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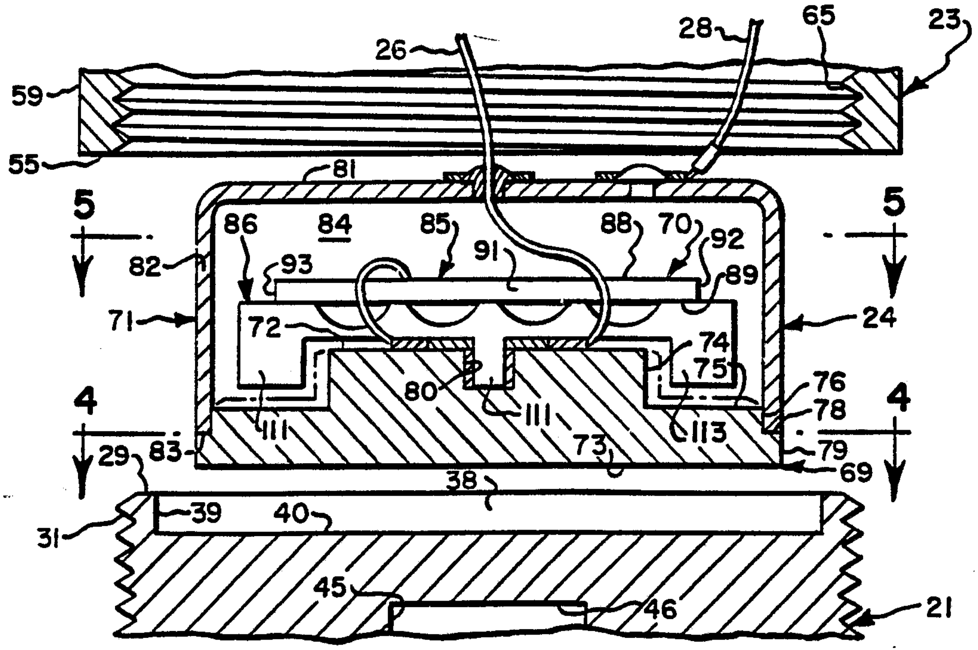

(57) Abstract

A flexure-type accelerometer (20) includes a composite beam (70) mounted on a base (69). The beam includes a piezoelectric element (85) mounted on a substrate member (86). A plurality of scalloped recesses (99) extend into the substrate member from the surface (100) against which the element is mounted. These recesses also position the neutral axis of the beam between the element and the substrate member in the vicinity of weakened portions (115) in which flexure occurs. Hence, during flexure, the element is placed entirely in tension or compression, as appropriate.

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FLEXURE-TYPE PIEZOELECTRIC TRANSDUCER

Technical Field

The present invention relates generally to the field of piezoelectric transducers for converting a physical parameter (*e.g.*, force, acceleration, pressure, etc.) into a proportional analog electrical signal, and, more particularly, to an improved piezoelectric transducer of the flexure type with increased sensitivity to variation of the sensed parameter.

Background Art

It is widely known that some materials exhibit piezoelectric properties; that is, they generate an electrical charge in response to mechanical strain, and *vice versa*. This charge may be amplified to produce a voltage reflective of the magnitude of the strain experienced by the piezoelectric material.

This principle has been used to form various types of transducers for measuring force (see, *e.g.*, U.S. Patent No. 3,151,258), pressure (see, *e.g.*, U.S. Patents No. 3,349,259 and 3,602,744), and acceleration (see, *e.g.*, U.S. Patents No. 3,482,121, 3,636,387 and 4,016,437). In some of these transducers, a stack of piezoelectric crystals is initially compressed by a preload force, and the sensed parameter is used to vary, either positively or negatively, the magnitude of the initial compression of the crystal stack. Thus, these devices utilize the change in initial compression to produce a usable output. Other devices utilize shear strain to produce the charge output. Still other devices rely on bending of the crystal to produce a flexural strain, and hence the output. For example, U.S. Patent No. 3,186,237 discloses various forms of a piezoelectric transducer in which a seismic mass is located at the outboard end of a piezoelectric crystal mounted for flexure. However, the neutral axis appears to be positioned symmetrically within the crystal such that, during flexure, one part of the crystal will be placed in tension and another part thereof will be placed in compression. Thus, during flexure, there is no net tension or compression on the crystal as a whole.

Disclosure of the Invention

The present invention provides an improved piezoelectric transducer of the flexure type which is believed to exhibit greater sensitivity (*i.e.*, is capable of generating a greater magnitude of electrical charge per unit of flexural deformation) than flexure-type transducers heretofore available in the prior art. As used herein, the term "transducer" is intended to refer generically to a device for converting a sensed parameter into an electrical charge. The sensed parameter may be force, pressure, acceleration, displacement, or some other parameter.

With parenthetical reference to the corresponding parts, portions or surfaces of the disclosed embodiment for purposes of illustration, the improved transducer (*e.g.*, 20) broadly includes a supporting base (*e.g.*, 69) and a composite or multiple-piece beam (*e.g.*, 70) mounted on the base for flexural movement relative thereto. The beam has a mass. The beam includes a substrate member (*e.g.*, 86) mounted on the base, and further includes a piezoelectric element (*e.g.*, quartz or some other operative material exhibiting piezoelectric properties) mounted on the substrate member. The piezoelectric element (*e.g.*, 85) has one surface (*e.g.*, 89) arranged to face a first surface (*e.g.*, 100) of the substrate member and has another surface (*e.g.*, 88) arranged to face away from the substrate member first surface. The substrate member first surface and the piezoelectric element one surface are constrained to move substantially together during flexure of the beam in at least one direction. More particularly, the element and substrate members may be suitably bonded together, as by an epoxy or the like. Alternatively, the end portions of the element may be clamped, or otherwise physically secured, to the substrate member.

A plurality (*i.e.*, one or more) of recesses (*e.g.*, 99) extend into the substrate member from its first surface (*e.g.*, 100) beneath the element. These recesses may have various cross-sectional shapes. For example, they may be configured as cylindrical segments, as rectangular slots or "saw cuts", or may have some other shape or configuration. The principal purpose of the recesses is to provide the beam with a corresponding plurality of weakened flexible webs (*e.g.*, 115) in which flexure may occur. Hence, the beam may flex segmentally, and the number, size, configuration and spacing of these recesses may be varied. It is presently preferred that each recess extends the full transverse width of the substrate member. In any event, the effect of these recesses is to position the neutral axis of the beam, when considered on a vertical plane taken through the flexible web, asymmetrically with respect to the piezoelectric element. In another form, these recesses are optionally filled with a suitable material (*e.g.*, an epoxy) having a stiffness (*i.e.*, modulus of elasticity) at least about an order of magnitude less than the stiffness of the materials of which the beam is formed, to damp the frequency response characteristics of the beam.

