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2,866,014

PIEZORESISTIVE ACOUSTIC TRANSDUCER

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2 Sheets-Sheet 1

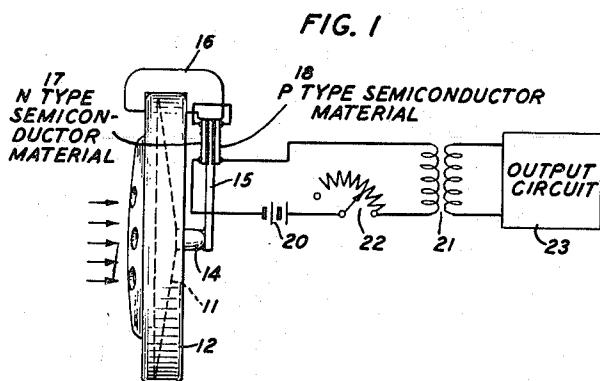
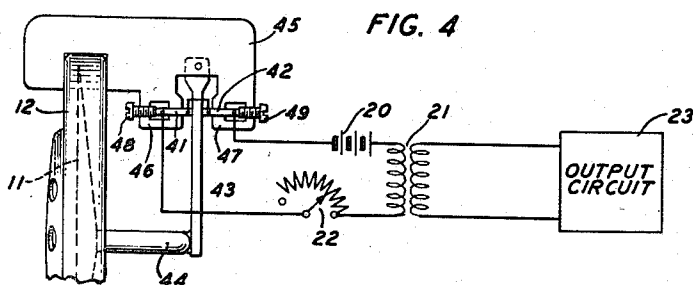
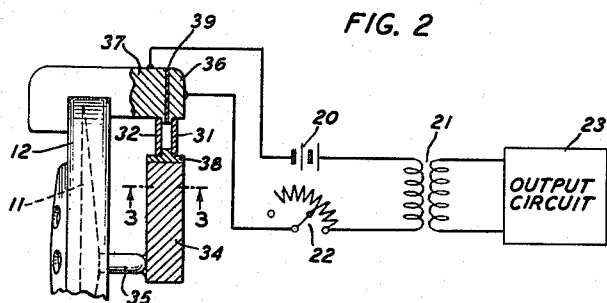
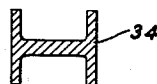


FIG. 3



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FIG. 5

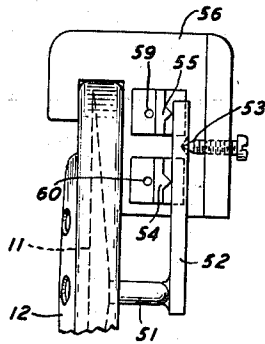


FIG. 6

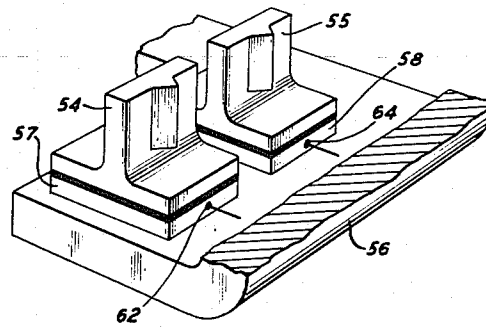


FIG. 7

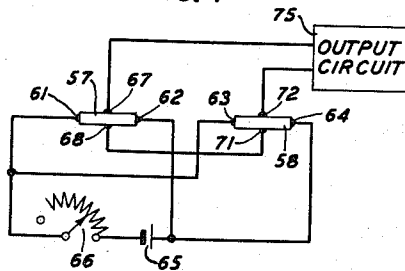


FIG. 8

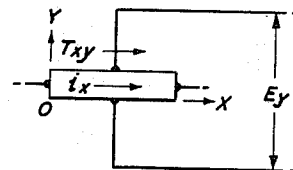
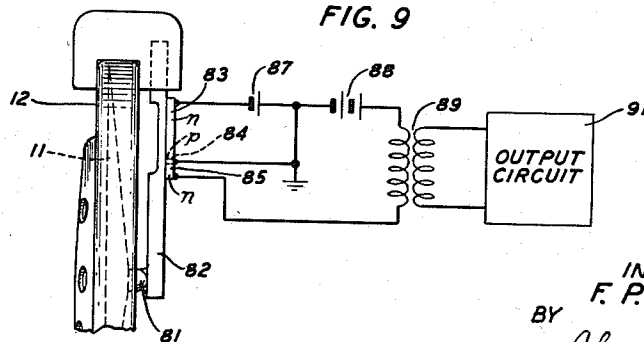


