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(72) Inventors JOHN FREDERICK SEAR and GEOFFREY
 MICHAEL GARNER



(54) PIEZOELECTRIC TRANSDUCERS

(71) We, THE PLESSEY COMPANY LIMITED, a British Company of 2/60 Vicarage Lane, Ilford, Essex, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to piezoelectric transducers.

Piezoelectric transducers in which an electrical output is obtained by using acoustic pressure to mechanically deform an inorganic piezoelectric material are well known. However, the usefulness of transducers of this kind is, particularly when used as a microphone in a telephone handset, limited by the mechanical properties of the transducer element and the relatively high cost of assembly of the transducer.

It is known that many plastics materials can be made to exhibit a piezoelectric effect after being subjected to various treatments which may involve heating, stretching, moulding and the application of electric fields.

The invention provides a piezoelectric transducer including a multi-layered diaphragm comprising at least two plastics layers separated by an electrode, at least one of the plastics layers being piezoelectric and having an electrode on its external face, said multilayered diaphragm being sandwiched in an untensioned state between support means to form said transducer element.

In one arrangement for the piezoelectric transducer the support means can be provided by two rigid members which each have an aperture therein, the multi-layered diaphragm being sandwiched in an untensioned state between the two rigid members so that each rigid member is contiguous with a separate one of the surfaces of the multi-layered diaphragm, the apertures in the rigid members being in register. The apertures in the two rigid

members are identical and can be of any shape or form and the resonant frequency of the transducer is dependent on the dimensions of the apertures and the thickness of the electroded multi-layered member.

In another arrangement of the piezoelectric transducer, the multi-layered diaphragm can be divided by the support means into a plurality of discrete regions which each form a separate transducer element and which are coupled together electrically in parallel. The support means for this arrangement can be provided by two rigid members of a perforated material and the multi-layered diaphragm member would be sandwiched in an untensioned state between the two perforated members so that each perforated member is contiguous with a separate one of the surfaces of the multi-layered diaphragm, the apertures of the two perforated members being in register. Alternatively, the support means can be provided by two rigid members between which the multi-layered diaphragm would be sandwiched in an untensioned state, one of the rigid members having a plurality of apertures therein and being contiguous with one surface of the multi-layered diaphragm whilst that surface of the other rigid member which is contiguous with the other surface of the multi-layered diaphragm would be roughened or profiled.

The piezoelectric layer or layers of the multi-layered diaphragm can be of any piezoelectric plastics material but is or are preferably of a fluorinated hydrocarbon piezoelectric material such as polyvinylidene fluoride, polyvinylfluoride or fluorinated ethylene propylene copolymer. These piezoelectric plastics materials are of the kind that produce an electrical output for a given mechanical deformation which is substantially undiminished over a period of years or by ambient temperature and humidity variations.

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The foregoing and other features according to the invention will be better understood from the following description with reference to FIGURES 1 to 5 of the drawings accompanying the provisional specification No. 49709/74 and FIGURES 6 to 11 of the accompanying drawings, in which:

FIGURE 1 diagrammatically illustrates in a cross-sectional side elevation one arrangement for a piezoelectric transducer not in accordance with the invention,

FIGURES 2 and 3 diagrammatically illustrate in cross sectional side elevations an arrangement for the transducer element of a piezoelectric transducer of FIGURE 1 in accordance with the present invention,

FIGURES 4 and 5 diagrammatically illustrate in cross-sectional side elevations further arrangements for a piezoelectric transducer according to the invention,

FIGURES 6 and 7 diagrammatically illustrate respectively in a partly cut-away front elevation and a cross-sectional side elevation on the line 'x-x' of FIGURE 6, one arrangement for a microphone which is suitable for use as a direct replacement for a carbon granules microphone used in telephone handsets,

FIGURE 8 diagrammatically illustrates in a cross-sectional side elevation a noise-cancelling microphone which utilizes a piezoelectric transducer according to the invention,

FIGURE 9 illustrates an impedance matching circuit for the noise-cancelling microphone of FIGURE 8, and

FIGURES 10A to 10C and FIGURE 11 diagrammatically illustrate second order pressure gradient noise-cancelling microphones which utilize the piezoelectric transducers according to the invention.

Referring to FIGURE 1 of the drawings, the piezoelectric transducer diagrammatically illustrated therein in a cross-sectional side elevation includes a member 1 composed of two layers 1a and 1b of a piezoelectric plastics material, for example a fluorinated hydrocarbon piezoelectric material such as polyvinylidene fluoride, polyvinyl fluoride or fluorinated ethylene propylene copolymer. The piezoelectric layers 1a and 1b are in close contact and may be, but are not necessarily, bonded together. The direction of polarisation of the layers 1a and 1b is such that known piezoelectric flexure structures can be formed. Such structures are described as series or parallel bimorphs. This means that the plane of polarisation of the layers 1a and 1b is normal to the major surfaces thereof and the polarisation of the layers may be in the same or opposite directions depending on whether a parallel or series bimorph is required.