In the presently-preferred embodiment, the neutral axis is positioned between the piezoelectric element and the weakened portion(s) (*e.g.*, the webs) of the substrate member. Hence, when flexure occurs, one of the element and substrate member will be placed entirely in tension and the other entirely in compression, or *vice versa*, depending upon the polarity of the beam deflection. Thus, by selectively positioning the neutral axis asymmetrically with respect to, and preferably spaced from, the piezoelectric element, the tensile or compressive strain in the element is mechanically amplified during flexure of the beam.

The beam may be mounted in many different ways (*e.g.*, simply supported, cantilever-mounted, etc.), and is operatively arranged to deflect as a function of the sensed parameter. For example, the beam may have an enlarged mass, formed either integrally or separately, at its distal end to cause the beam to deflect under inertial loads. Alternatively, a physical displacement (*e.g.*, of a diaphragm) may be coupled to cause such beam deflection.

Accordingly, the general object of the invention is to provide an improved flexure-type piezoelectric transducer.

Another object is to provide an improved flexure-type piezoelectric transducer in which the entire piezoelectric element is placed in tension or compression, such that the crystal experiences a net flexural strain during beam flexure.

Another object is to provide an improved flexure-type piezoelectric transducer which is capable of greater sensitivity (*i.e.*, magnitude of electrical charge generated per unit change in the sensed parameter) than similar devices heretofore available in the prior art.

Another object is to provide an improved flexure-type piezoelectric transducer having increased sensitivity and damped frequency response characteristics.

Still another object is to provide an improved flexure-type piezoelectric transducer for use in measuring acceleration, force, pressure, displacement or the like.

These and other objects and advantages will become apparent from the foregoing and ongoing written specification, the drawings, and the appended claims.

Brief Description of the Drawings

Fig. 1 is a side elevation of an accelerometer incorporating the improved transducer, and showing the mounting stud in exploded aligned relation to the body lower recess.

Fig. 2 is another view, partly in vertical section and partly in elevation, of the accelerometer shown in Fig. 1, and showing the mounting stud as having been threaded into the body lower recess.

Fig. 3 is an enlarged fragmentary vertical sectional view showing the lower portion of the housing, the transducer assembly, and the upper portion of the body, in exploded aligned relation to one another.

Fig. 4 is a fragmentary horizontal sectional view, taken generally on line 4-4 of Fig. 3, and depicts the transducer base in top plan.

Fig. 5 is a fragmentary horizontal sectional view, taken generally on line 5-5 of Fig. 3, and depicts the improved transducer in top plan.

Fig. 6 is a top plan view of the substrate member.

Fig. 7 is a side elevation of the substrate member.

Fig. 8 is a schematic side elevational view of the composite beam, showing its undeformed shape in solid and showing its deflected shape in phantom.

Fig. 9 is a schematic side elevation of a modified form of the composite beam in which the marginal end portions of the beam are clamped to the substrate member.

Fig. 10 is a schematic side elevation of a variant form of the improved composite beam, *albeit* mounted as a cantilever.

Fig. 11 is a schematic side elevation of the beam shown in Fig. 3, with the substrate member recesses filled with epoxy to damp the frequency response characteristics of the composite beam.

Fig. 12 is a schematic side elevation of the beam shown in Fig. 9, with the substrate recesses filled with epoxy.

Fig. 13 is a schematic side elevation of the beam shown in Fig. 10, with the substrate member recesses filled with epoxy.

Mode(s) of Carrying Out the Invention

At the outset, it should be clearly understood that like reference numerals are intended to identify the same structural elements, portions or surfaces consistently throughout the several drawing figures, as such elements, portions or surfaces may be further described or explained by the entire written specification, of which this detailed description is an integral part. Unless otherwise indicated, the drawings are intended to be read (*e.g.*, cross-hatching, arrangement of parts, proportion, degree, etc.) together with the specification, and are to be considered a portion of the entire written description of this invention. As used in the following description, the terms "horizontal", "vertical", "left", "right", "up" and "down", as well as adjectival and adverbial derivatives thereof (*e.g.*, "horizontally", "rightwardly", "upwardly", etc.), simply refer to the orientation of the illustrated structure as the particular drawing figure faces the reader. Similarly, the terms "inwardly" and "outwardly" generally refer to the orientation of a surface relative to its axis of elongation, or axis of rotation, as appropriate.

Referring now to the drawings, and, more particularly, to Figs. 1-3 thereof, this invention provides an improved piezoelectric transducer, of which a presently-preferred embodiment is generally indicated at 20, in which a piezoelectric element (*e.g.*, quartz, etc.) is subjected to mechanically-amplified flexural strain. The illustrated form of the improved transducer is shown as being an accelerometer. However, the principles of the invention could also be readily adapted to measure force, pressure, displacement or the like. The improved accelerometer broadly includes a body 21 adapted to be mounted on a suitable support (not shown) via a mounting stud 22, a bell-shaped housing 23 adapted to be mounted on the body, a transducer assembly 24 mounted on the body within the housing, and an electrical connector 25 mounted on the housing and operatively connected to the transducer via electrical conductors 26,28 (Fig. 2).

As best shown in Figs. 2 and 3, body 21 is a specially-configured solid member generated about a vertical axis, shown as being coincident with the vertical axis *y-y* of the improved accelerometer. Body 21 is preferably formed of 316L stainless steel or equivalent, although this material may readily be changed. More particularly, the body is depicted as having an annular horizontal upper face 29, an annular horizontal lower face 30, and an outer surface which sequentially includes: an externally-threaded portion 31 extending downwardly from the outer margin of upper face 29, an upwardly-facing annular horizontal surface 32, a vertical cylindrical surface 33, a downwardly-facing annular horizontal surface 34, and a vertical cylindrical surface 35 continuing downwardly therefrom to join the outer margin of lower end face 30. Surfaces 32,33,34 define an annular flange portion 36 which extends radially outwardly from an intermediate portion of the body.

Two blind recesses extend axially into the body from its upper and lower faces, respectively. As best shown in Fig. 3, the upper recess 38 is bounded by an inwardly-facing vertical cylindrical surface 39 extending downwardly from the inner margin of upper face 29, and by an upwardly-facing circular horizontal bottom surface 40. In Fig. 1, the lower recess 41 is shown as being sequentially bounded by: an inwardly-facing vertical cylindrical surface 42 extending upwardly into the body from the inner margin of lower face 30, a downwardly-facing annular horizontal shoulder surface 43, an internally-threaded portion 44 extending upwardly therefrom, an inwardly-facing vertical cylindrical surface 45, and a downwardly-facing circular horizontal bottom surface 46.