FIG. 9



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PIEZORESISTIVE ACOUSTIC TRANSDUCER

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Application October 31, 1955, Serial No. 543,860

9 Claims. (Cl. 179—110)

This invention relates to the translation of mechanical vibrations into electrical variations.

The principal object of the invention is the improvement and simplification of apparatus for transforming mechanical vibrations, such as those derived from sound waves, into electrical signals.

Many types of electro-acoustic transducers which employ pressure-sensitive resistive elements have been proposed heretofore. Of these, the best known is the carbon microphone, in which vibrations from a diaphragm are applied to carbon particles to vary their resistance. The resulting variations in the biasing current are employed to control an output circuit, such as a remote loudspeaker. However, because the change of resistance of carbon particles with displacement is nonlinear, substantial intermodulation occurs. This results in the introduction of "fuzziness" and distortion into the output signals from the transducer. In addition, the carbon microphone is sensitive to changes of position or orientation, and may also change its properties with the passage of time.

Accordingly, a specific object of the invention is to improve the quality and stability of resistance type microphones.

In accordance with the invention, mechanical vibrations are applied to single crystals of piezoresistive semiconductive material in which biasing currents are provided. In one form of the invention, acoustic vibrations and biasing currents are both directed along a selected crystal axis in which the maximum output voltage is obtained.

An important feature of the invention involves the use of at least two semi-conductive elements which are of opposite conductivity type, and which are subject to different stress conditions. This arrangement permits the use of a simple output circuit in which the piezoresistive elements are connected in series.

In accordance with another feature of the invention, the piezoresistive semiconductive material is subjected to shearing stresses, and the output voltage is derived in a direction perpendicular to the biasing current. In this embodiment, direct utilization is made of the shear coefficient of piezoresistance, which is particularly large in semiconductors.

Other objects and features and various advantages of the invention will become apparent by reference to the following description taken in connection with the following claims and the accompanying drawings forming a part thereof.

In the drawings:

Fig. 1 is an illustrative acoustic-electrical transducer in accordance with the invention, in which the piezoresistive effect in semiconductors is utilized;

Figs. 2 and 3 show an alternative arrangement in which a rigid beam is employed to couple the acoustic vibrations to the piezoresistive elements;

Fig. 4 is an embodiment of the invention in which the piezoresistive elements are mounted perpendicular to the vibrating beam;

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Figs. 5 and 6 show two views of a transducer structure in which the shear effect in semiconductor materials is employed;

Fig. 7 shows the electric circuit for the transducer of Figs. 5 and 6;

Fig. 8 is a diagram which is useful in explaining the mode of operation of the transducer structure and circuit shown in Figs. 5 through 7; and

Fig. 9 is a transducer for changing mechanical vibrations into electrical signals in which the piezoresistive element is a transistor.

Referring more particularly to the drawings, Fig. 1 shows, by way of example, a transducer utilizing the piezoresistive effect in which sound energy is converted into electrical vibrations. In Fig. 1, a diaphragm 11 is mounted in a frame 12, and has a mechanical coupling member 14 secured to its center. A flexible cantilever beam 15 is secured to the frame 12 by the clamp 16. Elongated elements 17 and 18 of N-type and P-type germanium, respectively, are secured to opposite sides of the beam 15. As sound energy is applied to the diaphragm 11, the beam 15 is strained, principally near the clamp 16. When the beam 15 bends, one of the germanium elements is compressed, while the other is extended.