The diaphragm which can be circular, is of a thickness that is preferably within the range 10 to 100 μm but may be in the range 5 to 500 μm .

Two thin electrically conductive electrodes 2 and 3 are provided, for detecting an electrical potential developed across the major surfaces. The electrodes 2 and 3 which can be provided by painting or evaporating the electrode material onto the major surfaces of the member 1 are each connected by means of connecting leads 4 to terminal pins or the like (not illustrated). In practice, the terminal pins or the like will be connected to suitable impedance matching and amplification devices. This arrangement is found in practice however, to produce a low electrical output.

As is diagrammatically illustrated in FIGURE 2 of the drawings which shows part of a modified arrangement of the diaphragm of FIGURE 1 in accordance with the present invention, another thin electrically conductive electrode 5 can be provided between the piezoelectric layers 1a and 1b of the member 1 and when the polarisations of the layers 1a and 1b are in the opposite directions then this structure is known as a series bimorph. This arrangement in accordance with the present invention gives a much greater electrical output than that of Fig. 1.

Other composite structures for the diaphragm of FIGURE 1 can have any number of piezoelectric layers, for example, as is diagrammatically illustrated, in part, in FIGURE 3 of the drawings, a composite diaphragm can be composed of three piezoelectric layers 1a, 1b and 1c sandwiched between the electrodes 2 and 3 and having thin electrically conductive electrodes 6 and 7 respectively provided between the layers 1a and 1c and the layers 1c and 1b.

Another structural arrangement which may be used for the diaphragm is one in which only one of the layers 1a and 1b of FIGURE 1, e.g. the layer 1a, is piezoelectric, the electrode 3 being situated between the layers 1a and 1b. This structure is known as a unimorph.

The diaphragm which may have any one of the structures outlined in preceding paragraphs, is, as is illustrated in FIGURE 1, sandwiched between two rigid members 8, the sandwiched structure being clamped together by means of a peripheral clamping arrangement 9. The members 8 each have an aperture 10 therein and the sandwiched structure is arranged so that the apertures 10 of the two rigid members 8 are in register, that part of the diaphragm exposed by the apertures 10 forming both diaphragm elements and transducing elements for the piezoelectric transducer.

The apertures 10 may be of any shape or

form, for example, in the form of a circle or a regular or irregular polygon with a diameter or maximum diagonal dimension within the range 0.05 to 100 mm, the preferred range being 1.0 to 15 mm.

In practice, the piezoelectric transducer of FIGURE 1 is mounted in a manner determined by the particular application in which it is being used, and may be mounted so that the front surface is acoustically isolated from the rear surface, or is separated from the rear surface by a well defined acoustic path length.

The resonant frequency of the transducer is dependent on the dimensions of the apertures 10 and the thickness of the diaphragm and can be situated anywhere in the audio or ultrasonic region by suitable choice of these dimensions.

In another arrangement for the piezoelectric transducer according to the invention which is diagrammatically illustrated in a cross-sectional side elevation in FIGURE 4 of the drawings, the diaphragm is sandwiched between two rigid members 11 of a perforated material, the sandwiched structure being clamped together by means of the peripheral clamping arrangement 9 and arranged so that the perforations of the two rigid members 11 are in register.

The two rigid members 11 divide the diaphragm into a plurality of discrete regions which each form a separate transducer element and which are coupled together electrically in parallel, the diaphragm forming both the diaphragm element and the transducing element of each of the transducer elements.

In a further arrangement for the piezoelectric transducer according to the invention which is diagrammatically illustrated in a cross-sectional side elevation in FIGURE 5 of the drawings and which is a modified arrangement of the piezoelectric transducer of FIGURE 4, one of the rigid perforated members 11 of FIGURE 4 is replaced by a rigid member 12 having that surface thereof which is in contact with the electrode 3 roughened or profiled.

In both of the piezoelectric transducer arrangements of FIGURES 4 and 5, the perforations or holes in the rigid member or members 11 may be of any shape and of a size limited only by the required acoustic performance and the necessity of rendering each of the separate transducer elements self supporting, but are preferably in the form of a circle or a polygon with a diameter or diagonal dimension within the range 0.05 to 10 mm. Variations in the size of the holes within this range can be used in the arrangement of FIGURE 4 in order to effect a variation in the acoustic resonance of the structure and to thereby effect control of its response. With the arrange-

ment of FIGURE 5, variations in the size of the holes in the rigid member 11 and variations in the surface roughness or pattern profile in the rigid member 12 may be used to effect the same results.