As comparatively shown in Figs. 1 and 2, mounting stud 22 is adapted to be threaded into body lower recess 41. This mounting stud is a vertically-elongated solid member, preferably formed of beryllium copper or equivalent, and is also shown as having its longitudinal axis coincident with accelerometer vertical axis *y-y*. More particularly, this mounting stud is shown as having, in pertinent part, upper and lower circular horizontal end faces 48,49, externally-threaded portions 50,51 immediately adjacent its upper and lower end faces, respectively, and an annular flange 52 extending radially outwardly from the midpoint of a radially-narrowed intermediate shank portion. Diametrical through-slots, severally indicated at 53, extend into the stud from its upper and lower end faces to receive a suitable turning tool (not shown), such as the flat blade of a screwdriver, by which the mounting stud may be selectively threaded into, and out of, engagement with the body. Stud threads 50 are adapted to matingly engage body threads 44, with stud flange 52 being received in the mouth of body lower recess 41. Thus, when the stud is threaded into engagement with the body, the annular horizontal upper surface of flange 52 will abut the downwardly-facing annular shoulder surface 43 of the body recess. As previously noted, the lower threaded portion 51 of the stud is adapted to be received in a suitable tapped hole provided in an object (not shown) upon which the improved accelerometer is to be mounted, in the usual manner.

Referring now to Figs. 2 and 3, housing 23, which may also be formed of 316L stainless steel or equivalent, is shown as being a stepped tubular member and as having its vertical axis arranged so as to be coincident with accelerometer axis *y-y*. More particularly, the housing has, in pertinent part, annular horizontal upper and lower end faces 54,55, and an outer surface which sequentially includes: the vertical cylindrical surface 56 extending downwardly from the outer margin of upper face 54, a hexagonal surface 58 which is adapted to be grasped and rotated by a suitable turning tool (not shown), and a vertical cylindrical surface 59 continuing downwardly therefrom to join the outer margin of lower end face 55. The housing inner surface sequentially includes: a vertical cylindrical surface 60 extending downwardly from the inner margin of upper end face 54, a downwardly- and inwardly-facing frusto-conical surface 61, a vertical cylindrical surface 62, a downwardly- and inwardly-facing frusto-conical surface 63, a vertical cylindrical surface 64, and an internally-threaded surface 65 continuing downwardly therefrom to join the inner margin of lower end face 55. Housing threads 65 are adapted to mate with body threads 31. Thus, the housing is adapted to be selectively threaded onto the body until housing lower end face 55 abuts the upper surface 32 of body flange 36. If desired, suitable seals (not shown) may be positioned between surfaces 55,32 to be compressed when the housing is threaded onto the body. Alternatively, if the housing is not to be removed from the base, the exposed circular line between surfaces 55,32 may be sealed by a peripheral weldment (not shown).

Electrical connector 25 is an off-the-shelf purchasable item, such as Part No. 328-2040-01 made by Amphenol Corp. of Sidney, New York. This connector has an externally-threaded body 66, from which a lowermost annular flange 68 extends radially outwardly. The lower face of this flange abuts housing upper end face 54. The connector is suitably secured to the housing, as by a peripheral weldment (not shown) sealing the joint between the connector flange and the housing upper end face. A blind axial recess (not shown) extends downwardly into the connector from its upper end face, to protectively surround two contact pins (not shown) by which the electrical output of the improved accelerometer may be supplied to other devices (not shown). These pins are electrically connected to the transducer assembly via conductors 26,28.

Referring now to Fig. 3, transducer assembly 24 is shown as including a base 69, a composite beam 70 mounted on the base and protectively enclosed by a cover 71.

As best shown in Figs. 3 and 4, base 69 is a specially-configured solid disk-like member, preferably formed of brass or equivalent, having a stepped outer surface. In Fig. 3, the vertical axis of base 69 is shown as being coincident with accelerometer axis *y-y*. More particularly, the base is depicted as including circular horizontal upper and lower end faces 72,73, and an outer surface which sequentially includes: a vertical cylindrical surface 74 extending downwardly from the outer margin of upper end face 72, an upwardly-facing annular horizontal surface 75, a vertical cylindrical surface 76, an upwardly-facing annular horizontal surface 78, and a vertical cylindrical surface 79 continuing downwardly therefrom to join the outer margin of lower end face 73. A diametrically-elongated blind slot 80, having parallel side walls and concave end walls, extends vertically downwardly into the base from its raised upper face 72. The transducer base is adapted to be received in upper body recess 38 as such that base lower end face 73 engages recess bottom surface 40. While there are many ways by which the transducer base may be secured to the body, it is presently preferred that a layer of Kapton tape, available from CHR, Inc. of New Haven, Connecticut, be positioned between facing surfaces 73,40 to electrically isolate the same. The base and body may be held together via a suitable epoxy or equivalent.

Cover 71 is shown as being a thin-walled inverted cup-shaped member, and is preferably formed of stainless steel or equivalent. In the accompanying drawings, the vertical axis of the cover is also shown as being coincident with accelerometer axis *y-y*.

More particularly, cover 71 is shown as including an uppermost circular portion 81 from which an integrally-formed down-turned peripheral cylindrical skirt portion 82 depends. The annular horizontal lower end face 83 of cover 71 is received in the corner recess defined by base surfaces 76,78, and may be held in this position by means of a suitable epoxy. Thus, the cover is operatively mounted on the internal base to form a sealed chamber 84 therewithin.

The composite beam, generally indicated at 70, is mounted on the base within chamber 84. As best shown in Figs. 3 and 5, beam 70 includes a piezoelectric element 85 mounted on a substrate member 86.

In the presently-preferred embodiment, element 85 is a horizontally-elongated X-cut solid rectangular quartz crystal. This crystal therefore has large area upper and lower horizontal surfaces 88,89, respectively; longitudinally-extending vertical side surfaces 90,91; and transversely-extending vertical end surfaces 92,93, respectively. In one form, the crystal has a horizontal length of about 0.480 inches [12.19 mm], a horizontal width of about 0.120 inches [3.05 mm], and a vertical thickness of about 0.022 inches [0.56 mm]. Thus, the crystal somewhat resembles a horizontally-elongated flat ribbon. The large area upper and lower faces 88,89 are plated with gold or some other electrically-conductive material.

As best shown in Figs. 6-7, substrate member 86 is depicted as being a horizontally-elongated specially-configured member, and is preferably formed of 303 stainless steel or equivalent. More particularly, member 86 has longitudinally-extending planar vertical side surfaces 94,95, and transversely-extending planar vertical end surfaces 96,98, respectively. Four longitudinally-spaced transversely-extending scallop-shaped recesses, severally indicated at 99, extend downwardly into member 86 from its planar horizontal upper surface 100. As best shown in Fig. 7, the lower surface of member 86 is stepped, and sequentially includes: a planar horizontal surface 101 extending rightwardly from the lower margin of left end face 96, a rightwardly-facing vertical surface 102, a downwardly-facing horizontal surface 103, a leftwardly-facing vertical surface 104, a downwardly-facing horizontal surface 105, a rightwardly-facing vertical surface 106, a downwardly-facing horizontal surface 108, a leftwardly-facing vertical surface 109, and a downwardly-facing horizontal surface 110 continuing rightwardly therefrom to join the lower margin of right end face 98. Each of surfaces 101-106 and 108-110 is rectangular, and extends the full horizontal width of the substrate between side faces 94,95. Surfaces 103,108 are coplanar, and surfaces 101,105,110 are also coplanar. Similarly, each of scallop surfaces 99 extends the full width of the substrate member between side surfaces 94,95. Each scallop surface is a cylindrical segment and, in the preferred embodiment, occupies an arc distance of about 135°.