As disclosed in an article entitled "Piezoresistance Effect in Germanium and Silicon," by C. S. Smith, Physical Review, vol. 94, pages 42 through 49, April 1, 1954, semiconductor material undergoes substantial changes in resistance with applied stress. When N-type germanium is compressed, its resistance increases while the extension of N-type germanium decreases its resistance. P-type germanium reacts in the opposite manner to applied stress, however, and compression and expansion have the effect of decreasing and increasing its resistance, respectively.

Thus, for example, when the diaphragm 11 moves to the right, the P-type germanium element 18 is compressed and the N-type germanium element 17 is extended. Under these circumstances, the resistance of both elements is decreased. Observing the circuit of Fig. 1, it may be noted that the semiconductor elements 17 and 18 are connected in series with the potential source 20 and the primary winding of a transformer 21. Accordingly, the increased resistance of both elements when the lower end of the beam 15 is deflected to the right increases the current flowing in the primary of the transformer 21. Similarly, when the flexible beam 15 is deflected to the left, resistance of both semiconductor elements is increased, and current flow in the primary of transformer 21 is decreased. The variations in current flow in the primary of the transformer 21 therefore follow the variations in position of the beam 15; and the audio frequency electrical signals supplied to the output circuit 23 are a faithful reproduction of the acoustic energy applied to the diaphragm 11. For completeness, it may be noted that the biasing current for elements 17, 18 may be controlled or turned off by the combined switch and potentiometer 22. In addition, the output circuit 23 may include suitable amplification means and a utilization circuit such as a remote loudspeaker.

By the use of N-type and P-type semiconductive elements on opposite sides of the beam 15, a cumulative piezoresistive effect is obtained, despite the opposed stresses on the two elements. This serves to increase the output power of the transducer, while retaining the simple series output circuit arrangement which is possible when a single variable resistance unit is employed.

The remaining Figs. 2 through 9 of the drawings show other embodiments of piezoresistive transducers. In each case however, a diaphragm 11, a circular support 12 for

the diaphragm, and a mechanical linkage member secured to the center of one diaphragm are employed.

Figs. 2 and 3 show an alternative transducer structure. In Fig. 2, the semiconductor elements 31 and 32 are of opposite conductivity types, and correspond to elements 17 and 18 of Fig. 1. A stiff light "I" beam 34 having the cross section indicated in Fig. 3 is mounted to receive energy from the mechanical link 35 which is connected to an acoustic diaphragm 11 and to transmit it to the semiconductor elements 31, 32. The elements 31 and 32 are rigidly soldered to the brass foundation elements 36 and 37 and to the brass mounting element 38 which is also firmly secured to the beam 34. Under these circumstances, practically all of the energy transmitted by the mechanical link 35 is absorbed by the semiconductive elements 31 and 32. This increases the stress and the resultant variations in resistance of the elements, as compared with the embodiment of Fig. 1.

The electrical circuit in the arrangement of Fig. 2 is substantially the same as that of Fig. 1, and the circuit elements including voltage source 20, transformer 21, potentiometer-switch 22, and the output circuit 23 have accordingly been given the same designation numbers in both figures. The brass mounting plates 36, 37 are separated by an insulating layer 39 to prevent short-circuiting across the elements 31, 32. The other ends of the semiconductor elements are electrically connected together by the solder connections to the common brass mounting element 38. Separate mechanical and electrical connections to the piezo-resistive elements may of course be made when a semiconductor such as silicon (which is not easily soldered) is employed.

As mentioned above, the transducer shown in Figs. 2 and 3 has the advantage of increased energy absorption by the semiconductor elements. In addition, the broad area solder connections reduce the noise often associated with conductor to semiconductor connections, and higher fidelity output signals are therefore obtained.

Fig. 4 shows another transducer arrangement which is similar to the embodiments of Figs. 1 and 2 in the use of two semiconductor elements of opposite conductivity types and a series output circuit. In Fig. 4, however, the semiconductor elements 41 and 42 are mounted perpendicular to the beam 43. One end of the beam 43 is connected to a diaphragm 11 by the mechanical link 44, and the other end is pivotally secured to an insulating frame member 45.

