and compressed without buckling. In the best mode of practicing the invention, the dimensions of the filament are such that it is nonbuckling under all possible compressive loads, that is, the dimensions are such that the active or free portion of the filament that is subjected to strain has the properties of an Euler column.

The support member or base **126** of the electrosensitive unit of FIG. 5 is formed of a laminated sheet that consists of a central body or substrate **144** composed of insulating material sandwiched between two layers or sheets **130** and **132** of conductive material such as copper. In a practical embodiment of the invention, the support bar has a length of 0.4″, a width of 0.06″, and a thickness of 0.02″, and the diameter of the filament is less than about 0.01″.

The upper surface is grooved lengthwise to a depth sufficient to enable the resultant shallow groove **134** to receive and support the ends of the filament **120**. For this purpose, the depth and width of the upper groove is about equal to the diameter, or other average transverse dimension, of the filament.

To provide two support arms **122** and **124**, support bar **126** is cut crosswise midway of its length to form a deep gap **136**. The groove **134** and the gap or cross slot **136** cut the upper metal sheet **132** into four separate segments **132***a*, **132***b*, **132***c*, and **132***d*. The lower metal sheet remains intact. In this process a maximum amount of the thickness of the substrate material is removed in forming the groove **136** for reasons explained below. The width of the slot **136** in the direction of the length of the bar is 0.010″. The copper sheets **130** and **132** have a thickness in the range of 0.0005″ to 0.003″, in the present case being only about 0.0013″.

The cross slot is cut by some suitable mechanical means, such as by means of a diamond saw. The insulating material forming the substrate or intermediate layer of the laminate is preferably an epoxy board made with a fiberglass base which is resistant to deformation or destruction at temperatures at which soldering is performed. Such laminates are commonly used for printed circuits in the electronic fields.

The filament, which may have a total length of about 0.1″ to 0.2″, is supported firmly in the groove by soldering the ends to the segments **132***a*, **132***b*, **132***c*, and **132***d* of the metallic sheet at the upper surface of the support. Usually indium solder is employed for this purpose since it has a low soldering temperature. One end **142** of the bar is coated with the metallic material in order to provide an electrical jumper **138** to connect the upper metal segments **132***c*, **132***d* at that end of the bar **126** with the lower metallic sheet **130**. The filament is further supported in the grooves with epoxy cement for added strength.

The two segments **132***a* and **132***b* at the end **144** of the support bar **126** remote from the jumpered end **142** form one electrical terminal, or electrode, **133** and one end of the other layer **130** at that end **144** forms a second electrical terminal, or electrode, **135** of the electrosensitive unit. The two terminals **133** and **135** are thus electrically connected to opposite ends of the filament. In this way, an electrosensitive unit **100** is formed which is extremely compact and simple and rugged in construction, and which is provided with two relatively pivotable arms **122** and **124** by a Cardan, that is leaf-spring, hinge **140** at the lower end thereof and which is provided with a piezoresistive element **120** that is subjected to strain in accordance with the relative rotation of the two arms.

In effect, the support bar **126** constitutes a beam that is narrowed at its center to provide a central hinge. When this beam is in use, it acts in a cantilever manner.

In another embodiment of the invention illustrated in FIG. 6, no longitudinal groove **134** is formed along the upper surface of the electrosensitive unit. Except for the absence of the groove **134** the support bar **126** of FIG. 6 is substantially the same as that of FIG. 5. In this case, the upper electrode **132** is divided crosswise by the slot **136** into two segments **132***e* and **132***f*. In the embodiment of the invention illustrated in FIG. 6, the piezoresistive element is of flat hourglass configuration, being provided with a reduced neck between two flat pads **154** and **156**. The pads are soldered to the metal segments **132***e* and **132***f* on opposite sides of the transverse slot **136** as shown in FIG. 6.