It should be noted that the piezoelectric transducers according to FIGURES 4 and 5 can utilise any one of the piezoelectric structures outlined in preceding paragraphs for the diaphragm.

As previously stated, the diaphragm of FIGURES 4 and 5 is divided into a plurality of discrete regions which each form a separate transducer element and which are coupled together electrically in parallel. The area of each of the discrete regions is determined in the arrangement of FIGURE 4 by the size of the registering perforations in the members 11 and in the arrangement of FIGURE 5 by the combined effect of the perforations in the member 11 and the surface roughness and/or pattern of the member 12.

Each of the separate transducer elements behaves as a simple transducer whose acoustic performance is governed by its physical dimensions, but all of the separate transducer elements work co-operatively in parallel to produce a transducer having a resonant frequency that can be placed either within or remote from the frequency band of interest if the perforations in the members 11 are of the same size. Alternatively, the resonance of the transducer can be smoothed out to give any desired frequency response by having a range of different sized perforations with different resonances in each of the members 11.

The impedance of the piezoelectric transducers of FIGURES 4 and 5 is determined by the total dimensions of the diaphragm and can, therefore, be made relatively low to effect a desired impedance match into any conventional impedance matching and amplification circuitry.

The overall sensitivity of the piezoelectric transducers according to the invention can be controlled by variation of the piezoelectric co-efficient of the diaphragm which is readily achieved by varying the polarising conditions during the process carried out to make the plastics material piezoelectric or by varying the ratio of hole area to the total area of the member 1; for maximum sensitivity this ratio should approach as closely as possible to unity whilst retaining a rigid clamping support structure for the diaphragm.

Other advantages of the piezoelectric transducer according to the present invention are that (a) the transducer structures are easily constructed and thereby relatively cheap to manufacture, (b) the piezoelectric plastics member 1 is in an untensioned state and thereby gives high

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sensitivity and freedom from long term sensitivity variations due to plastics creep, (c) the use of a light plastics transducer confers robustness, good transient response and freedom from solid borne noise, (d) the relatively small front to rear dimension of the transducer allows noise cancelling techniques to be applied by permitting the easy assembly of coaxial transducer arrays, and (e) the inherent symmetry of the device enables improved matching of the front and rear acoustic characteristics of the device, which is an advantage in the construction of noise cancelling microphones.

The piezoelectric transducers according to the present invention have a particular but not necessarily an exclusive application as microphones in telephone handsets, the acoustic pressure causing mechanical deformation of the exposed region or regions of the diaphragm and thereby the development of an electrical potential between the electrodes 2 and 3 representative of the acoustic pressure.

FIGURES 6 and 7 of the drawings diagrammatically illustrate respectively in a partly cut-away front elevation and a cross-sectional side elevation on the line 'x-x' of FIGURE 6 one arrangement for a microphone which is suitable for use as a direct replacement for the carbon granules microphone used in telephone handsets.

The microphone arrangement of FIGURES 6 and 7 includes a piezoelectric transducer 13 according to the present invention housed within an enclosure 14 and connected to an integrated circuit amplifier 15.

The piezoelectric transducer 13 includes two piezoelectric plastics layers 13a, and 13b which are polarised in opposite directions and electrically connected in series and which are electroded with a metal such as aluminium or gold.

The two piezoelectric layers 13a and 13b are rolled together and supported in an edge-clamped configuration between two clamping plates 13c and 13d which have co-incident circular apertures 13e therein.

In practical arrangement, the plates 13c and 13d can be of 3mm thick polycarbonate, the apertures 13e can be 6mm in diameter, the layers 13a and 13b can be each of 25 μ m thick polyvinylidene fluoride having a piezoelectric coefficient of 10pC/N^{-1} obtained by applying an electric field of 1.6MVcm^{-1} across the film thickness at a temperature of 90°C , and aluminium electrodes can be $1000\text{\AA}$ thick and deposited by vacuum evaporation. Thus the individual transducer diaphragm disc elements formed in the apertures 13e in the plates 13c and 13d are $50\text{ }\mu\text{m}$ thick and 6 mm in diameter and behave mechanically as stiff plates. The disc elements are un-

tensioned and, therefore, plastics 'creep' problems are avoided. The disc elements are brought into flexural vibration by sound waves, the output being an alternating voltage of the same frequency.