The semiconductor elements 41, 42 are held firmly in engagement with opposite sides of the beam 43 by the arms 46 and 47 of the insulating frame member 45. Adjusting screws 48 and 49 are employed to insure contact between the elements 41, 42 and the beam 43 without forcing the diaphragm 11 away from its normal rest position. The series electric circuit includes the semiconductor elements 41 and 42, which are of opposite conductivity types, the battery 20, the primary winding of the transformer 21, and the potentiometer-switch 22. When force is applied to the beam 43, the resistance of one of the semiconductor elements increases, and that of the other element decreases. Accordingly, the mechanical vibrations of the beam 43 are transmitted as electrical signal variations to the output circuit 23 by the transformer 21.

An advantage of the transducer of Fig. 4 is its applicability to the problem of matching the impedance of a diaphragm (not shown) to the mechanical impedance of the other constants of the transducer, including the elements 41 and 42. By properly proportioning the lever arms between the pivot point of the beam 43 and the elements 41, 42, and between the pivot point and the linkage 44, maximum output at the transformer 21 may be obtained.

In the devices of Fig. 1 through 4, the biasing current and the acoustic vibrations are both applied to the semi-

conductor in the same direction, and the variations in resistance are also measured in this direction.

In the devices of Figs. 1 through 4, the orientation of the crystal structure in the semiconductor elements affects the magnitude of the output signal to a substantial extent. The crystal axis which yields the maximum output signal when it is aligned with the direction of biasing current and applied forces will be designated the "optimum piezoresistance alignment direction" in the following description and in the claims. For P-type silicon and for germanium elements of both conductivity types, it is desirable for maximum output signal that the crystal direction designated (111) be aligned with the direction of compression or extension and the direction of biasing current. For N-type silicon, however, the optimum piezoresistance alignment axis is in the (100) direction. In general, this optimum axis may be determined by tests on samples cut from semiconductor crystals along the principal crystal axes. The designations (111) and (100) are in accordance with the so-called Miller indices which are commonly used in the crystallographic art, and which are discussed, for example, on page 14 of the text entitled "Piezoelectric Crystals and Their Application to Ultrasonics," by W. P. Mason, D. Van Nostrand Company, Inc., New York, 1950.

A somewhat different form of the invention will now be described in connection with Figs. 5 through 8. In Fig. 5, the link 51 is secured to the center of the diaphragm 11 and supports one end of the beam 52. Acoustic energy incident on the diaphragm 11 produces mechanical vibrations in the mechanical link 51 and in the beam 52. The other end of the beam 52 is positioned by the screw 53 and by the knife edge supporting members 54 and 55 which are of rigid insulating material. The pointed screw 53 extends into a shallow recess in the side of the beam 52 and thus prevents lateral movement of the beam while permitting pivotal movement in response to vibrations from the diaphragm 11. The knife edge supports 54 and 55 are employed instead of broader area mechanical supports to avoid the introduction of unnecessary strains which would not contribute to the output piezoresistive effect of the transducer. The other two supporting elements 54 and 55 make line contact with one side of the beam 52 on opposite sides of the pivot screw 53.

Fig. 6 is a perspective view of the transducer of Fig. 5 in which the beam 52 is removed and a portion of the supporting bracket 56 for the adjusting screw 53 is broken away. As clearly shown in Fig. 6, the insulating supports 54 and 55 are rigidly cemented to the semiconductor plates 57 and 58, which may, for example, be of opposite conductivity types. The semiconductor plates are in turn rigidly cemented to the insulating frame member 56. Accordingly, the force on the knife edge supporting elements 54 and 55 produces a transverse force on the upper surface of the elements 57 and 58. Shearing stresses are then established in the semiconductor elements 57 and 58 between the upper surface to which the force is applied and the lower surface, which is rigidly secured to the frame member 56.

The electrical connections to the elements 57 and 58 are shown in Fig. 7. To establish the relationship between Fig. 7 and Fig. 6, the terminals 62 and 64 on the germanium elements 57 and 58 are shown in both figures. In Fig. 7, the biasing electric circuit, including the voltage source 65 and the potentiometer-switch 66, is connected to the germanium elements 57 and 58 in parallel. Biasing currents are supplied to the germanium element 57 at terminals 61 and 62, and to the element 58 at terminals 63 and 64. The output voltage from the germanium elements 57 and 58 is taken off in series from terminals 67 and 68 of element 57, and from terminals 71 and 72 of element 58.