A piezoresistive element **150** of this type may be formed of a piezoresistive sheet having a thickness of 0.005″ and a length of 0.075″. The reduced neck is formed by etching on the sides thereof slots **158** and **158** that have widths of 0.008″ and etching grooves **160** and **160** in the top and bottom surfaces thereof. The reduced neck, which thus forms an Euler column **159**, has a thickness of about 0.007″ at the thinnest point in a horizontal direction and

a thickness at the thinnest point of about 0.001″ in a vertical direction. The cross section is not square but more or less of oval configuration. A piezoresitive element of this type has been more fully described and claimed in the aforesaid Patent No. 3,351,880.

Either of the electrosensitive units of FIG. 5 and FIG. 6 may be employed in the cartridge of FIGS. 1 and 2. In either event, one member of one pair of the cartridge terminals **24, 24** is pressed by one embedment block **104** against the upper electrode **133** and the other terminal is pressed against the lower electrode **135** of the electrosensitive element **100** embedded in that block. The end **144** of the electrosensitive unit that bears the electrodes **133** and **135** is thus anchored in the embedment block **104** between the electrodes. The other end of each electrosensitive element **100**, that is, the end remote from the embedment block, is free to rotate about its Cardan hinge **140** as indicated by the curved arrow A of FIG. 5. A reduced movement occurs between the upper ends of the cross slot **136** causing the piezoresistive element mounted between the opposite edges of this slot to be subjected to strain by alternate extension and compression, as the free end **142** of the electrosensitive unit **100** vibrates under the influence of the needle in the groove of the rotating phonograph record.

High efficiency of energy generation is obtained by employing a Cardan hinge which has a very low torsion constant compared with that provided by the piezoresistive element. By this is meant that the force required to produce a given displacement of the free end **142**, if a piezoresistive element were removed, would be very small compared with the force required to produce that same displacement with the piezoresistive element in place. To this end, substantially all of the substrate material forming the core of the laminate is removed at the hinge leaving substantially only the thin metallic sheet **130** joining the two support blocks **122** and **124**. The axis of rotation is located substantially at the hinge **140** itself thus producing only a very minute torsion constant. In practice, a somewhat larger torsion constant than that provided by the copper sheet **130** itself can be withstood such as by leaving a small amount of the substrate in position at the bottom of the slot thereby giving some support to the Cardan hinge, while still maintaining the torsion constant of the Cardan hinge about the axis of rotation less than about 5% of the torsion constant produced by the piezoresistive element itself. The Cardan hinge provides the electrosensitive unit with only very little stiffness about the vibration axis X—X and also provides the unit with substantial rigidity about the neutral axis Z—Z and an intermediate stiffness against bending about the axis Y—Y.

The free end **142** of the electrosensitive unit vibrates around a vibration axis X—X which is parallel to the slot **136**, thus causing the piezoresistive element to extend and compress along a strain axis Y—Y which is parallel to the length of the support. Very little movement, however, can occur around the neutral axis Z—Z which is perpendicular to the two aforementioned axes.

As indicated above, one of the electrosensitive units **100** responds to undulations on one side of the record groove while the other electrosensitive unit **100** responds to undulations on the other side of the record groove. The signals produced by the two piezoresistive elements are applied through the pairs of terminals **22, 22** to corresponding inputs of two amplifiers employed to reproduce the sound record stereophonically.

As indicated in FIG. 7, the terminals **133** and **135** of each of the electrosensitive units **100** is connected through the cartridge terminals **24, 24** between a pair of input terminals **170** and **171** of the amplifier **33**. The input stage of this amplifier includes a transistor Q which may be connected as indicated to the electrosensitive unit **100**. In this particular amplifier, one of the electrodes **133** of the unit **100** is connected through a bleeder resistor R_1 to a negative voltage at the terminal B— of the voltage supply and the other terminal **135** is connected to ground G which in turn is connected to the positive terminal B+ of a voltage supply. With this arrangement, an electric current flows through the piezoresistive element **120** or **150** as the case may be. This current varies in a manner corresponding to that of the undulations on the phonograph record. The variable electrical signals so produced are applied to the base *b* of the transistor Q through the coupling capacitor C_1.

A voltage divider network comprising resistors R_2 and R_3 are connected between the negative terminal B— and ground G, the junction between the two resistors being connected to the base *b*. A feedback, or emitter follower, resistor R_4 is connected between ground G and the emitter *e* in parallel with the capacitor C_2. A collector load resistor R_5 is connected between the collector *c* of the transistor Q and the negative terminal B—.

