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X 84579
X 89175

SEARCH ROOM

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United States I

SUBSTITUTE FOR MISSING XR

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Continuation of Ser. No. 557,120,
June 13, 1966, abandoned.

[45] Patented Dec. 15, 1970

[73] Assignee Motorola, Inc.
Franklin Park, Ill.
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[56]

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Assistant Examiner—Thomas W. Brown

[54] ACOUSTIC TRANSDUCER INCLUDING
PIEZOELECTRIC WAFER SOLELY SUPPORTED
BY A DIAPHRAGM
3 Claims, 11 Drawing Figs.

[52] U.S. Cl.....	179/110
[51] Int. Cl.....	H04r 17/00
[50] Field of Search.....	179/107, 110, 110.1

ABSTRACT: A conversion between electrical and mechanical stimuli is accomplished in speakers and microphones by attaching a bimorph piezoelectric annular crystal at its center to the apex or axis of the speaker or microphone diaphragm. The bimorph crystal is driven in an extension mode to effect conversion of electrical signals applied to the crystal into audio signals at the diaphragm or vice versa. The attachment of the bimorph crystal at its center to the apex of the diaphragm is the sole means of attachment of the crystal.

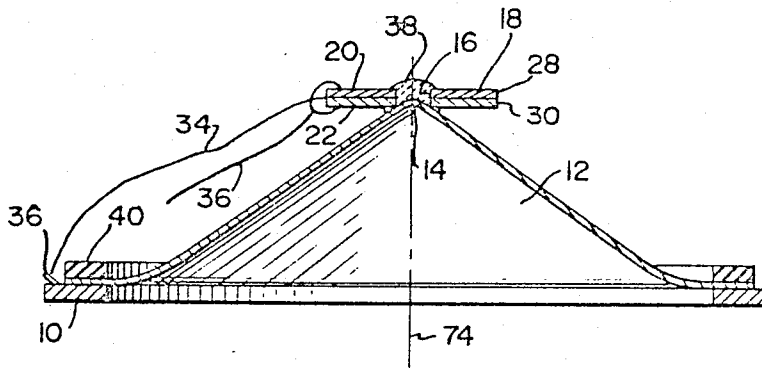


FIG. 1

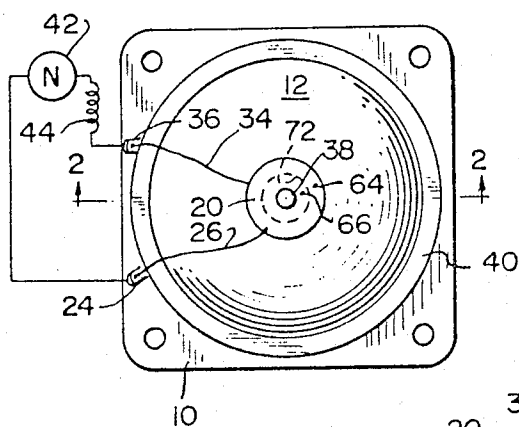


FIG. 4

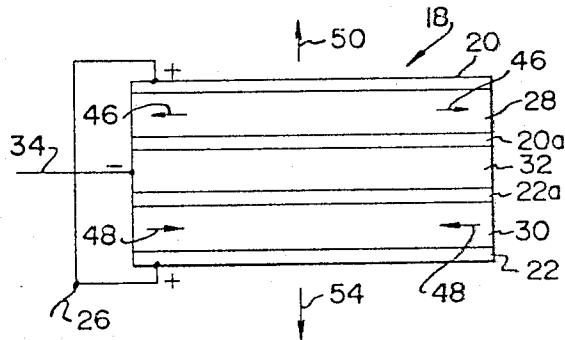


FIG. 2

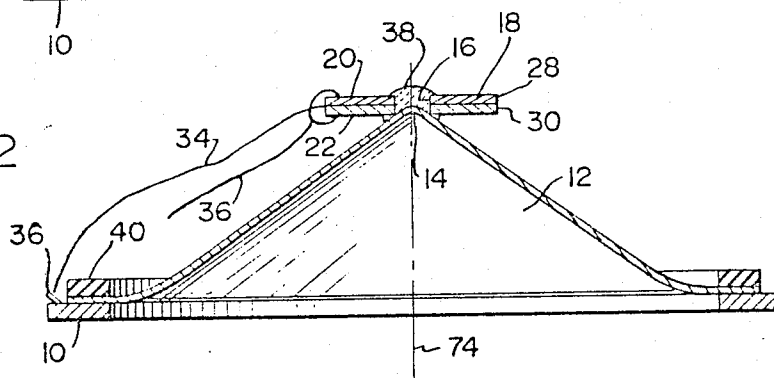


FIG. 3

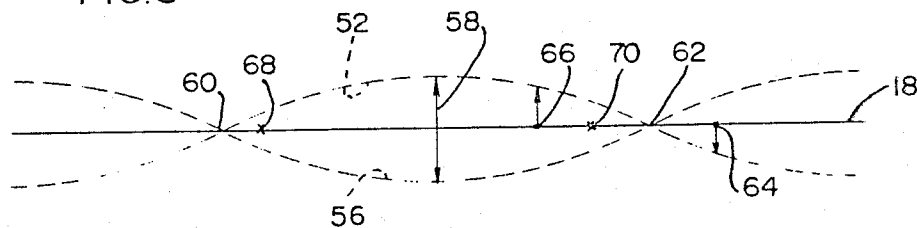
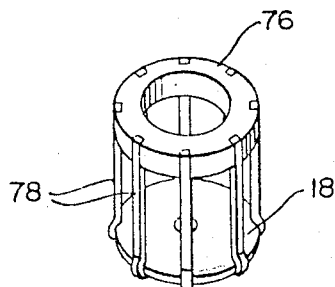


FIG. 5



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FIG. 7

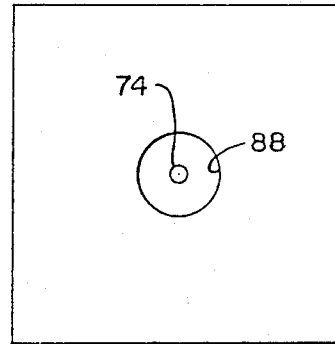


FIG. 8

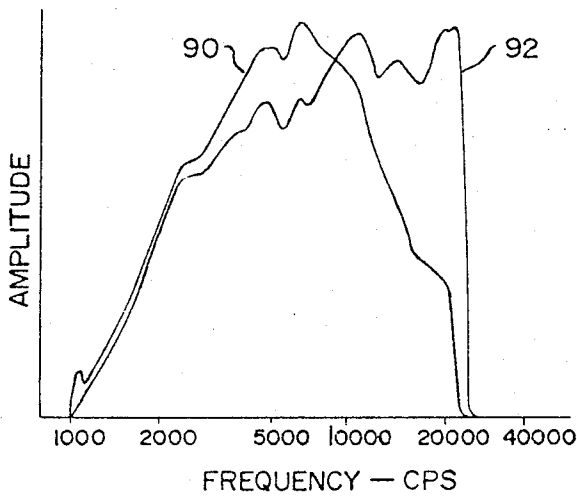
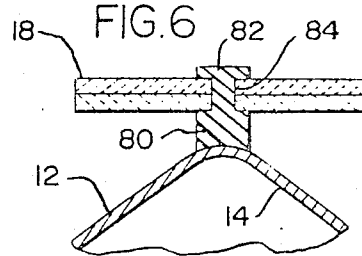