The integrated circuit amplifier can be provided by a commercially available Mullard TAA970 microphone amplifier, the amplifier terminals being identified in FIGURE 7 with the reference numerals that are used to identify the corresponding terminals on the Mullard TAA970 amplifier. The terminals 8 and 9 are connected to the aluminium or gold electrodes of the transducer 13 by means of insulated connecting lead 16, the terminals 2 and 4 are the output terminals for the microphone and a $0.22\text{ }\mu\text{F}$ capacitor C1 is connected between the terminals 6 and 10. The leads 16 pass through a 1 mm diameter hole 17 in the main body 14a of the enclosure 14. In a practical arrangement, the microphone amplifier and capacitor C1 would be suitably mounted on the surface 18 of the body 14a in a manner whereby the enclosure 14 acts as a heat sink for the amplifier. Also, the front electrode and that one of the leads 16 which is connected to the terminal 9 could be connected to a metal enclosure 14 to effect screening of the assembly.

The acoustic design of the microphone is largely determined by the numbers in front of the disc elements of the transducer. A protective front plate 14b of the enclosure 14 has a hole pattern 14c therein which together with the mouthpiece of the telephone handset acts as a protective shield against touching the transducer element.

A foam disc 19, for example, of polyester is interposed between the transducer 13 and the front plate 14b and is located in a recess in the front plate 14b. In the practical arrangements previously referred to, the recess in the front plate 14b would be 1.5 mm deep and would be filled with a 3.5 cm diameter compressed disc of 5 mm thick polyester foam having a linear pore count of 20 pores/cm.

The recess and the foam disc 19 give rise to a low Q resonance in the aforementioned practical arrangements at approximately 1 KHz. The depth of the recess and the volume of air in the entire front cavity of the microphone define the resonant frequency whilst the Q of the resonance is mainly dependent upon the linear pore count of the disc 19. The disc 19 which acts as an acoustic resistance due to the viscous friction between air particles as the sound wave is transmitted through the porous material, also acts as a windshield discriminating against high velocity air streams produced by the wind but allowing

acoustic pressures to pass through.

The hole 17 is adapted to provide equalisation of the pressure variations on both sides of the diaphragm at frequencies less than 100 Hz.

Also, because of the reversible nature of the piezoelectric effect, the transducers outlined in preceding paragraphs may be used equally well as receivers or as generators of sound and thus may be utilized not only in microphones but also in earphones and in applications such as ultrasonic transmitters and receivers and hydrophones.

The piezoelectric transducers according to the invention have particular advantages in relation to microphones, especially miniature microphones because the capacitance of a piezoelectric transducer is of a value which allows impedance matching of the transducer to be readily effected. In a typical first order gradient noise cancelling microphone of known type, a carefully controlled acoustic path length difference is incorporated between the front and rear surfaces of the diaphragm, in more complex microphones a number of such units are arranged co-axially in a linear array or a single diaphragm is subjected at front and rear to sounds introduced by a four port arrangement. Microphones of conventional type utilize relatively bulky mechanisms such as mechanical linkages and electromagnets and because of this it is extremely difficult to arrange the required acoustic path lengths and the linear configuration previously referred to without making the microphone unwieldy and unsuitable as a practical device. It is also difficult for the same reason to obtain the required good matching of the front and rear acoustic components of a noise cancelling microphone. However, with the piezoelectric transducers according to the present invention, the restriction caused by the relatively bulky mechanisms of known microphone arrangements is avoided because the diaphragm and the transducer are constituted by the same composite piezoelectric member, the thickness dimension of the composite piezoelectric member is inherently small and the composite piezoelectric member and its associated supports are inherently symmetrical. Thus an efficient single diaphragm noise cancelling microphone or an array of such units of optimum dimensions can be readily achieved with the previously stated advantages including robustness and long term stability.

A noise-cancelling microphone is diagrammatically illustrated in FIGURE 8 of the drawings in a cross-sectional side elevation and includes a piezoelectric transducer 20 according to the invention, two

protective plates 21 situated one on each side of the transducer 20 and two foam discs 22 which are each interposed between the transducer 20 and a separate one of the plates 21. The discs 22 are each preferably located within a recess in a separate one of the apertured clamping plates 20a of the transducer 20.

The transducer 20 includes two piezoelectric layers 20b and 20c which are polarised in the same direction and electrically connected in parallel and which have electrodes 20d, 20e and 20f associated therewith.

The layers 20d, 20b, 20e, 20c, and 20f are rolled together and supported in an edge-clamped configuration between the plates 20a which have coincident circular apertures 20g therein.