Commonly the input resistance of such a transistor amplifier may be easily established at a value of several hundred to several thousand ohms. The dynamic resistance of the piezoresistive elements **120** or **150** described herein is about 1,000 ohms but can have other values within a wide range. It is thus an easy matter to match the effective input resistance of the amplifier **33** with the effective resistance of the piezoresistive element.

The amplifier **33** includes other stages and various filters and volume control elements as required to provide electric signals at its output for feeding to a loudspeaker.

In order to minimize low frequency noise, the current flowing through the piezoresistive elements is maintained sufficiently low so that the temperature of the thin portion or neck of the piezoresistive element will not vary in temperature to such a large extent that the resistance changes simply because of changes in temperature. For instance, with the piezoresistive elements illustrated in FIGS. 5 and 6, a current of about 5 to 15 milliamperes is suitable.

Electrosensitive units employing piezoresistive elements of the type employed in this invention respond to very low frequency signals as well as to high frequency signals. Experience has shown that with this invention the electrical energy at 50 cps. may be as much as 100 times greater with conventional transducers employing piezoelectric elements and 10,000 times greater than with transducers employing variable reluctance elements. By virtue of this fact, base compensation or other frequency compensation may be more easily attained with a phonograph record pickup made in accordance with this invention than with others commonly used. Other advantages involve the fact that the need for preamplifiers to produce electrical impedance matching is avoided thus reducing the overall cost of a phonograph record player.

By virtue of the physical properties of the piezoresistive element and the leverage mechanism for transmitting froce thereto from the groove of a phonograph record, it is relatively easy to obtain a match of mechanical impedance. This makes possible efficient transfer of energy from the moving phonograph record to the piezoresistive element. By virtue of this fact and the further fact that the piezoresistive element has a high gauge factor, it becomes possible to produce relatively high electrical signals at the output of the electrosensitive unit. In practice, with this invention, it has been found that it is feasible to obtain excellent reproduction of sound from a phonograph record even though the downward force of the phonograph needle on the record is only one-half of a gram. Accordingly, with this invention, phonograph records attain greater longevity.

The invention may also be employed in many other forms than that described above and may be employed for other purposes than for reproducing sounds from phonograph records.

For example, FIGS. 8 and 10 illustrate simple accelerometers employing the invention. The accelerometer of

FIG. 8 employs two piezoresistive elements **150*a*** and **150*b*** bonded together back-to-back by means of an electrically non-conductive bonding layer **151**.

Here, the pad **154*a*** of one of the piezoresistive elements, such as **150*b***, is supported on an object **152** that is subjected to acceleration and the other pad **156*a*** extends beyond the support **152** and supports at its outer end a mass M by means of a flexible wire W or other connector. With this arrangement, in effect, each of the piezoresistive elements acts as a Cardan hinge with respect to the other. Each of the elements is compliant about the axis of rotation X—X but is stiff about the neutral axis Z—Z, that is, the axis parallel to the direction in which the force is applied to the end of the articulated beam to cause the free part thereof to rotate about the hinge relative to the anchored or stationary part thereof. By making the Euler column portions **159*a*** very wide, as well as thin, throughout substantially the overall width of each element, sufficient strength is imparted so that each portion **159*a*** itself serves as a Cardan hinge. In the arrangement shown, each wide portion **159*a*** thus serves as the hinge for the other element.

In effect, an electrosensitive dual unit **153** is provided, as shown in FIG. 8, which comprises a pair of the piezoresistive elements **150** of FIG. 6 secured together back-to-back with the mentioned bonding layer **151**.

The dual unit **153** so formed is provided with an electrical jumper wire **138*a*** at the outer end of the assembly. It is also provided at its mounted end with leads **155** and **155*a*** which, together with a lead **157** on the support **152**, are connectable to a bridge circuit within the amplifier **33*a*** as indicated in FIG. 9. This circuit includes a transistor Q having a base *b*, a collector *c* and an emitter *e*. The lead **155** is connected to the base *b* through the coupling capacitor C_1. The lead **155*a*** is connected to a negative voltage at the terminal B— of the voltage supply and the lead **157** is connected to the ground G which in turn is connected to the positive terminal B+ of the voltage supply. The signals produced are applied to the base *b* of the transistor Q through the capacitor C_1.