FIG. 9

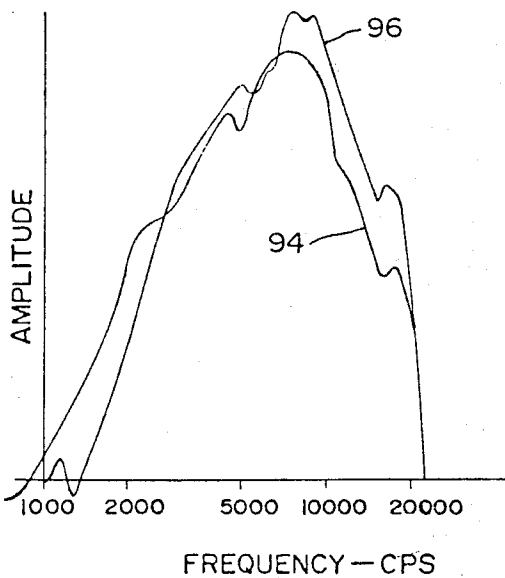


FIG. 11

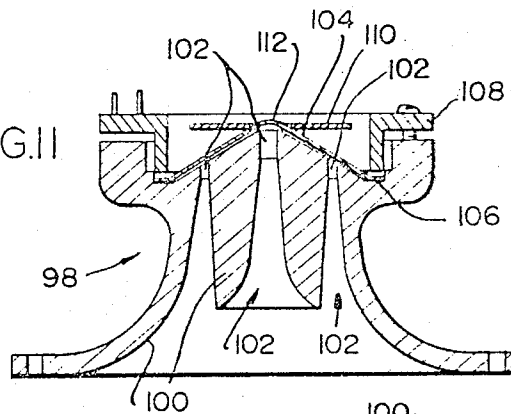
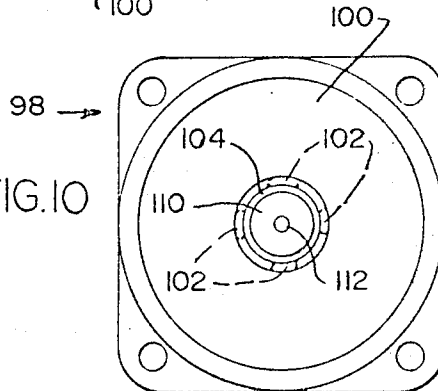


FIG. 10



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ACOUSTIC TRANSDUCER INCLUDING PIEZOELECTRIC WAFER SOLELY SUPPORTED BY A DIAPHRAGM

RELATED APPLICATION

This application is a continuation of application Ser. No. 557,120 filed June 13, 1966 now abandoned.

Electromechanical transducers having piezoelectric crystals as a transducing element in the past have provided a frame mount for the crystal. Therefore, speakers using such crystals as driving and conversion elements require in addition to a frame supporting the flexible diaphragm an additional frame to support the crystal and its associated equipment. In providing such mounted crystals care has to be exercised such that the conversion between electrical signals and mechanical or audio signals is faithful, i.e., the conversion does not introduce noise nor unduly distort the applied signals. Similar difficulties are encountered in using an electrodynamic type of speaker which requires a permanent magnet bias to coax with a signal coil mounted on the speaker diaphragm. The additional frame requires space, adds weight and cost to the transducer.

It is also desired to provide a maximum coupling factor between electrical and mechanical stimuli. The definition of coupling factor is:

$$K^2 = \frac{\text{Electrical energy converted to mechanical energy}}{\text{input electrical energy}}$$

For the reverse conversion:

$$K^2 = \frac{\text{Mechanical energy converted to electrical energy}}{\text{input mechanical energy}}$$

Therefore, an object of this invention is to provide a piezoelectric transducer of simple construction, low cost and having a high coupling factor.

It is another object of this invention to provide an electromechanical transducer which faithfully makes conversions between electrical and mechanical stimuli.

According to this invention there is provided a piezoelectric crystal which is direct coupled to a compliant diaphragm. The piezoelectric crystal is operated in a mode and mounted so as to provide good mechanical connection between the crystal stresses and the compliant diaphragm stimuli or vibrations. Damping may be provided in the connection between the crystal and the diaphragm to prevent reflected waves of the diaphragm and crystal from interacting. The crystal-diaphragm connection is so arranged that the crystal may be easily and securely mounted on the diaphragm, provide faithful and high coupling between electrical and mechanical stimuli, and eliminate spurious resonances from separate mountings.