In a practical arrangement, the plates 20a can be of 5 mm thick material, for example brass, or metallised plastics material, the apertures 20g can be 5 mm in diameter, the layers 20b and 20c can each be of 16 μ m thick polyvinylidene fluoride having a piezoelectric coefficient of 10pC/N^{-1} obtained by applying an electric field of 1MVcm^{-1} across the film thickness at a temperature of 90°C , and the electrodes 20d, 20e and 20f can be of 1000Å thick metal films of say gold deposited by vacuum evaporation. Thus, the individual transducer diaphragm disc elements defined by the apertures 20g formed in the plates 20a are 32 μ m thick and 5 mm in diameter and behave mechanically as stiff plates. The disc elements are untensioned and, therefore, plastics 'creep' problems are avoided. The disc elements are brought into flexural vibration by sound waves, the output being an alternating voltage of the same frequency. The output voltage is taken from the centre electrode 20e which is connected to an output terminal 23 and the electrodes 20d and 20f are connected to earth potential. The output terminal 23 is, in a practical arrangement, connected to an impedance matching circuit.

The acoustic design of the microphone of FIGURE 8 is entirely to the front and rear of the disc elements of the transducer in a symmetrical arrangement. The protective plates 21 which can be of aluminium and which act as protective shields against touching the transducer element, each have a single hole 23 therein. In the practical arrangement previously referred to, the hole 23 would be 3 mm in diameter, the recesses in the plates 20a would be 18 mm in diameter and 1.5 mm deep and the discs 22 would each be in the form of an 18 mm diameter compressed disc of 5 mm thick polyester foam having a linear pore count of 30 pores/cm.

The microphone of FIGURE 8 is a noise-

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5 cancelling first order pressure gradient
operated device. Its characteristics derive
from the fact that gradient microphones are
more sensitive to spherical waves than to
10 plane waves. Sound waves of speech are
spherical in character near the mouth,
whereas the wavefront of distant noise
sources are nearly plane in comparison with
the relatively small dimensions of the
microphone. In addition, the acoustic signal
to noise ratio is increased due to the figure-
of-eight directional characteristic
associated with the first order devices.

15 The capacitance of the previously
referred to practical arrangement of the
microphone of FIGURE 8 is 3000pF when
measured at a frequency of 1kHz in a
capacitance bridge and the impedance
matching for the microphone can be
20 effected in a manner as is illustrated in
FIGURE 9 of the drawings.

25 The microphone of FIGURE 8 is
indicated in FIGURE 9 by the reference 24
and the impedance matching is effected
with an emitter follower pre-amplifier
circuit which should preferably be mounted
close to the microphone in order to convert
the high impedance of the microphone to a
practical value of about 500 ohms. The pre-
30 amplifier circuit includes a transistor VT1
having the collector thereof connected to a
potential of 1.5 volts, the emitter thereof
connected to earth potential via a resistance
R3 and the base thereof connected to the
35 junction 25 of two resistances R1 and R2
which are connected in series between
earth potential and the 1.5 volts supply. The
microphone 24 is connected between earth
potential and the junction 25, and the low
40 impedance output of the circuit is taken
across the resistance R3 by means of output
terminals 26 and 27.

45 The microphone arrangement of
FIGURES 8 and 9 is not susceptible to
electromagnetic pick-up due to the use of a
parallel bimorph connection arrangement
for the transducer, the signal voltage being
taken from the centre electrode 20e which
is shielded from external electromagnetic
50 fields by the outer earthed electrodes 20d
and 20f and the microphone housing.
Furthermore, the microphone arrange-
ment is insensitive to solid-borne vibration
because the total effective mass per unit
55 area of the diaphragm is relatively low i.e.
 1.3×10^{-3} gm.cm⁻² in the practical arrange-
ment previously referred to. As a
consequence of this the microphone
arrangement is very robust since the
60 possibility of damage from shock is
extremely remote.

65 Higher order pressure gradient micro-
phones can be obtained by arranging first
order pressure gradient units in suitable
combinations, for example, a second order

pressure gradient microphone can, as is dia-
grammatically illustrated in FIGURES 10A
to 10C of the drawings, be constructed from
two first order pressure gradient units with
their electrical outputs connected in
opposition.

As illustrated in FIGURES 10A to 10C,
the second order pressure gradient micro-
phone includes two transducers 28 situated
one at each end of an enclosure 30 and
70 acoustically separated from each other by a
sound proof disc 31. A number of holes 32
and 34 are provided in the enclosure 30 for
respectively providing sound ports for the
space 33 and the space 35.

80 The transducers 28 each include two
piezoelectric layers 29 and 36 which have
electrodes 37, 38 and 39 associated there-
with. The layers 29 and 36 which can be
polarised in any desired direction and be
electrically connected either in series or in
parallel, are rolled together with the
electrodes 37, 38 and 39 and supported in an
edge-clamped configuration between two
plates 40 which have coincident circular
90 apertures 41 therein.