A voltage divider network comprising resistors R_2 and R_3 are connected between the negative terminal B— and ground G, the junction between the two resistors being connected to the base *b*. A feedback, or emitter follower, resistor R_4 is connected between ground G and the emitter *e* in parallel with the capacitor C_2. A collector load resistor R_5 is connected between the collector *c* of the transistor Q and the negative terminal B—.

When the object **152** vibrates or oscillates along the neutral axis Z—Z the two piezoresistive elements **150** bend about the axis X—X of rotation in a corresponding manner. During this action, one of them is elongated while the other is compressed so that the resistance of one increases while the resistance of the other decreases. The variations in the difference in resistance of the two piezoresistive elements acts on the amplifier **33*a*** to produce a signal in its output which varies in amplitude and frequency in accordance with the amplitude and frequency of the component of acceleration of the object **152** along the axis Z—Z.

A further alternative embodiment for accelerometer use as indicated above, is illustrated in FIG. 10 to show another simple type of accelerometer making use of this invention. In this accelerometer, a mass M is fastened to one end of a flexible bar or arm **161**, the other end of which is firmly attached to an object **162**, undergoing oscillatory or other acceleration along an axis Z—Z that is perpendicular to the length of the bar **161**. In this case, assuming that the axis Z—Z is vertical, and the bar **161** has a flat upper surface, one piezoresistive element is fastened to the bar **161** on opposite sides of a groove **164** cut in the upper surface of the bar and another is fastened on opposite sides of a second groove **166** cut in the lower surface of the bar. The grooves establish a hinge at which the bending of the bar is greatest, thus increasing the sensitivity of the unit.

In this particular accelerometer, the upper piezoresistive element is extended when the lower strain piezoresistive element is compressed and is compressed when the lower piezoresistive element is extended. Thus, the resistance of one of the piezoresistive elements increases when the resistance of the other piezoresistive element decreases. The piezoresistive elements thus act as strain gauge elements.

For illustrative purposes, a bridge circuit that may be employed to record the changes in strain is illustrated in FIG. 11. There it will be noted that the strain gauge element **150** and resistances R_{11}, R_{12}, and R_{13} are connected in the four arms of the bridge. A DC signal from a source S is supplied to one diagonal of the bridge, and a recording system RS, such as a conventional amplifying system and recording oscillograph, is connected to the other diagonal of the bridge circuit. In this case, the bridge circuit may be unbalanced by manipulation of the values of the resistors such as by adjustment of a variable resistor R_{11}.

The bridge circuit of FIG. 11 may be employed to detect changes in the difference in resistance between the two piezoresistive elements of the accelerometer of FIG. 10 during measurement of acceleration. In this case also, the bridge may be unbalanced so that the polarity of the signal that is fed to the recording system remains the same regardless of the sign of the acceleration.

In the specific embodiment of the accelerometer illustrated in FIGS. 10 and 12, the piezoresistive element **200** is in the form of a very small elongated block of semiconductive material having a reduced neck or Euler column **210** of smooth hourglass configuration separating two enlarged pads **212** and having a pair of electrical leads **214** conductively bonded to the pads. The piezoresistive element illustrated in FIG. 12 is in the form of a rod or block of rectangular cross section. The element has an overall length L of 0.25 cm., overall width W of 0.13 cm. and a thickness H of 0.028 cm. The pads are of square configuration as viewed from the top, being about 0.13 cm. on each side. The reduced neck is formed by means of a pair of opposed notches **216** that lie on opposite sides thereof and by a second pair of notches or grooves **218** on the upper and lower sides thereof. The notches **216** have semicylindrical surfaces at their inner ends. The radii of these surfaces is about 0.03 cm. The notches **218** are cut to a depth of about 0.007 cm. As a result, the reduced neck has a cross section of about 0.015 cm. x 0.015 cm., the smallest section having an area of about 0.0002 $cm.^2$. The neck is very nearly of square cross section, but is slightly rounded at the edges by chemical etching. The neck is joined by outwardly flaring portions that connect the neck to the pads by means of smooth curves. The piezoresistive element has been more fully described and claimed in the aforesaid Patent No. 3,351,880.