A feature of the preferred usage of a disc or square shaped piezoelectric wafer is the large mechanical displacement of the wafer for small amplitude voltages. Such wafers also exhibit the highest resonant frequency of piezoelectric elements, permitting a large wafer to be used for a given range of frequencies thereby increasing power level capabilities.

Referring now to the accompanying drawings:

FIG. 1 is a plane view of the reverse or driver side of a speaker constructed according to the teachings of this invention;

FIG. 2 is an enlarged sectional view of the FIG. 1 illustrated speaker as taken along line 2-2 in the direction of the arrows;

FIG. 3 is a diagrammatic showing of the vibrational mode of a crystal wafer used in the FIG. 1 speaker;

FIG. 4 is a diagrammatic and enlarged side view of a bimorph wafer used in connection with the FIG. 1 speaker;

FIG. 5 shows a crystal transducer element which is designed especially for providing a low resonant frequency in a transducer;

FIG. 6 is an enlarged cross-sectional and partial view of a modification of the FIG. 2 speaker;

FIG. 7 is a plan view of a square bimorph transducer element;

FIG. 8 is a graph showing the frequency response of the FIG. 1 speaker;

FIG. 9 is a graph showing the frequency response of an electrodynamic tweeter and a tweeter built as illustrated in FIG. 1; FIG. 10 is a plan view of an audio horn embodying this invention; and

FIG. 11 is a sectional view taken in the direction of the arrows along line 3-3 of FIG. 9.

In practicing this invention a compliant diaphragm, for example, one having a conical shape with an elliptical cross section, is secured at its outer edges in the usual manner. An apex is formed at the center most rearward portion of the diaphragm. Alternatively the apex portion can be off center for providing different transducer characteristics. The diaphragm has an axis that extends through the apex along which the vibrations occur when producing or receiving sound waves. On the apex portion of the diaphragm there is mounted a piezoelectric crystal which extends transversely to the axis and is preferably located coaxial therewith. The crystal is directly mounted on the diaphragm for exchanging mechanical vibrations therewith and operating in a bending mode. In a preferred embodiment the piezoelectric crystal is an annular wafer assembly with the apex of the diaphragm extending into and possibly through a center aperture formed in the wafer assembly. A resilient adhesive may be used to glue the wafer to the diaphragm. Preferably the wafer has a mass greater than that of the diaphragm, such that when the diaphragm vibrates the wafer will set up an oscillation mode wherein the crystal wafer is subjected to undulations along its extent radially outwardly from the axis similar to vibrations of a mass in free space. Such undulations induce electric voltages in the wafer corresponding to mechanical stimuli and which may be picked up by electrodes plated or otherwise secured to the crystal. Conversely, electrical signals imposed on the crystal induce such undulations therein, called a bending movement, for imparting mechanical vibrations to the diaphragm for action as a speaker. The ratio of the output energy to the input energy of the crystal is termed the coupling factor. This factor is high for a disc-shaped and a square wafer operating in the described mode because the planar coupling coefficient applies.

Alternatively the crystal may be freely mounted at its outer edge. It should be remembered, however, that the mounting is such that the radially occurring axially directed undulations are permitted. An important advantage of this invention permits the free mounting of the crystal directly on the diaphragm without additional supports.

It is preferred that the piezoelectric transducing means be laminated. That is, two piezoelectric wafers are secured together by a metal shim for stiffening and for providing an intermediate electrode. Outer electrodes are placed on the outwardly and axially opposing faces of the wafer with the electric stimuli appearing in parallel between the intermediate and the two outer electrodes. The wafers are chosen such that one will expand radially outwardly and the other contract radially inwardly when a given voltage is applied across the electrodes. This coaction causes the wafer to bend in an axial direction along every diameter.