As mentioned above, and as shown in Fig. 6, the contacts 62 and 64 to germanium elements 57 and 58 re-

spectively are secured to the end faces of the crystals. Similarly, contacts 61 and 63 are secured to the opposite end faces of crystals 57 and 58, which do not appear in the perspective view of Fig. 6. The support members 54 and 55 and the frame member 56 are made of insulating material and are provided with holes to accommodate the leads connected to terminals 67 and 68 on the broader surfaces of the semiconductor element 57, and to terminals 71 and 72 of element 58. Two such holes 59 and 60 in support members 54 and 55, respectively, are shown in Fig. 5. To avoid confusion between electrical circuitry and structural elements of the transducer, however, the leads passing through holes 59 and 60 are not shown in Fig. 5.

Fig. 8 is a diagram which relates the input forces and biasing currents with the output voltage for semiconductor material under simple shear conditions. The formula for the output voltage from each of the elements 57, 58 is as follows:

$$E_y = \rho \pi_{44} i_x T_{xy}$$

where E_y is the output voltage in the y direction as shown in Fig. 8, ρ is the resistivity of the semiconductor material, π_{44} is the piezoresistive shear coefficient, i_x is the biasing current in the x direction as shown in Fig. 8; and T_{xy} is the shearing stress which is positive in accordance with the convention set up by W. G. Cady at page 51 of his book entitled "Piezoelectricity," McGraw-Hill Book Co., Inc., New York, 1946.

When mechanical vibrations are applied to the beam 52 by the mechanical link 51, the shearing stress on one of the germanium elements 57 is increased, and that on the other element is decreased. Accordingly, the change in the voltage developed at terminals 67 and 68 of element 57 and the voltage developed at terminals 71 and 72 of element 58 is additive, and a substantial change in voltage is observed at the output circuit 75.

In the embodiment of Figs. 5 through 7, the output circuit connections to the semiconductor element are separate from the input biasing circuit connections. In view of the noise which is often associated with conductor to semiconductor contacts carrying relatively large direct currents, this separation of the biasing and the output contacts is advantageous. This technique may also be applied to the transducers of Figs. 1 through 4 by the use of an extra set of contacts on each semiconductor element, and parallel biasing circuits for each pair of elements. Another matter relating to contacts which is worthy of mention is that the semiconductor connections employed in the transducers of Figs. 1, 4, and 5 through 8, are low resistance, localized contacts. These may be simple solder connections in the case of germanium, while in the case of silicon the successive steps of localized plating and soldering to the plated material may be employed.

In the circuit of Fig. 9, the piezoresistive element is also employed as an amplification element. In the structure of Fig. 9, mechanical vibrations from a diaphragm 11 are coupled to the beam 82 by the mechanical linkage 81. As the beam 82 bends, the N-P-N transistor 83, 84, 85 is extended and compressed. As this portion of the transistor is compressed and extended, current through the elongated emitter section 83 of transistor 83, 84, 85 varies substantially. The emitter circuit includes the voltage source 87 which biases the junction between the N-type germanium material 83 and the P-type material 84 in the low resistance direction. The collector circuit of the transistor includes a voltage source 88 which biases the N-type collector section 85 of the transistor in the high resistance direction with respect to the P-type section 84. In addition, the collector circuit includes the primary of transformer 89. Variations in emitter current caused by the vibrations of the beam 82 produce substantially increased electrical signal variations in the collector circuit of the transistor. These ampli-

fied signals are coupled to the output circuit 91 by the transformer 89.

Each of the devices which are illustrated in Figs. 1 through 6 has two semiconductive elements. While the two elements of each device are preferably of opposite conductivity type as disclosed hereinabove, they may also be of the same conductivity type. When the semiconductor elements in the transducers of Figs. 1 through 4 are of like conductivity type, however, a somewhat more complex coupling circuit employing an output transformer with a center tapped primary winding, for example, may be employed. This type of coupling circuit is required to accommodate the opposite variations in resistance of the two semiconductor elements. In the transducer of Figs. 5 through 8, the use of semiconductor elements 57, 58 of the same conductivity type requires the reversal of either the biasing connections 63, 64 or the output connections 71, 72 of the semiconductor element 58 with respect to the connections to the companion semiconductor element 57.