In practice, the line of desired sound
wave propagation is directed along a path
indicated in FIGURE 10C by the arrow 'A',
i.e. towards the front of the microphone.

95 The two transducers 28 are, therefore,
positioned one behind the other, preferably
on a common axis along the line of desired
sound wave propagation, the distance be-
tween the transducers 28 being small
100 compared with the wavelength of the sound
waves and such that there is an optimum
amount of phase difference of desired
sound to be picked up in the acoustic path
between the diaphragms of the trans-
ducers. The acoustic response of this com-
bination is proportional to the difference in
the pressure gradients at two closely spaced
points in the acoustic field, i.e. the force
experienced by each diaphragm as a result
110 of the sound waves that are applied thereto
via the holes 32, 34 and 41 gives rise to a
second order pressure gradient effect and
the microphone thereby exhibits a higher
degree of noise discrimination than a simple
first order pressure gradient unit.

115 Third order pressure gradient micro-
phones can be constructed by using pairs of
second order pressure gradient units
arranged in a similar manner to the arrange-
ment of FIGURES 10A to 10C.

120 It should be noted that in a practical
arrangement for the microphone of
FIGURES 10A to 10C an apertured
protective plate would be provided at each
end of the enclosure 30 and an acoustic
125 resistance in the form of a foam disc would
be situated between each protective plate
and the associated transducer.

A second order pressure gradient 130

microphone can, as is diagrammatically illustrated in FIGURE 11 of the drawings in a pictorial view, also be constructed using only one of the transducers 28 of FIGURES 10A to 10C. With this microphone arrangement, a cylinder 42 which is closed at each end thereof, is divided into two separate chambers 43 and 44 by the piezoelectric transducer which is indicated by the reference 45 and which can have the same structural arrangement as one of the transducers 28 of FIGURES 10A to 10C but could be provided by any one of the piezoelectric transducers outlined in preceding paragraphs where external sounds can have access to both sides of the diaphragm. Two sound ports 46 and 47 for the chamber 43 and two sound ports 48 and 49 for the chamber 44 are formed in the wall of the cylinder 42 and the spacing of the sound ports 46 to 49 is arranged so that the transducer 45 experiences a force proportional to the second order of the pressure gradient.

A second order pressure gradient microphone is one whose output depends on pressure variations at four points in space and in the microphone arrangement of FIGURES 10A to 10C the four points are provided by the front and rear surfaces of each of the transducers 28 whereas with the microphone arrangement of FIGURE 11, the sound ports 46 to 49 allow sound pressures to act on different sides of a single transducer 45. The sound ports 46 and 48 together with the transducer 45 form one first order pressure gradient unit and the sound ports 47 and 49 together with the transducer 45 form a second first order pressure gradient unit. By arranging for the sound ports which are opposite to each other to admit pressures to the same surface of the transducer 45, the resultant force is the difference of the forces obtained from the two first order pressure gradient combinations; the effective force on the diaphragm is then proportional to the second order of the pressure gradient, which is the characteristic of a second order microphone.

It should be noted that the metal use for the electrodes of the diaphragm must be such that it adheres to the plastics material and does not corrode under the intended conditions of use and that, in practice, when gold electrodes are used for the electroded multi-layered member, a thin layer of nickel chromium alloy is interposed between the gold electrode and the plastics material in order to ensure good adhesion. In the description and claims the term electrode includes any other layer interposed between an electrode and a piezoelectric layer to ensure good adhesion.

It should also be noted that the

electrodes, such as the electrodes 6 and 7 of FIGURE 3 and the electrode 5 of FIGURE 2, sandwiched between the plastics layers of the diaphragm would in practice be formed by two electrode layers because each plastics layer would, prior to assembly in the diaphragm, be formed with two electrodes thereon and polarised as required.

It is to be understood that the foregoing description of specific examples of this invention is made by way of example.

WHAT WE CLAIM IS:—

1. A piezoelectric transducer including a multi-layered diaphragm comprising at least two plastics layers separated by an electrode, at least one of the plastics layers being piezoelectric and having an electrode on its external face, said multi-layered diaphragm being sandwiched in an untensioned state between support means to form said transducer element.

2. A piezoelectric transducer as claimed in claim 1 in which all of the plastics layers are piezoelectric and in which each piezoelectric plastics layer has electrodes on both faces.

3. A piezoelectric transducer as claimed in claim 1 in which only one of said plastics layers is piezoelectric and in which said piezoelectric plastics layer has an electrode on both faces.