The bimorph wafer may have several configurations. It is preferred that a circular cross section be provided. With this configuration the distance from the outer edge of the wafer of the center axis is the same for all points keeping the wave reflected distance constant within the crystal. Alternatively a square cross section may be used. Or, if other transducer characteristics are desired, yet other shapes may be used.

Referring now to FIGS. 1 to 4 there is shown a piezoelectrically driven tweeter mounted on frame 10. The compliant diaphragm or driving piston 12 is preferably made of 2 mil aluminum having a conical shape with an elliptical cross section, as best seen in FIG. 2. The diaphragm 12 has an apex section 14 extending into aperture 16 of bimorph crystal 18 for supporting the crystal and making mechanical coupling therewith. Bimorph crystal 18 has outer electrodes 20 and 22

electrically connected together which are in turn connected to terminal 24 by wire 26. Bimorph 18 further includes two piezoelectric wafers 28 and 30 which mount the electrodes 20 and 22 and are fastened together by metal shim 32 which stiffens the bimorph and forms an electrode intermediate the two wafers. Each wafer 28 and 30 also has inner electrodes 20A and 22A (FIG. 4). Wire 34 connects the intermediate electrode 32 to a second terminal 36. Epoxy adhesive 38 in and about aperture 16 securely mounts bimorph 18 to diaphragm 12. Diaphragm 12 is mounted on frame 10 and has vibration damping rubber ring 40. Frame 10, ring 40 and diaphragm 12 are secured together in the usual manner.

An electrical signal to be transduced is supplied by source 42 across terminals 24 and 36. Coil or inductance 44 may be inserted intermediate the source 42 and one of the terminals for improving tweeter response, as will be later described.

The action of bimorph 18 to convert electrical stimuli to corresponding mechanical stimuli for driving diaphragm 12 will now be described. Bimorph 18 is schematically indicated in FIG. 3 as a solid line. When alternating electric signals are imposed between electrodes 20 and 22 and intermediate electrode 32, stresses are set up within the crystal which cause it to mechanically vibrate schematically indicated by dotted lines 52 and 56 in FIG. 3.

The piezoelectric responses of the individual wafers 28 and 30 to applied electrical signals causing the above referred to vibrations are described with reference to FIG. 4. Assume the applied electrical signal is positive on electrodes 20 and 22 with respect to intermediate electrode 32. Wafer 28 is termed a "plus-type" piezoelectric crystal material. It reacts to the described positive field by expanding radially outward as indicated by arrows 46 in an extension mode. Wafer 30 is termed a "negative-type" of crystal and responds to the described electric field by contracting radially inwardly in an extension mode. Such radial contraction is indicated by the arrows 48. Making such oppositely acting piezoelectric crystals as described herein is well known in the art.

Bimorph 18 is constructed to be relatively thin as between electrodes 20 and 22 with respect to its lateral dimension permitting it to flex along its diameters. With the above described electric fields, bimorph 18 tends to flex at its center axially upwardly as indicated by arrow 50 producing a configuration indicated by dotted line 52 in FIG. 3. Reversing the electric field polarity between intermediate electrode 32 and outer electrodes 20 and 22 causes wafer 28 to contract radially inward while wafer 30 expands radially outward causing an axially directed force at the center of bimorph 18 indicated by arrow 54. Force 54 causes the bimorph to bend as indicated by dotted line 56 in FIG. 3.

Impressing an alternating voltage across the electrodes causes the bimorph 18 to oscillate between dotted lines 52 and 56 as indicated by double-ended arrow 58 (FIG. 3). Nodal points will be produced in the wafer, such as at 60 and 62, which points are subjected to no axial movement. These two nodal points on one diameter of bimorph 18, correspond to nodal ring 72 (FIG. 1). In this vibrational mode there is no axial displacement at any point on nodal ring 72. Outwardly of nodal ring 72 bimorph 18 moves in an axial direction opposite to that within the nodal ring. Therefore, point 66 inside nodal ring 72 moves upwardly while point 64 outside of nodal ring 72 (point 62) moves downwardly.