In effect, the portion **210** of the piezoresistive element of FIG. 12, that lies between the pads, is an Euler column of stubby smooth hourglass configuration that is free of any lateral support. The length a of the neck, that is, the distance between the pads, is somewhat greater than the minimum thickness of the neck, that is, the thickness at its narrowest portion. In any event, the length of the neck is less than the length (about three or four times the minimum thickness of the neck) which could result in buckling.

The entire element is in the form of an Euler column, though this is not always essential to the operation. In other words, in the embodiment of the invention illustrated, if longitudinal compressive forces are applied along the longitudinal axis Y—Y of the element, the element would not bend or buckle but would gradually enlarge or thicken at the neck until it is crushed. While buckling could occur if the element were of great length so that, in effect, the element would be a rod or bar, still the portion of the element between the pads could be considered as having the properties of an Euler column when viewed in terms of forces applied to the element at the portions of the pads nearest the neck. The piezoresistive element is symmetrical about its central axis Y—Y, being symmetrical about two mutually perpendicular planes that pass therethrough. With this arrangement, the neck is concentric with the central axis Y—Y and lies midway between the lateral edges and surfaces of the pads.

The importance of employing a reduced neck that is non-buckling lies in the fact that with such a neck the piezoresistive element may be compresed up to the crushing point without buckling. This facilitates response of compression-like strains as well as tension-like strains over a large range of strain without biasing the unit with a static tension force. This, in effect, doubles the range of strain to which the element can be subjected without a biasing force.

Various kinds of piezoresistive material may be employed in the piezoresistive elements of this invention. The most satisfactory materials are semiconductor materials, such as silicon that has been doped with a small proportion of boron. Other suitable materals include suitably doped germanium, silicon carbide, and gallium arsenide. A material having a resistivity of 3 ohm-cm. at room temperature while the material is not subject to strain has proved to be very satisfactory. With such a material, the strain gauge element having the dimensions described above has a resistance of about 350 ohms. This value of resistance makes the piezoresistive element very satisfactory for use as a strain gauge for many reasons which are well known. For one thing, the resistance is sufficiently low to avoid excessive pickup of stray signals induced from power lines and the like, but is sufficiently large to facilitate matching with other resistors in a bridge circuit or otherwise matching impedances of an amplifying system, especially if they be of the solid-state type. Generally, a resistance between 10 ohms and 3000 ohms is readily attained and is satisfactory.

Such a piezoresistive element has a high gauge factor and still does not exhibit extreme changes in characteristics as a result of electrical heating in spite of the fact that the active, that is strain-sensitive, part thereof is not intimately bonded to the object undergoing test.

The maximum positive strain, or elongation, that can be detected depends upon the yield strength of the material, that is, the yield point of the strain gauge element when stretched. The maximum negative strain, or compression, that can be detected depends upon the maximum load which can be withstood by the piezoresistive element without crushing. Measurements of this resistance change are facilitated by the fact that large currents can be carried through the neck of the piezoresistive element without overheating. In practice, it is found that changes in resistance of $\pm 20\%$ occur over the range of strain which can be measured without danger of damage to the strain sensitive element. In fact, a resistance change of 45% may occur before fracture. With small cross-sectional areas in the fibre range, changes in resistance of $\pm 60\%$ have been observed before fracture.

The sensitivity of a piezoresistive element depends upon the direction in which the strain is applied relative to axes of the crystal structure. In the case of silicon, maximum sensitivity is obtained in the **[111]** direction. For this reason, the strain gauge element is made with the strain axis Y—Y along the **[111]** direction of the crystal. For best results, the piezoresistive element is formed of a single crystal.