The central portion bounded by surfaces 104-106 forms an integrally-formed depending rectangular post member 111, which is adapted to be received in base slot 80. The left and right marginal end portions 112,113 of the substrate member (*i.e.*, defined between surfaces 96,101,102 and 109,110,98, respectively) are vertically thickened to increase the mass of the beam at locations spaced longitudinally from the vertical center-line axis, also shown as being coincident with axis *y-y*, of post portion 111. Alternatively, additional mass could be added to the substrate ends, if desired. This particular configuration thus defines, in longitudinal cross-section, an alternating series of vertically-thickened relatively-stiff portions 114 (*i.e.*, defined between substrate upper and lower surfaces 100,103) and vertically-weakened relatively-flexible web portions 115 (*i.e.*, defined between scallop surfaces 99 and substrate lower face 103), with enlarged mass portions 111,112 at either end. In the preferred embodiment, member 86 has an horizontal length of about 0.560 inches [14.22 mm], a horizontal width of about 0.165 inches [4.19 mm], and a maximum vertical thickness of about 0.090 inches [2.29 mm]. The vertical dimension of surfaces 102,104,106 and 109 is about 0.050 inches [1.27 mm]. Surfaces 103 and 108 each have an axial length of about 0.187 inches [4.75 mm]. Four scallop surfaces are provided, and the radius of each is about 0.046 inches [1.67 mm]. The horizontal dimension from the bottom dead center position of one of scallop surfaces 99 to the corresponding bottom dead center position of its immediate neighboring scallop, is about 0.102 inches [2.59 mm]. Each weakened portion 115 has a transverse horizontal dimension of about 0.165 inches [4.19 mm], and a vertical dimension (*i.e.*, from surface 103 or 108 to the bottom dead center position of the associated scallop surface 99) of about 0.012 inches [0.30 mm]. Each thickened portion 114 has a transverse horizontal dimension of about 0.165 inches [4.19 mm], but a vertical dimension (*i.e.*, from surface 103 or 108 to upper surface 100) of about 0.040 inches [1.02 mm].

In the presently-preferred embodiment, the large area crystal lower face 89 is suitably bonded, as by an epoxy, to the proximate portions of substrate member upper surface 100, as shown in Fig. 5, with the crystal being symmetrically mounted on the substrate member. Thus, the crystal is cemented to portions of upper surface 100 which are interrupted by scallops 99. Hence, during flexure, the crystal is caused to follow the contour of substrate member upper surface 100 when the beam and crystal are cemented together. In this arrangement, the crystal will be flexed, regardless of whether the ends of the substrate member move upwardly or downwardly from their undeflected positions. Alternatively, the epoxy or other bonding material may be omitted, and the distal ends of the crystal may be secured to the substrate member, as by L-shaped clamps 116 shown in Fig. 9. This alternative arrangement will work equally as well if the mass ends of the beam are displaced downwardly. However, if such distal ends experience an upward displacement, the crystal may separate from the substrate portion, and may follow a chordal distance between the two end clamps during flexure.

The composite beam thus formed between the substrate member and the crystal, is mounted on base 69 at an intermediate portion of its longitudinal extent. Hence, if the object upon which the improved accelerometer is mounted experiences an upward acceleration, the outboard mass ends of the beam will experience a relative downward deflection (δ) from their neutral positions, as shown in Fig. 8. Thus, the effect of such upward acceleration causes the beam to flex to a position in which substrate upper surface 100 is convex. Alternatively, if the object were to experience a downward acceleration, the ends of the beam would experience a relative upward acceleration, and the upper surface of the substrate would be concave.

Flexure of the composite beam may be best understood by making a few simplifying assumptions. First, it is assumed that the piezoelectric element and the substrate member are both homogeneous and have constant respective moduli of elasticity. Secondly, in the case of the bonded beam, it is assumed that no slippage occurs between the cemented facing surfaces of the crystal and substrate member. Third, it is assumed that the beam does not flex uniformly along its length. Rather, it is assumed that the beam flexes segmentally (*i.e.,* that flexure occurs solely in the weakened portions 115 and that any flexure in thickened portions 114 is *de minimis* and can be ignored). It is further assumed that the crystal may follow a quasi-chordal distance over the open mouths of the scallops when the beam is flexed either upwardly or downwardly. With these assumptions, flexure can be understood in terms of conventional beam deflection theory.

Having assumed that substantially all flexure occurs in the four weakened portions 115, a vertical cross-section taken through the bottom dead center of each scallop would reveal that the transverse cross-section of the piezoelectric element is in vertically-spaced relation to the cross-section of the substrate weakened portion. In the arrangement shown and described, the crystal would have a rectangular cross-section, and such rectangular shape would have a horizontal dimension of about 0.12 inches [3.05 mm], and a vertical dimension of about 0.022 inches [0.56 mm]. Similarly, the substrate member weakened portion would also appear as a rectangle, when viewed in transverse cross-section, and this rectangle would have a horizontal dimension of about 0.165 inches [4.19 mm] and a vertical dimension of about 0.12 inches [3.05 mm]. The two rectangles are separated by a vertical dimension of about 0.028 inches [0.71 mm]. In accordance with conventional composite beam theory, one may calculate the configuration of an equivalent beam section, assuming that the beam and crystal were formed of the same material. From this, one may calculate the location of the neutral axis of the beam through the section (*i.e.*, including weakened portion 115) in which flexure is assumed to occur. The neutral axis is, by definition, a line through such section in which neither tension nor compression occurs when the beam is flexed (*i.e.*, the centroidal axis of the equivalent section). If it is assumed that the moduli of elasticity of the substrate material and the crystal are substantially the same, then for the configuration described, the neutral axis would be located about 0.0201 inches [0.51 mm] above the bottom dead center of the scallop and about 0.007 inches [0.18 mm] below the lower surface of the piezoelectric element.

The point of the foregoing is to demonstrate that the neutral axis of the beam taken through a section including the bottom dead center of the scallop, is located at an imaginary point located between the substrate and element sections. Thus, if the ends of the beam deflect downwardly, the entire crystal will be in tension and the entire substrate will be in compression. Conversely, if the beam ends flex upwardly, the entire crystal will be in compression and the entire substrate will be in tension. Hence, regardless of whether the ends of the beam are flexed upwardly or downwardly, the polarity of the flexure stress in the piezoelectric element will be opposite the polarity of the flexure stress in the substrate material. In other words, if one is in tension, the other is in compression, and *vice versa*.