Attaching diaphragm 12 to wafer 18 at its center adds mass thereto which reduces the resonant frequency of the wafer. The vibration of wafer 18 at its resonant frequency, as shown in FIG. 3, is modified in that nodal ring 72 diameter is reduced to a smaller diameter as indicated by points 68 and 70.

The described vibrational mode is that of a mass vibrating in free space. The mechanical coupling of diaphragm 12 to wafer 18 alters the vibrations, yet by keeping the effective mass of diaphragm 12 small, the vibrational mode is preserved.

By applying sound waves from in front of the speaker, diaphragm 12 is stimulated to vibrate along axis 74 which extends through apex portion 14. Such vibrations of diaphragm

12 are transferred to bimorph 18 which also vibrates as above described. Such vibrations create electric fields between electrodes 20, 22 and intermediate electrode 32 for supplying a voltage gradient thereacross indicative of the received sound. Several tests on bimorphs 18, constructed generally as shown in FIG. 4 were conducted. In one test bimorph 18 had an outside diameter (O.D.) of 0.78 inch, inside diameter (I.D.) of 0.19 inch with a thickness of 0.24 inch. Resonance frequencies were 6 kilocycles and 20 kilocycles was obtained. Such frequencies are an indication of the operating range of a transducer using such an element. In another test wherein the wafer had an O.D. of 0.530 inch, I.D. of 0.16 inch and 0.019 inch thick, the resonant frequency response was 13.5 kc and 79.3 kc. In yet another test the wafer was made to have an O.D. of 0.955 inch, an I.D. of 0.445 inch and a thickness of 0.019 inch to provide resonant frequencies of 4.4 kc and 39.6 kc. In this test, nodal ring 72 was observed to have an 0.730 inch diameter. Further testing of wafers showed that the highest coupling factor was provided with the wafer having a 1 inch O.D. and an 0.16 inch I.D. (a. 6:1 ratio).

It is desired that the aperture 16 be sufficiently small so as not to adversely affect the FIG. 3 illustrated vibration mode. It is desired to have an aperture 16 with a sufficiently large diameter to facilitate mounting on diaphragm 12. The testing showed that an O.D. to I.D. ratio of about 6 to 1 provided an aperture meeting both requirements. It is to be understood that no aperture need be provided in wafer 18 to come within the spirit of this invention. A nonapertured wafer 18 may be cemented, as by an epoxy adhesive, directly to the apex portion 14. When so doing it is desired, but not required, that the apex portion 14 have a flat end rather than the illustrated rounded end.

FIG. 5 illustrates an alternate embodiment wherein a mass in the form of a ring 76 is attached to the outer periphery of the wafer as by a plurality of clips 78. Ring 76 serves to decrease the resonant frequency of wafer 18, permits a heavier diaphragm 12, but increases mechanical losses.

FIG. 6 illustrates an alternate method of attaching wafer 18 to apex portion 14. A rubber plug 80 is attached to apex portion 14 by a suitable adhesive. Wafer 18 is slipped over end 82 of plug 80 into annular outwardly opening groove 84 which resiliently holds wafer 18 as shown. Rubber plug 80 serves to dampen vibrations between diaphragm 12 and wafer 18. It also reduces the coupling between the wafer and diaphragm 12.

FIG. 7 shows an alternate wafer shaped in the form of a square 86 having aperture 88 and which can be mounted in the same manner as wafer 18. The square shape has a somewhat lower coupling factor than wafer 18, however, it is symmetrical with respect to axis 74 and therefore still provides a good coupling factor. It is to be understood that yet other shapes of wafer may be used to accomplish the results of this invention.