The piezoresistive element **150** of FIG. 4 is of a construction and composition very similar to that of the piezoresistive element **200** of FIG. 12. However, it employs a neck of reduced cross section for reasons explained below. The piezoresistive element **120** of FIG. 5 may also have such a reduced cross section. In the best mode of practicing the invention, the piezoresitive elements are such construction or are so supported that the active portion thereof which is subjected to strain constitutes an Euler column. By employing a very small cross-sectional area in the fibre range, the effective electrical resistance of the active portion may be made higher. At the same time, advantage may be taken of anomolous phenomena described below which involves an increase in the yield strength of the piezoresistive element as its cross-sectional area is reduced.

It has been found that as the cross-sectional area of the neck decreases, the yield strength (dynes/cm.^{2}) passes through an anomolous zone in which the tensile strength is substantially constant and independent of the cross-sectional area. In effect, the yield strength of the material is higher beneath that zone than above, but for some unexplained reason, varies inversely as the cross-sectional area in that zone. In the best mode in which the invention has been practiced, the cross-sectional area of the neck is such that it lies within the zone of constant tensile strength (dynes).

A graph representing the variation of yield strength with cross-sectional area of a thin rod composed of silicon is represented in FIG. 13. Here it will be noted that the yield strength modulus has a value of 3×10^{10} dynes/cm.^{2} where the cross-sectional area is about 2×10^{-5} cm.^{2} and a value of 4×10^9 dynes/cm.^{2} where the cross-sectional area is about 2×10^{-4} cm.^{2} and varies inversely as the area in the intervening region which is the zone Z of substantially constant yield force. This phenomenon is described in an article entitled, "Deformation and Fracture of Small Silicon Crystals," by G. L. Pearson, W. T. Read, Jr., and W. L. Feldman, in Actametallurgica, vol. 5, pp. 181–191, April 1957, in the case of silicon. The yield strength modulus of 4×10^9 dyne/cm.^{2} which is characteristic of large cross-sectional area rods is called the bulk value. The cross-sectional area below which the yield strength modulus increases from 4×10^9 dynes/cm.^{2} is known as the fibre range.

By establishing the cross section of the piezoresistive element in the zone of constant yield point, the upper limit of strain that can be detected without yielding is independent of the cross-sectional area and is, therefore, substantially free of variations that might otherwise arise because of variations in cross-sectional areas of various piezoresistive elements. When operating in this range, the resistance value may be chosen over a wide range of values without altering the change in yield force. Measurements of the resistance change are facilitated by the fact that large currents can be carried through the neck of the strain gauge element without overheating because of the heat absorbing effects of the enlarged pads.

In the piezoresistive element of FIGS. 5 and 6 that have so far been found most suitable for use in this invention, the minimum cross-sectional area is 5×10^{-5} cm.^{2}. This area is in the fibre range and, in fact, is in the range within which the breaking force is independent of cross-sectional area and, in fact, is near the shoulder of the tensile strength curve.

All the piezoresistive elements of this invention may be looked upon as strain-gauge elements and they may be employed for measuring steady or constant displacements instead of vibrations.

It will, of course, be understood that the invention is not limited to the exact construction described herein, but that the piezoresistive element of this invention may be embodied in many other forms and may be composed of other materials and may be incorporated in electromechanical transducers in other ways.

The invention claimed is:

1. In an electromechanical transducer element:

a hinged two-part support, each said part comprising an insulating body member, each said body member having conductors thereon at two spaced parts thereof, the conductive material on one of said body members being electrically connected together, such two parts being spaced apart and connected by mechanical

hinge means, said hinge means also electrically connecting two conductors on the respective parts; and

a semiconductive piezoresistive means electrically connecting the remaining two conductors and mechanically connecting said two parts in spaced relation from said hinge means.

2. A transducer element as in claim **1** wherein said hinge means is a Cardan hinge.

3. An electromechanical transducer as defined in claim **1** wherein said two-part support and said mechanical hinge means constitute an elongated flexural beam member having on one side thereof a recess providing on the opposite side a portion of reduced thickness constituting said hinge;

said piezoresistive element bridging said recess opposite said hinge to yield a change in electrical resistance on subjection of said beam member to a bending force about said hinge.