Thus, by mounting the piezoelectric element on a substrate member to form a composite beam, and by providing recesses (*e.g.*, scallops) in the substrate member from the surface to which the crystal is bonded (or which is engaged by the crystal if the ends thereof are clamped), the beam may be dimensionally configured to deliberately position the neutral axis somewhere between the crystal and the substrate member, all with the object of insuring that the entire crystal will be placed either in tension or compression (as appropriate) during deflection of the beam ends. If it be further assumed that the portions of the crystal which are bonded to the substrate upper surface 100 move with the proximate thickened substrate sections, then it can be seen that the intermediate portions of the crystal which are located immediately above the scalloped areas, will be placed in tension or compression, as appropriate. Thus, if the crystal is bonded to the substrate, longitudinally-spaced interrupted portions of the crystal will be placed in tension or compression when the beam is flexed. Alternatively, in the clamped embodiment, if the beam ends flex downwardly such that beam surface 100 is convex, the entire length of the crystal between the two clamping points will be placed in tension. As noted above, if the beam flexes upwardly, the crystal may be regarded as being biased to the chordal distance between such clamping points.

Figs. 11-13 show three further modifications of the composite beams shown in Figs. 3, 9 and 10, respectively. The embodiments shown in Figs. 3, 9 and 10 were not deliberately damped in that nothing occupied the spaces between the recess surfaces and the underside of the crystal. Figs. 11-13 show arrangements which are structurally identical to the composite beams shown in Figs. 3, 9 and 10, except that the various substrate recesses are now filled with an epoxy or some other suitable material, generally indicated at 118, having a modulus of elasticity at least about an order of magnitude less than the moduli of elasticity of the materials of which the beam is formed. Thus, for example, if the substrate member is formed of steel having a modulus of elasticity of about 30×10^6 psi [2.109×10^6 kg/cm^2], then the modulus of elasticity of the filler epoxy material 118 would be on the order of about 3.0×10^6 psi [2.109×10^5 kg/cm^2], or less. The epoxy filler material is poured into the recesses, and the upper surface thereof lapped smooth before the crystal is mounted thereon. Thus, the damping material is not bonded to the crystal itself. The object of such damping material is simply to improve the frequency response characteristics of the composite beam by reducing the amplitude spike that normally occurs at the resonant frequency. Such damping may well, however, induce phase-shifting at lower frequencies due to the mechanical response of the structure. Other types, such as squeeze film damping, constrained layer damping, oil damping, or use of a tuned absorber, may be substituted. The use of such damping is, however, entirely optional.

Therefore, the invention provides an improved transducer, damped or undamped, in which a piezoelectric element (*e.g.*, quartz crystal, etc.) is mounted on a specially-configured substrate member such that the neutral axis of the composite beam thus formed in the region of flexure is located somewhere between the substrate material and the crystal. Hence, when the beam is caused to flex, the various portions of the piezoelectric element will all be placed in tension or compression, as appropriate, with the extent of mechanical amplification being related to the distance of the crystal from the neutral axis.

Modifications

The present invention contemplates that many changes and modifications may be made. First, the materials of construction are not deemed to be critical, and may be readily changed or varied, as desired. The number and spacing of such scalloped portions may also be changed or modified, as desired. In a further modified embodiment, as shown in Fig. 10, a plurality of parallel transverse saw cuts or slots may extend into the substrate member from its upper surface. The substrate member need not have a rectangular shape, but may be irregularly shaped as well. For example, the substrate member could be a beam having an inverted T-shaped transverse cross-section. Other transverse cross-sections might also be used as well.

Similarly, the invention is not limited to use with a quartz crystal, and other types of piezoelectric elements and bimorphs may be substituted therefore. Similarly, the piezoelectric element need not be mounted for flexure symmetrically about a central point. Alternatively, the beam may be mounted as a cantilever, as shown in Fig. 10. In this form, the beam 70' is shown as having a piezoelectric element 85' bonded to the upper surface of a substrate member 86'. Beam 70' is shown as extending horizontally outwardly from a suitable support 69', with its distal end having been deflected downwardly by a distance δ such that the facing surfaces of the element and support member are concave. In this configuration, the element will be placed in tension. The embodiment shown in Fig. 10 is shown as having three spaced rectangular recesses, severally indicated at 99', extending downwardly into the substrate member from its upper surface 100' to define an alternating series of vertically-thickened relatively-stiff portions 114' and vertically-weakened relatively-flexible web portions 115'. If desired, the distal end of composite beam 70' may have an enlarged mass (not shown). Here again, beam 70' is assumed to flex segmentally, with substantially all flexure occurring in weakened portions 115'.

The crystal is not necessarily limited to an elongated ribbon-like shape, and the improved transducer is not limited to use as an accelerometer. Suitable linkages, for example, may be used to transmit a force or force analog (*e.g.*, pressure) to a deflectable portion of the beam to cause flexure thereof in response to variation in a sensed parameter.

The composite beam may be in the form of a T-shaped structure, or may be simply supported at either end with a central mass acting thereon, or may be a cantilever, or may have some other shape or configuration.

Therefore, while the preferred embodiment of the improved transducer has been shown and described, and several modifications thereof discussed, a person skilled in this art will readily appreciate that various additional changes and modifications may be made without departing from the spirit of the invention, as defined and differentiated by the following claims.

Claims

1. A piezoelectric transducer, comprising:

a base; and

a composite beam mounted on said base for flexural movement relative thereto, said beam having a mass, said beam including a substrate member mounted on said base and including a piezoelectric element, said substrate member having a first surface, said piezoelectric element having one surface arranged to face said substrate member first surface and having another surface arranged to face away from said substrate member first surface, said element and substrate member being operatively coupled such that said substrate member first surface and said piezoelectric element one surface are constrained to substantially move together during flexure of said beam, and at least one recess extending into said substrate member from said first surface.

2. A piezoelectric transducer as set forth in claim 1 wherein said beam is mounted on said base as a cantilever.

3. A piezoelectric transducer as set forth in claim 1 wherein said piezoelectric element is a quartz crystal.

4. A piezoelectric transducer as set forth in claim 3 wherein said crystal is X-cut.

5. A piezoelectric transducer as set forth in claim 1 wherein said substrate is elongated, and has a substantially-rectangular transverse cross-section except in the vicinity of said recess.

6. A piezoelectric transducer as set forth in claim 1 wherein said substrate member is formed of stainless steel.

7. A piezoelectric transducer as set forth in claim 1 wherein said base is formed of brass.

8. A piezoelectric transducer as set forth in claim 1 and further comprising a mounting member arranged intermediate said base and said beam for holding said beam in spaced relation to said base.

9. A piezoelectric transducer as set forth in claim 8 wherein said substrate member is elongated and wherein said mounting member engages said substrate member proximate the midpoint of its longitudinal extent.