4. A piezoelectric transducer as claimed in any one of the preceding claims wherein the or each piezoelectric layer is polarised in a plane normal to the major surfaces thereof, and wherein the direction of polarisation of the or each piezoelectric layer is arranged so that a piezoelectric flexure structure is provided.

5. A piezoelectric transducer as claimed in any one of the preceding claims wherein the thickness of the multi-layered diaphragm is in the range 5 to 500 micrometres.

6. A piezoelectric transducer as claimed in claim 5 wherein the thickness of the multi-layered diaphragm is in the range 10 to 100 micrometres.

7. A piezoelectric transducer as claimed in any one of the preceding claims wherein the support means include two rigid members which each have an aperture therein, the multi-layered diaphragm being sandwiched in an untensioned state between the two rigid members so that each rigid member is contiguous with a separate one of the surfaces of the multi-layered diaphragm, the apertures in the rigid members being in register.

8. A piezoelectric transducer as claimed in any one of the claims 1 to 6 wherein the support means form a plurality of transducer elements from the multi-layered



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microphone can, as is diagrammatically illustrated in FIGURE 11 of the drawings in a pictorial view, also be constructed using only one of the transducers 28 of FIGURES 10A to 10C. With this microphone arrangement, a cylinder 42 which is closed at each end thereof, is divided into two separate chambers 43 and 44 by the piezoelectric transducer which is indicated by the reference 45 and which can have the same structural arrangement as one of the transducers 28 of FIGURES 10A to 10C but could be provided by any one of the piezoelectric transducers outlined in preceding paragraphs where external sounds can have access to both sides of the diaphragm. Two sound ports 46 and 47 for the chamber 43 and two sound ports 48 and 49 for the chamber 44 are formed in the wall of the cylinder 42 and the spacing of the sound ports 46 to 49 is arranged so that the transducer 45 experiences a force proportional to the second order of the pressure gradient.

A second order pressure gradient microphone is one whose output depends on pressure variations at four points in space and in the microphone arrangement of FIGURES 10A to 10C the four points are provided by the front and rear surfaces of each of the transducers 28 whereas with the microphone arrangement of FIGURE 11, the sound ports 46 to 49 allow sound pressures to act on different sides of a single transducer 45. The sound ports 46 and 48 together with the transducer 45 form one first order pressure gradient unit and the sound ports 47 and 49 together with the transducer 45 form a second first order pressure gradient unit. By arranging for the sound ports which are opposite to each other to admit pressures to the same surface of the transducer 45, the resultant force is the difference of the forces obtained from the two first order pressure gradient combinations; the effective force on the diaphragm is then proportional to the second order of the pressure gradient, which is the characteristic of a second order microphone.

It should be noted that the metal use for the electrodes of the diaphragm must be such that it adheres to the plastics material and does not corrode under the intended conditions of use and that, in practice, when gold electrodes are used for the electrode of multi-layered member, a thin layer of nickel chromium alloy is interposed between the gold electrode and the plastics material in order to ensure good adhesion. In the description and claims the term electrode includes any other layer interposed between an electrode and a piezoelectric layer to ensure good adhesion.

It should also be noted that the

electrodes, such as the electrodes 6 and 7 of FIGURE 3 and the electrode 5 of FIGURE 2, sandwiched between the plastics layers of the diaphragm would in practice be formed by two electrode layers because each plastics layer would, prior to assembly in the diaphragm, be formed with two electrodes thereon and polarised as required.

It is to be understood that the foregoing description of specific examples of this invention is made by way of example.

WHAT WE CLAIM IS:—

1. A piezoelectric transducer including a multi-layered diaphragm comprising at least two plastics layers separated by an electrode, at least one of the plastics layers being piezoelectric and having an electrode on its external face, said multi-layered diaphragm being sandwiched in an untensioned state between support means to form said transducer element.

2. A piezoelectric transducer as claimed in claim 1 in which all of the plastics layers are piezoelectric and in which each piezoelectric plastics layer has electrodes on both faces.

3. A piezoelectric transducer as claimed in claim 1 in which only one of said plastics layers is piezoelectric and in which said piezoelectric plastics layer has an electrode on both faces.

4. A piezoelectric transducer as claimed in any one of the preceding claims wherein the or each piezoelectric layer is polarised in a plane normal to the major surfaces thereof, and wherein the direction of polarisation of the or each piezoelectric layer is arranged so that a piezoelectric flexure structure is provided.

5. A piezoelectric transducer as claimed in any one of the preceding claims wherein the thickness of the multi-layered diaphragm is in the range 5 to 500 micrometres.