FIG. 8 illustrates the frequency response in one construction of the FIG. 1 embodiment. Curve 90 illustrates the frequency response of the speaker when the capacitance of wafer 18 is not tuned to source 42. Insertion of coil or inductance 44 in series circuit with the capacitance of wafer 18 and tuning the two reactances to the center frequency of the desired bandwidth produces frequency response 92. FIG. 9 compares the FIG. 1 speaker frequency response with that of an electrodynamic speaker having comparable dimensions. Curve 94 shows the frequency response of a piezoelectric speaker while curve 96 is the frequency response curve of the electrodynamic speaker. Curve 94 does not include compensation for the capacitance of wafer 18. All tests described herein and all frequency response curves were made with a constant amplitude input to the respective devices.

Referring now to FIGS. 10 and 11 there is shown an audio horn 98. The horn body 100 has the usual exponential or hyperbolic shape. A plurality of sound passageways 102 are formed in the horn body. Such passageways provide an audio wave impedance transformation between the horn compres-

sion chamber, later described, and the acoustic impedance of air.

A small diameter diaphragm 104 is mounted in closely spaced apart relation to horn body 100 as by annular spacer 106. For example, spacer 106 may have the thickness of 0.0001 inches. Annular clamp 108, bolted to body 100, firmly holds diaphragm 104 and spacer 106 against body 100. The horn compression chamber is formed by the space between diaphragm 104 and body 100 as is in communicative relation to passageways 102.

A piezoelectric wafer 110, which may be constructed in the same manner as wafer 18 as best seen in FIG. 4, is mounted on diaphragm 104 as afordescribed for wafer 18 and diaphragm 12. Electrical connection to wafer 110 may be made in the usual manner. Apex portion 112 of diaphragm 104 extends into the aperture of wafer 110.

As wafer 110 is electrically actuated to vibrate in the mode illustrated in FIG. 3, diaphragm 112 correspondingly axially vibrates. Air in the horn compression chamber space between diaphragm 104 and body 100 is moved toward and from passageways 102 wherein the resulting compressional waves transmit the audio vibrations in the usual manner.

While it is preferred that the diaphragm to which the piezoelectric wafer is connected is formed generally as shown in FIGS. 2 and 11, no limitation to such specific form is intended. A piezoelectric wafer as described herein may be suitably mounted on other shape diaphragms and accomplish the results of this invention.

I claim:

1. Apparatus for making conversions between electrical and mechanical stimuli including in combination:
 - a diaphragm with an axis and having an axially movable portion in the form of an apex capable of having mechanical stimuli thereon;
 - a piezoelectric bilayer wafer having faces lying in substantially parallel planes and having a substantially circular cross section in a plane parallel to the faces, with an aperture located at the center of the wafer and with the apex of the diaphragm extending into the aperture;

means for connecting the wafer to the diaphragm by connecting the apex of the diaphragm to the side of the aperture, said connection mechanically coupling the wafer to the diaphragm and forming the sole support for the wafer; means for applying to or obtaining from the faces of the piezoelectric wafer an electrical stimulus; and said piezoelectric wafer having a pass for providing inertia.

2. The combination according to claim 1 wherein the aperture is filled with a resilient damping material comprising the connecting means such that the damping material forms a support connection between the diaphragm apex portion and the wafer.

3. A sound transducer device for converting between electrical signals and mechanical vibrations, including in combination:

- a conical diaphragm having an apex with an axis therethrough and an axially movable portion capable of vibrating in response to mechanical stimuli;
- a multi layer piezoelectric disc in the form of a circular wafer having faces lying in substantially parallel planes and having its circular cross section in a plane parallel to such faces;
- means securing the center of one of the faces of said disc to said apex of said diaphragm along the axis thereof thereby mechanically coupling said piezoelectric disc to said diaphragm and forming the sole support for said disc;
- circuit means for applying to or obtaining from the faces of said piezoelectric disc electrical signals; and
- said disc having a mass substantially greater than that of said diaphragm and providing resonance and bending mode oscillation concentrically about the center of the disc within the sound range to be translated in said device, said disc flexing in response to sound signals to form a circular node concentric with the circumference of said disc with the diameter of said node depending upon the mass of said diaphragm, and said piezoelectric disc providing the sole inertia with respect to mechanical coupling between said disc and said diaphragm.