10. A piezoelectric transducer as set forth in claim 8 wherein said substrate member is disk-shaped, and wherein said mounting member engages said substrate member proximate its center.

11. A piezoelectric transducer as set forth in claim 1 wherein the mass of said beam is the sole seismic mass acting on said element.

12. A piezoelectric transducer as set forth in claim 1 wherein said beam is elongated and wherein a number of said recess extend into said substrate member from longitudinally-spaced locations along said first surface.

13. A piezoelectric transducer as set forth in claim 12 wherein each recess is bounded by an arcuate wall.

14. A piezoelectric transducer as set forth in claim 1 wherein said recess is bounded by an arcuate wall.

15. A piezoelectric transducer as set in claim 1 wherein said recess is rectangular.

16. A piezoelectric transducer as set forth in claim 1 wherein each recess is provided to lessen the resistance of said substrate member to flexure.

17. A piezoelectric transducer as set forth in claim 1 wherein the neutral axis of said beam is located within said substrate material.

18. A piezoelectric transducer as set forth in claim 1 wherein multiple recesses extend into said substrate member from spaced locations along said first surface, and wherein said recesses are configured to cause said piezoelectric element one surface to bend in a substantially-smooth continuous curve during flexure of said beam.

19. A piezoelectric transducer as set forth in claim 1 wherein said piezoelectric element one surface is bonded to said substrate member first surface.

20. A piezoelectric transducer as set forth in claim 1 wherein portions of said piezoelectric element are clamped to said substrate member.

21. A piezoelectric transducer as set forth in claim 1 and further comprising a damping material arranged in said recess.

22. A piezoelectric transducer as set forth in claim 21 wherein said damping material is epoxy.

23. A piezoelectric transducer as set forth in claim 21 wherein said damping material has a modulus of elasticity about an order of magnitude lower than the moduli

of elasticity of the materials of which said composite beam is formed.

Fig. 1.

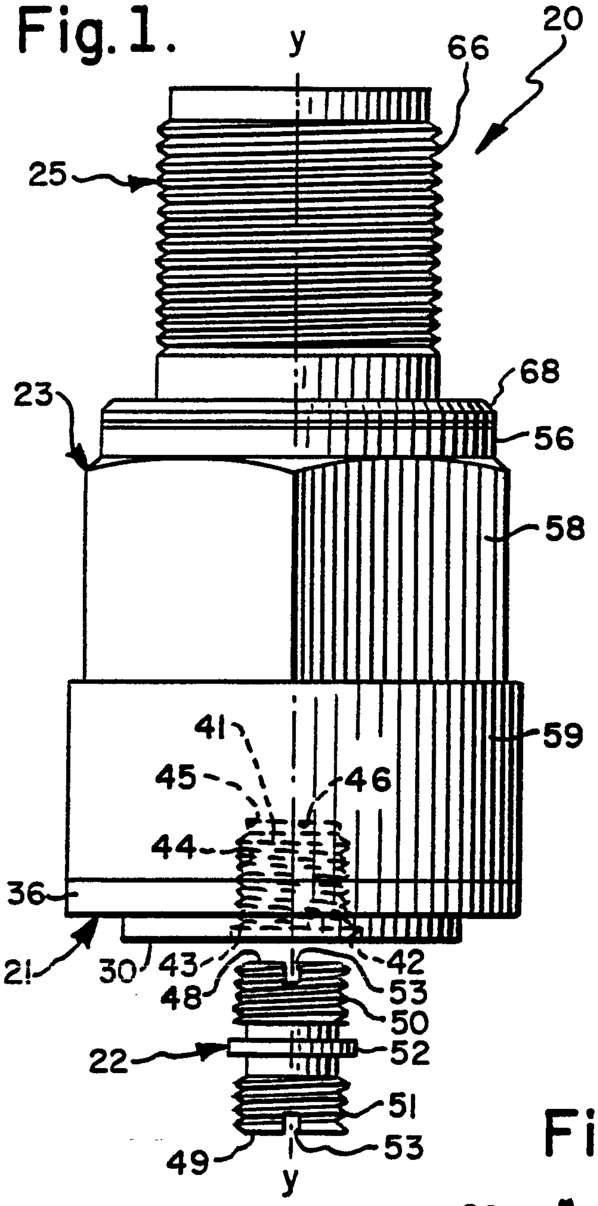


Fig. 2.

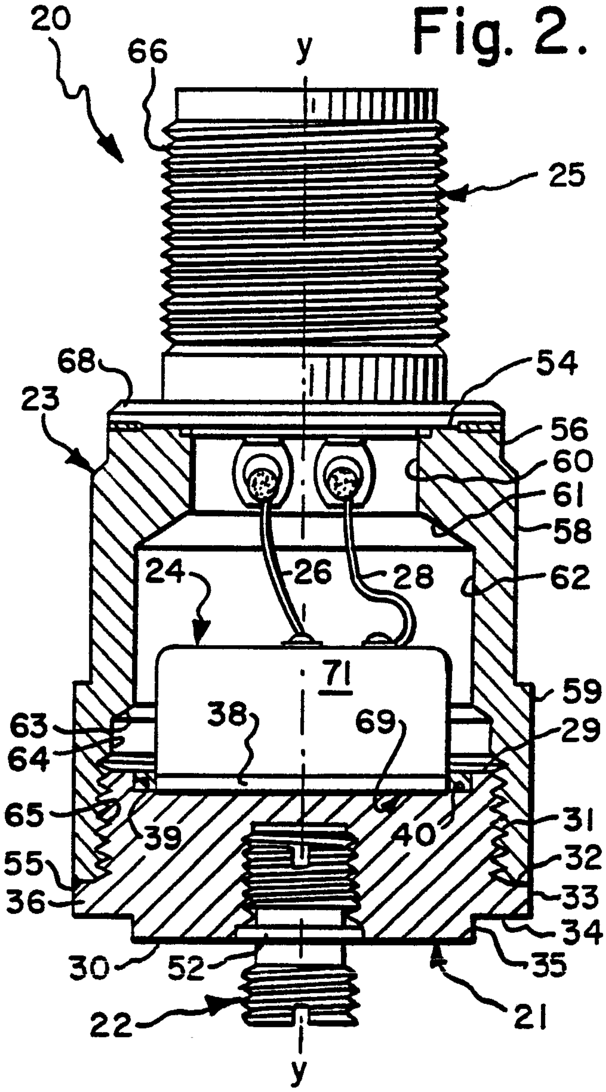


Fig. 3.