Two other applications which are assigned to the assignee of the present invention and which are directed to related subject matter are W. P. Mason application Serial No. 543,859, filed October 31, 1955, entitled "Variable Resistance Semiconductive Devices" and D. C. Hoosterey application Serial No. 543,853, filed October 31, 1955, entitled "Piezoelectric Field Effect Semiconductor Device."

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements, such as the use of the transducers described above as phonograph pickup heads, may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, an acoustic diaphragm, first and second spaced substantially parallel anisotropic elements of piezoresistive semiconductor material each of a single conductivity type, means for mounting said elements for extension and compression in the optimum piezoresistance alignment direction, mechanical coupling means for matching the acoustic impedance of said diaphragm with the mechanical impedance of said elements in said optimum direction, and means for applying a biasing current to said elements, whereby sound incident on said diaphragm varies the resistance of said semiconductor elements and the current passing through said elements.
2. A combination as defined in claim 1 wherein said two piezoresistive elements are of opposite conductivity types, and circuit means for connecting said two elements in series.
3. In combination, a source of acoustic vibrations, two separate semiconductor elements of opposite conductivity type and each of a single conductivity type, a mechanical linkage coupling said source of acoustic vibrations to said semiconductor elements, and combined biasing and output circuit means for connecting said semiconductor elements in series, whereby said acoustic vibrations vary the resistance of said elements and of said combined biasing and output circuit means.
4. In combination, a frame member, a diaphragm mounted on said frame member, a flexible beam rigidly connected to said frame member at one end and secured to the center of said diaphragm at the other end, a semiconductor element of P-type conductivity secured to one side of said beam adjacent said frame member, a semiconductor element of N-type semiconductor material connected to the other side of said beam adjacent said frame member, and circuit means connecting said two semiconductor elements in series.
5. In combination, an acoustic diaphragm, a beam mechanically coupled to said diaphragm, two separate semiconductor elements of opposite conductivity type and each of a single conductivity type, means for mechanically

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linking said two elements to said beam, means for applying a biasing current to said semiconductor elements, and an output coupling circuit connected to said semiconductor elements in series, whereby sound incident on said diaphragm varies the resistance of said semiconductor elements and produces an electrical signal in said output coupling circuit.

6. In combination, two separate semiconductor elements of opposite conductivity type and each of a single conductivity type, means for connecting said elements in series, and means for applying mechanical vibrations oppositely to said semiconductor elements, whereby said mechanical vibrations vary the resistance of said semiconductor elements.

7. In an acoustic-electrical transducer, a source of acoustic vibrations, a base plate, two semiconductor plates each of a single conductivity type secured to one surface of said base plate, two supporting elements secured to the other side of said semiconductor plates, means including a beam mounted against said two supports for applying shearing stress to said plates, means for mechanically linking said beam to said source of acoustic vibrations, whereby the resistance of said semiconductor plates is varied in accordance with said acoustic vibrations.

8. In combination, a source of acoustic vibrations, a frame member, a flexible beam rigidly secured to said

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frame member and mechanically linked to said source of vibrations, and a junction transistor having an elongated emitter portion mounted on said beam adjacent said frame member.

9. In a transducer for converting acoustic energy into electrical signals, a frame member, a diaphragm mounted on said frame member, an elongated semiconductor element having a substantial portion of its length of a single conductivity type, means including a mechanical linkage coupled to said diaphragm for applying longitudinal forces to said portion of said semiconductor element, two electrical terminals secured to and making low resistance contact with said element, a source of biasing potential, and an electrical circuit connected in series with said terminals, said semiconductor element and said potential source, the optimum piezoresistance alignment direction of the semiconductor material in said element oriented along the direction of flow of the biasing current, whereby sound incident on said diaphragm varies the resistance of said semiconductor element and the current flowing through said electrical circuit.

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