4. An electromechanical transducer element including:

two opposing electrically non-conductive support parts, such two parts being separated by a groove;

mechanical hinge means electrically connecting said two support parts at one side of said groove;

semiconductive piezoresistive means bridging said groove and electrically and mechanically connecting said two parts;

an electrically conductive first coating affixed to adjacent sides of said two parts opposite from said piezoresistive means and constituting a part of said hinge means;

a pair of electrically conductive coatings affixed to the respective sides of said parts connected by said piezoresistive means and electrically connected by said piezoresistive means; and

an electrically conductive jumper electrically connecting said first coating with one of said pair of coatings;

said piezoresistive means including an Euler column overlying said groove.

5. A transducer element as in claim **4** wherein said piezoresistive Euler column is a rod filament embedded in a groove in said two parts transversely of said hinge means and in electrical connection with said plural conductive coatings.

6. A transducer element as in claim **4** wherein said piezoresistive means includes spaced pads in electrical contact with said pair of coatings and a reduced neck connecting said pads and constituting said Euler column overlying the groove.

7. A piezoresistive transducer, comprising

a rectangular elongated electrically nonconductive beam,

said beam having a transverse groove therein extending inwardly from one side thereof and terminating short of the other side thereof to define a narrow integral hinge section interconnecting opposite end portions of the beam;

a first thin flat conductor overlying one end portion of the beam at said one side of the beam and having one end terminating at said groove;

a second thin flat conductor overlying the other end portion of the beam at said one side thereof and having one end terminating at said groove;

a third thin flat conductor overlying the other side of the beam with one end of the third conductor at the one end of the beam and the other end of the third conductor at the other end of the beam;

a fourth thin conductor connecting the second and third conductors at the other end of the beam;

and a piezoresistive element having the characteristic of changing in internal electrical resistance when subjected to an applied mechanical force,

said element having opposite ends secured conductively to adjacent one end of the first and second conductors,

said element having a central portion overlying said groove opposite from the hinge section of the beam and clear of both the first and second conductors, whereby said central portion of said element is compressed when said other end of the beam is pressed in one direction to flex said hinge section so that the internal resistance of said element is lowered while pressure is applied at said other end of the beam in said one direction.

8. A piezoresistive transducer as defined in claim 7 wherein said central portion of said piezoresistive element is a semiconductor element and has a smaller cross-sectional area than either of said end portions.

9. A transducer according to claim 7 further comprising electrical conductors connected to said first and third conductors at said one end of the beam for passing electric current through the conductors and piezoresistive element,

whereby said electric current increases in magnitude when pressure is applied to said other end of the beam in said one direction to lower the internal resistance of said element.

10. A piezoresistive transducer, comprising

a rectangular elongated electrically nonconductive beam,

said beam having a transverse groove therein extending inwardly from one side thereof and terminating short of the other side thereof to define a narrow integral hinge section interconnecting opposite end portions of the beam;

a first flat conductor overlying one end portion of the beam at said one side of the beam and having one end terminating at said groove;

a second flat conductor overlying the other end portion of the beam at said one side thereof and having one end terminating at said groove;

a third flat conductor overlying the other side of the beam with one end of the third conductor at the one end of the beam and the other end of the third conductor at the other end of the beam;

a fourth conductor connecting the second and third conductors at the other end of the beam;

said conductors being thin compared with said beam;

and a piezoresistive semiconductor element having end portions secured conductively to the adjacent one end of the first and second conductors,

said element having a central portion overlying said groove opposite from the hinge section of the beam and clear of both said first and second conductors,

so that said central portion is subjected to mechanical forces when the beam is bent at the hinge section to change the internal electrical resistance of said element.

11. A piezoresistive transducer as defined in claim 10 wherein said central portion of said semiconductor element has a smaller cross-sectional area than either of said end portions.

12. A piezoresistive transducer as defined in claim 11 wherein said central portion has a length which is less than the length of either end portion.

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BERNARD KONICK, Primary Examiner

R. F. CARDILLO, JR., Assistant Examiner

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