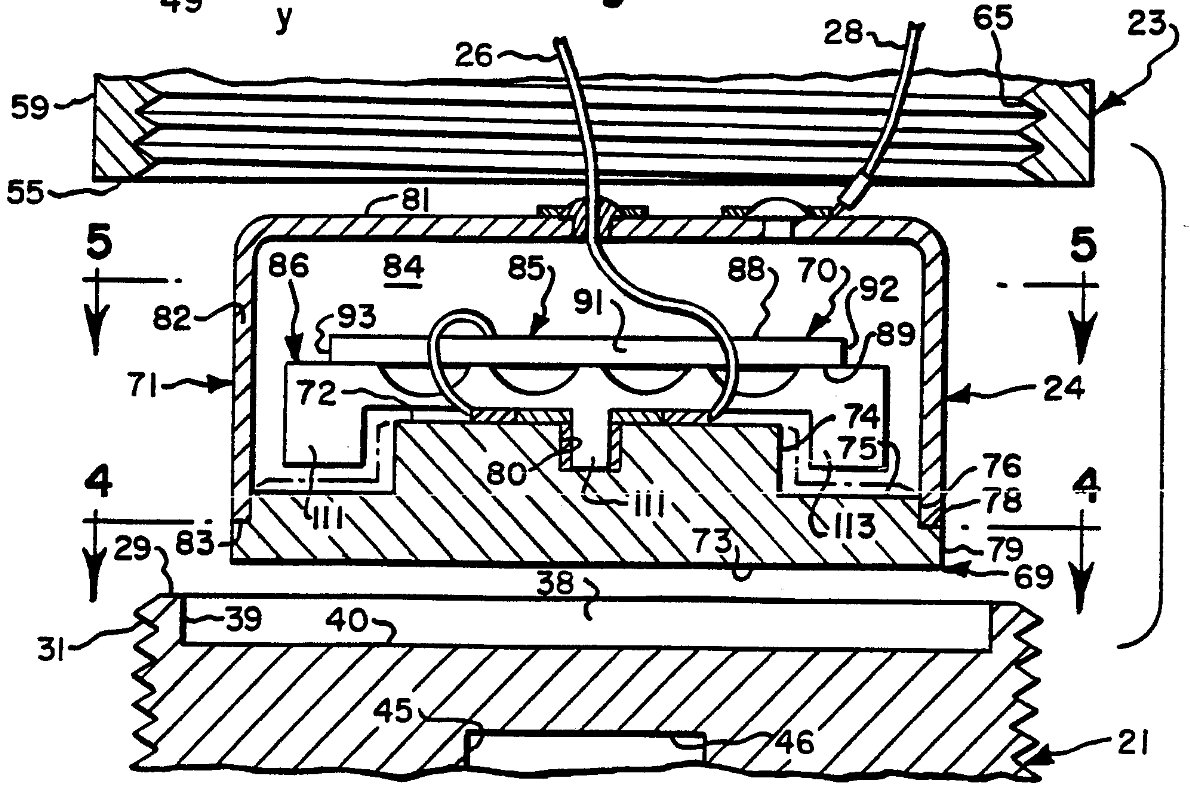


Fig. 4.

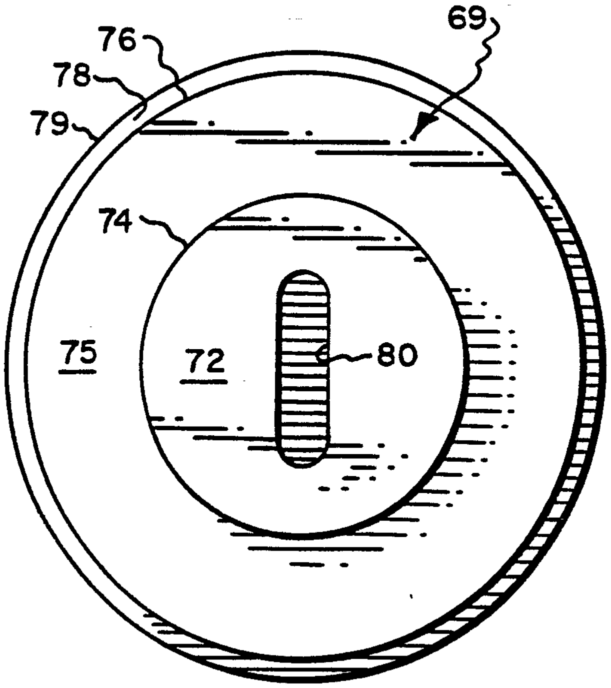
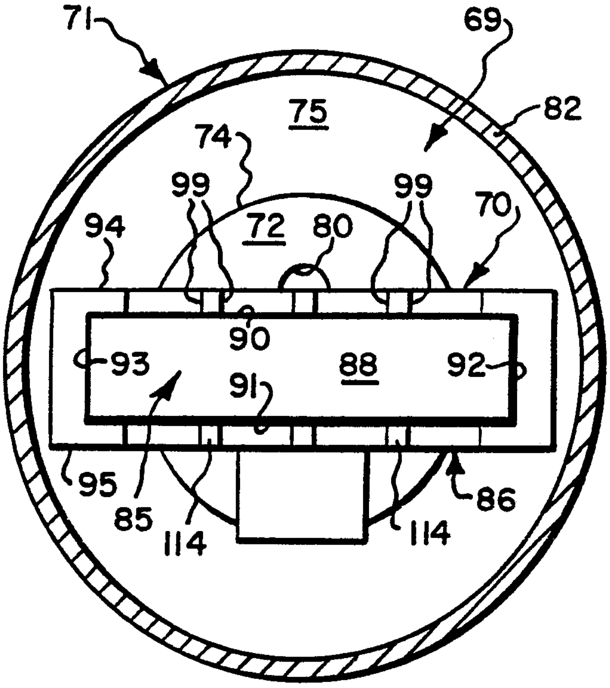


Fig. 5.



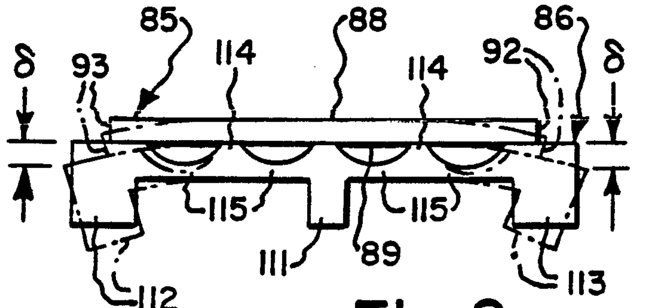


Fig. 8.

Fig. 6.