6. A piezoelectric transducer as claimed in claim 5 wherein the thickness of the multi-layered diaphragm is in the range 10 to 100 micrometres.

7. A piezoelectric transducer as claimed in any one of the preceding claims wherein the support means include two rigid members which each have an aperture therein, the multi-layered diaphragm being sandwiched in an untensioned state between the two rigid members so that each rigid member is contiguous with a separate one of the surfaces of the multi-layered diaphragm, the apertures in the rigid members being in register.

8. A piezoelectric transducer as claimed in any one of the claims 1 to 6 wherein the support means form a plurality of transducer elements from the multi-layered

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diaphragm, the transducer elements being coupled together electrically in parallel.

9. A piezoelectric transducer as claimed in claim 8 wherein the support means include two rigid members of a perforated material, the multi-layered diaphragm being sandwiched in an untensioned state between the two perforated members so that each perforated member is contiguous with a separate one of the surfaces of the multi-layered diaphragm, the apertures of the perforated members being in register.

10. A piezoelectric transducer as claimed in claim 8 wherein the support means include two rigid members between which the multi-layered diaphragm is sandwiched in an untensioned state so that each rigid member is contiguous with a separate one of the surfaces of the multi-layered diaphragm, wherein one of the rigid members has a plurality of apertures therein and wherein that surface of the other rigid member which is contiguous with the multi-layered diaphragm is roughened or profiled.

11. A piezoelectric transducer as claimed in claim 7 wherein the apertures in the rigid members of the support means are in the form of a circle or a polygon having a diameter or maximum diagonal dimension in the range 0.05 to 100 mm, the resonant frequency being dependent on the aperture dimensions and the thickness of the multi-layered diaphragm.

12. A piezoelectric transducer as claimed in claim 11 wherein each aperture has a diameter or maximum diagonal dimension in the range 1.0 to 15 mm.

13. A piezoelectric transducer as claimed in any one of the preceding claims wherein the piezoelectric layer or layers of the multi-layered diaphragm are of a fluorinated hydrocarbon piezoelectric material.

14. A piezoelectric transducer as claimed in claim 13 wherein the fluorinated hydrocarbon piezoelectric material is polyvinylidene fluoride, polyvinylfluoride or fluorinated ethylene propylene copolymer.

15. A piezoelectric transducer as claimed in any one of the claims 7 to 14 wherein the ratio of the aperture area to the total area of the multi-layered diaphragm is close to but less than unity.

16. A piezoelectric transducer substantially as hereinbefore described with reference to FIGURE 1 as modified by FIGURE 2 or FIGURE 3 of the drawings accompanying the provisional specification No. 49709/74.

17. A piezoelectric transducer substantially as hereinbefore described with reference to FIGURE 4 of the drawings accompanying the provisional specification No. 49709/74.

18. A piezoelectric transducer substantially as hereinbefore described with reference to FIGURE 5 of the drawings accompanying the provisional specification No. 49709/74.

19. A microphone which includes at least one of the piezoelectric transducers as claimed in any one of the preceding claims.

20. A microphone as claimed in claim 19 which also includes for at least one side of the or each piezoelectric transducer, an aperture cover plate for protecting the or each diaphragm, and an acoustic resistance interposed between the cover plate and the or each respective diaphragm.

21. A microphone as claimed in claim 19 or claim 20 which also includes an impedance matching network connected to the output of the piezoelectric transducer.

22. A microphone as claimed in any one of the claims 19 to 21 which includes two piezoelectric transducers situated one at each end of an enclosure member; a sound proof member for acoustically separating the transducers from each other, the sound proof member being spaced apart from each of the transducers, and the enclosure member having a number of apertures therein for providing sound ports for the spaces on each side of the sound proof member.

23. A microphone as claimed in claim 19 including a piezoelectric transducer which is such that external sound pressure can have access to both sides of the diaphragm; and a cylinder which is enclosed at each end thereof, which is divided into two separate chambers by the piezoelectric transducer and which has two sound ports for each of the chambers formed in the cylinder wall, the sound ports of each chamber being diametrically opposite each other.

24. A microphone substantially as hereinbefore described with reference to FIGURES 6 and 7 of the accompanying drawings.

25. A microphone substantially as hereinbefore described with reference to FIGURES 8 and 9 of the accompanying drawings.

26. A microphone substantially as hereinbefore described with reference to FIGURES 10A to 10C of the accompanying drawings.



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27. A microphone substantially as herein-
before described with reference to
FIGURE 11 of the accompanying drawings.

28. A receiver which includes a piezo-
electric transducer as claimed in any one of
the claims 1 to 18.

R. NICHOLSON,
Chartered Patent Agent,
For the Applicant.

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