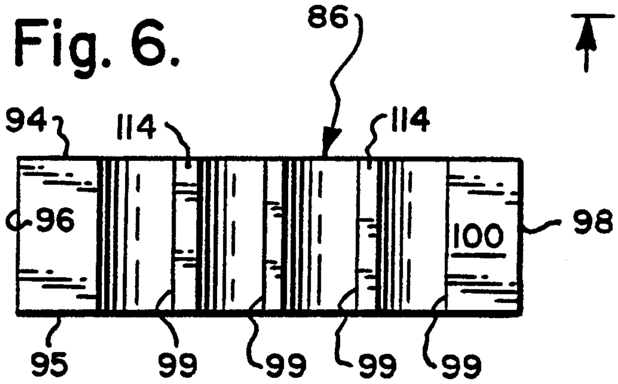
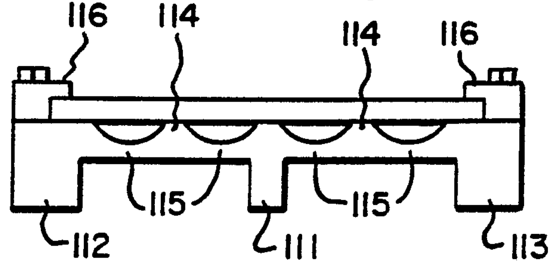


Fig. 9.



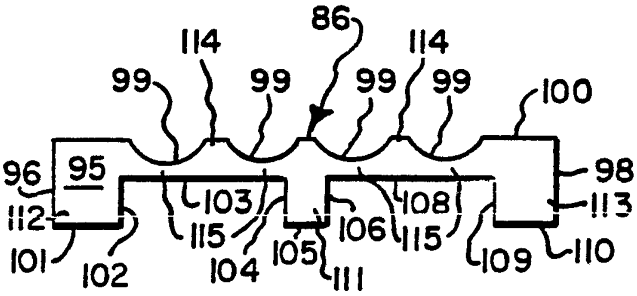


Fig. 7.

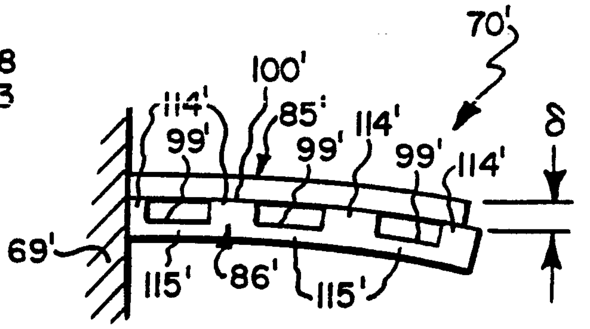


Fig. 10.

Fig. 11.

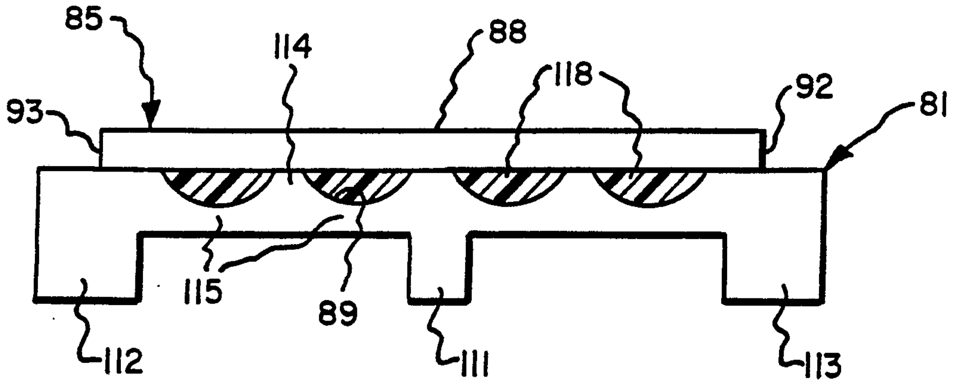
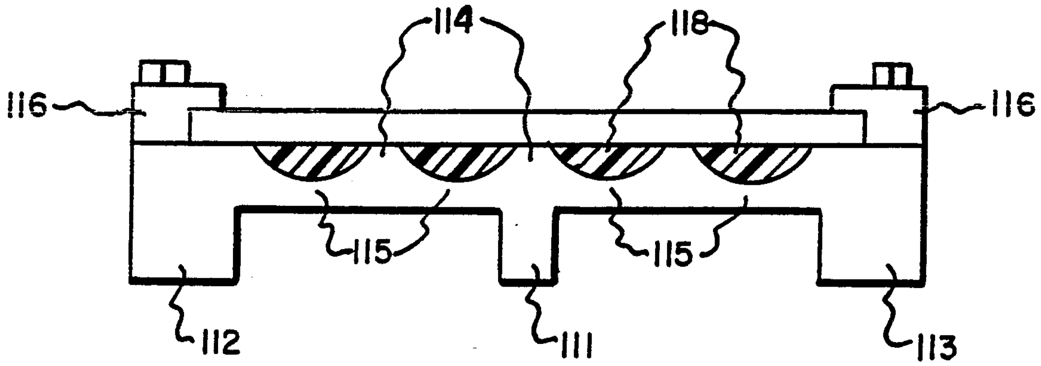


Fig. 12.



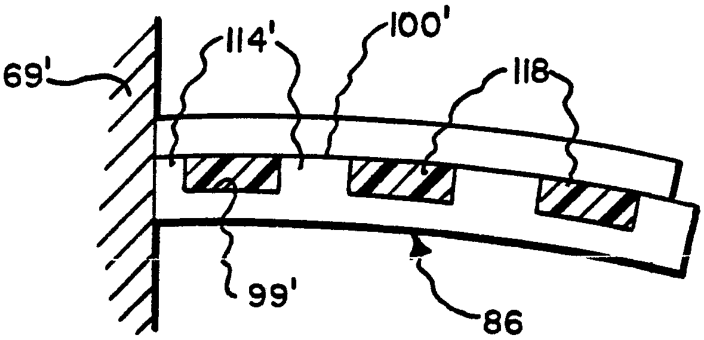


Fig. 13.

INTERNATIONAL SEARCH REPORT

International Application No PCT/US91/00240

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(5): H01L 41/08
U.S.CL.: 310/329

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	310/329-332,348 73/35,854,517R

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X	US, A, 4,660,410 (ASANO ET AL) published 28 April 1987 See entire document.	1-23
X	US, A, 4,254,354 (KEEM) published 03 March 1981 See entire document.	1-23
X	US, A, 4,924,131 (NAKAYAMA ET AL) published 08 May 1990 See entire document.	1-23
Y	US, A, 4,494,409 (KONDO ET AL) 22 January 1985 See entire document.	1-23
Y	US, A, 4,393,688 (JOHNSTON ET AL) publihsed 19 July 1983. See entire document.	1-23
A	US, A, 3,148,290 (DRANETZ ET AL) published 08 September 1964. See entire document.	1-23
A	US, A, 2,808,522 (DRANETZ) published 01 October 1957 See entire document.	1-23

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2] 21 MAY 1991	Date of Mailing of this International Search Report [2] 02 JUL 1991
International Searching Authority [1] ISA/US	Signature of Authorized Officer NGUYEN NGOC-HO INTERNATIONAL DIVISION For MARK BUDD/C.D. 6-6-91 Ngoc Ho Nguyen

Form PCT/ISA/210 (second sheet) (May 1986)